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Wind Resource Characterization Results to Support the Sandia Wind Farm Feasibility Study August 2008 through March 2009

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Abstract

Sandia National Laboratories Wind Technology Department is investigating the feasibility of using local wind resources to meet the requirements of Executive Order 13423 and DOE Order 430.2B. These Orders, along with the DOE TEAM initiative, identify the use of on-site renewable energy projects to meet specified renewable energy goals over the next 3 to 5 years. A temporary 30-meter meteorological tower was used to perform interim monitoring while the National Environmental Policy Act (NEPA) process for the larger Wind Feasibility Project ensued. This report presents the analysis of the data collected from the 30-meter meteorological tower.

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1 INTRODUCTION

Sandia National Laboratories Wind Technology Department is investigating the feasibility of using local wind resources to meet the requirements of Executive Order 13423 and DOE Order 430.2B. These Orders, along with the DOE TEAM initiative, identify the use of on-site renewable energy projects to meet specified renewable energy goals over the next 3 to 5 years. A temporary 30-meter meteorological tower was used to perform interim monitoring while the National Environmental Policy Act (NEPA) process for the larger Wind Feasibility Project ensued. While the information collected was not at a height that is traditionally used for wind assessments, the data analysis estimates the potential wind resource at the monitoring site.

1.1 Background

Various wind assessment model estimates indicate the potential for fair to excellent wind energy resources in a narrow band along the higher terrain and ridges located in the vicinity of the Department of Energy (DOE) / Kirtland Air Force Base (KAFB) complex. Wind classification is based on the modeled estimate of the wind speed, and is identified in wind power classes [1]. A wind power resource of fair corresponds to a wind power class of 3 that predicts 300 to 400 W/m^2 wind power density for the area. An excellent resource, with a power class of 5, suggests a power density between 500 and 600 W/m^2 for the area. Accurate and complete characterization of the wind is needed to identify the actual wind resources in the vicinity of the DOE/KAFB complex. An evaluation of the wind resource is needed to include in the decision to move forward with all other regulatory, permitting, environmental, and educational matters. Lack of a suitable resource indicates the project will not generate enough electricity to recover expenses. A large resource may indicate that funding would be available to mitigate perceived or real concerns. There are many other environmental facets and additional work that fold into the decision of suitability of a site for wind power.

A number of potential monitoring sites were reviewed in the effort to identify a site that a 50-meter meteorological tower would be located. In the interim period, a 30-meter tower was located in an accessible permitted area to assist with the wind resource investigation. The interim monitoring site was located on DOE permitted land in the Manzanita Mountains. The site was commissioned on August 4th, 2008, and removed on April 6th, 2009. The location of the meteorological tower was: N 34° 59’ 20.7” W 106° 24’ 43.3” with an elevation of approximately 2270 meters above Mean Sea Level (MSL). The site was located in a clearing near a ridge above Coyote Canyon. Figure 1 provides an overview of the area.

2 DATA COLLECTION AND PROCESSING

The 30-meter meteorological tower was equipped with two wind speed sensors, two wind direction sensors, two temperature sensors, one relative humidity sensor, and one barometric pressure sensor. The atmosphere was sampled once a second, and data was averaged in 10 minute intervals. Standard deviations and maximums were also recorded for some of the parameters. The actual measurement heights were 10 and 29.3 meters. The top measurement height is identified throughout this report as 29 or 30 meters.

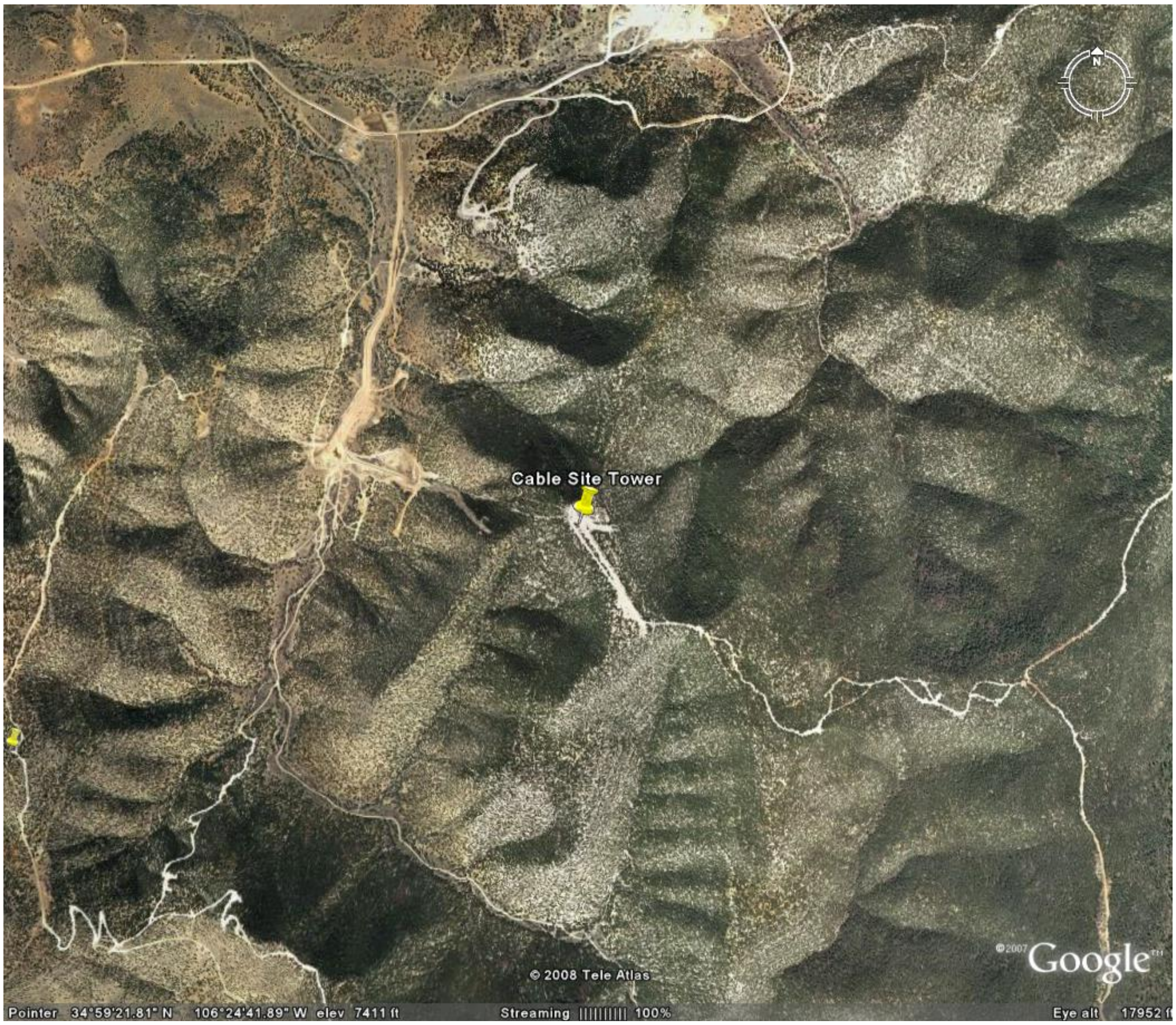


Figure 1. Google Earth image of the cable site meteorological tower location.

All data were reviewed for accuracy. Data were considered invalid if they did not seem to represent the actual conditions at the site. There were a few periods of missing data due to the need for manual data collection and the capacity of the data logger. In December 2008, icing and cloudy conditions impacted the solar driven batteries, resulting in lost data and several hours of invalidated data while the data logger slowly lost the capacity to function.

Data recovery for December was only 33%, and the data is not evaluated in this report. The tower configuration included automated low powered radio telemetry, but communications were incomplete and intermittent. To ensure maximum data recovery, data were collected once a week.

2.1 Summarized Data Results

The data summarized in this report were kept in the 10-minute averaging intervals. Data were not conditioned into hourly averages in an effort to keep the temporal scale of the data and nature of the site from being smoothed. Table 1 is a summary of data taken at the Cable Site between August 4th 2008, and March 31st of 2009.

Table 1. Climatological Summary for the Cable Site Tower August 2008 through March 2009.

	Data	30 meter		10 meter		Relative	Local (hPa)
Month	**Recovery**	**WS(m/s)**	**Temp (C)**	**WS(m/s)**	**Temp (C)**	**Humidity**	**Pressure**
August	90.6%	5.97	18.39	4.98	18.64	56.43	777.9
September	100.0%	6.26	16.35	5.08	16.72	43.84	779.8
October	100.0%	6.78	11.32	5.40	11.54	42.91	779.3
November	100.0%	7.42	5.32	5.48	5.48	44.61	777.2
December	33.1%	MM	MM	MM	MM	MM	MM
January	100.0%	7.00	1.50	5.24	1.69	47.65	776.48
February	100.0%	8.15	3.73	6.37	4.01	31.33	775.1
March	100.0%	8.15	5.32	6.38	5.60	40.57	773.0

3 WIND SPEED AND TURBULENCE ANALYSES

Data summarized in the previous section can be used as an indicator of wind potential for a given area, but details of wind analyses are important to get a better estimate of the wind power that may be generated at that site. Figure 2 depicts the 29-meter level scalar wind speed (WS) observations and two distributional fits for the data. The two fits were the gamma distribution (solid black) and the Weibull distribution (dashed), a special case of the gamma distribution. The information in the insert for summary statistics is for the Weibull curve, though there seems to be a better fit of the gamma distribution for the 10 minute data. The average wind speed over the seven month period used in the analyses was approximately 7.15 m/s.

Figure 3 identifies the hourly averages of WS and turbulence intensity (TI) for each month. Turbulence intensity, which is defined in wind industry terms as σ/WS, is used to characterize rapid disturbances and irregularities in the wind [2]. These rapid disturbances may decrease power output for a given wind speed, and cause unbalanced loading on turbine components. While the graph is busy, careful review of the figure reveals a number of features. It should be noted that the trends identified in this section are based on summarized data, and the timing of strong synoptic systems may nullify the patterns observed in the summarized data.

It is easily noted that there is a period of increased wind speeds at night, mainly after local sunset, for all months except January. An increase in winds above the surface at night usually occurs as a function of frictional decoupling from the surface as the atmosphere becomes stable. The intensity and period of the nocturnal wind varies. Based on January and November trends, the increase of nocturnal winds over the speeds found in the afternoon may be minimized during low sun season. For most months, the nocturnal winds between 1900 and 2400 local time are the maximum winds found in the diurnal trace. The exceptions to this are January, since winds do not increase after sunset, and March, when strong winds tend to mix the lower boundary layer and tight pressure gradients may keep the wind blowing most of the day and night.

The maximum TIs in Figure 3 are generally found in mid-afternoon, which is consistent with the timing of maximum convective overturning of the surface and lower atmospheric boundary layer. Higher TIs are more apparent during August and September, the period of lowest winds and strongest daytime instability and convective mixing during the data collection period.

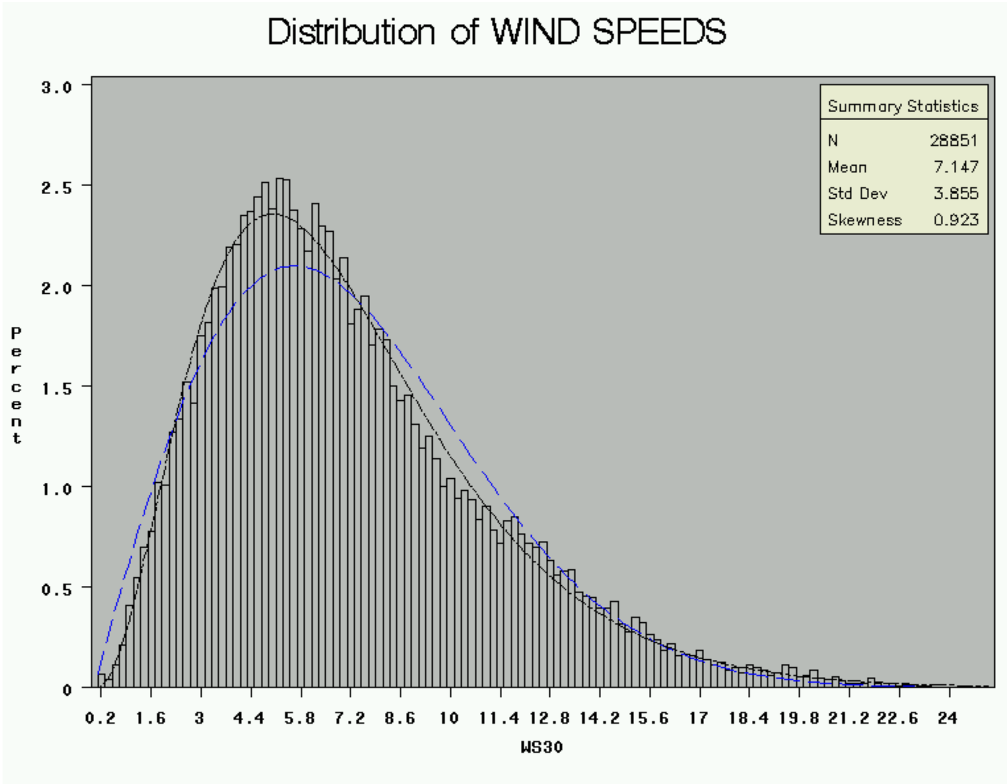


Figure 2. Distribution of 10 minute wind speeds for August-November 2008 and January-March 2009 at the 29 meter level.

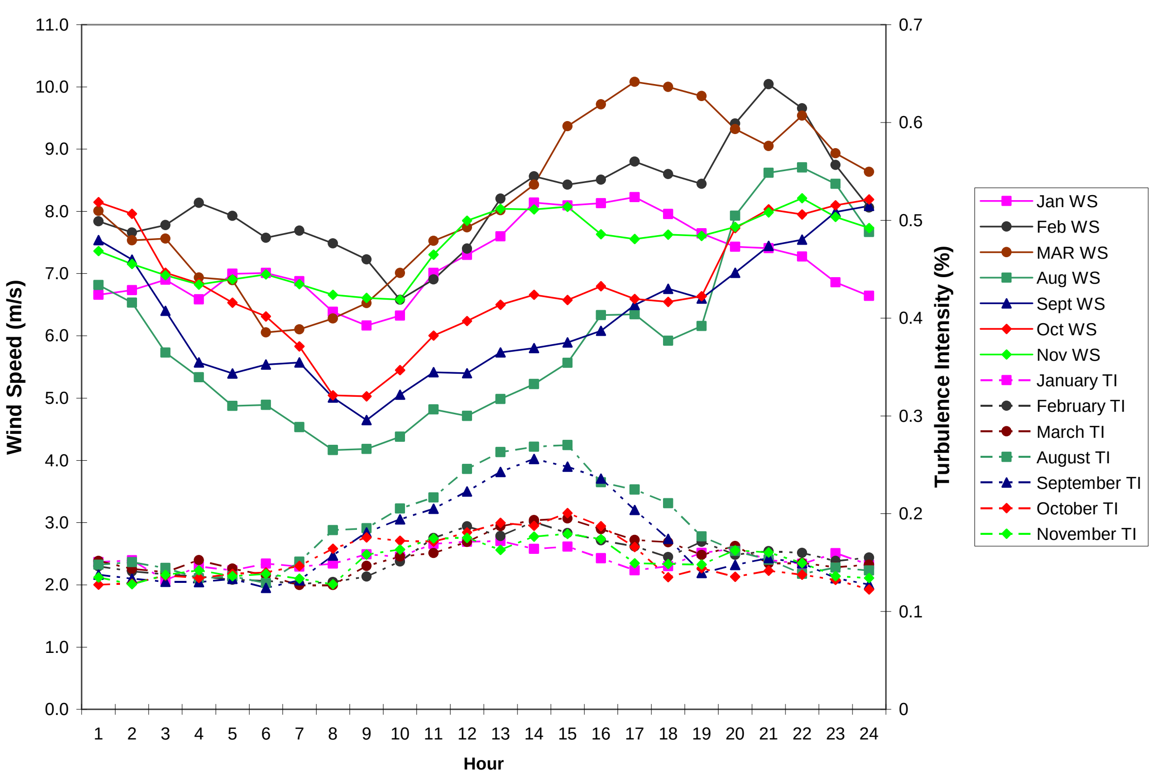


Figure 3. Diurnal trace of wind speeds and the TI for each month.

The use of averaged and smoothed TI does not provide detail that may benefit wind farm operations. Another analysis of TI at a site is based on the 10-minute data. Figure 4 includes the 10-minute TI plotted as a function of WS when the WS at 30m is at least 4.0 m/s. Note that large TI values can be found at speeds where most power curves indicate rapidly increasing derived power. The higher TIs may have operational implications during these 10 minute time intervals. TIs are generally thought to decrease with height, but increases in turbulence with increasing height are noted in some locations. Additional investigation will be needed to identify TIs above 30 meters at this complex terrain location. Figure 4 indicates a decreasing scatter of the TI values as wind speed increases. The mean of the TI samples is 0.155, or 15.5 percent.

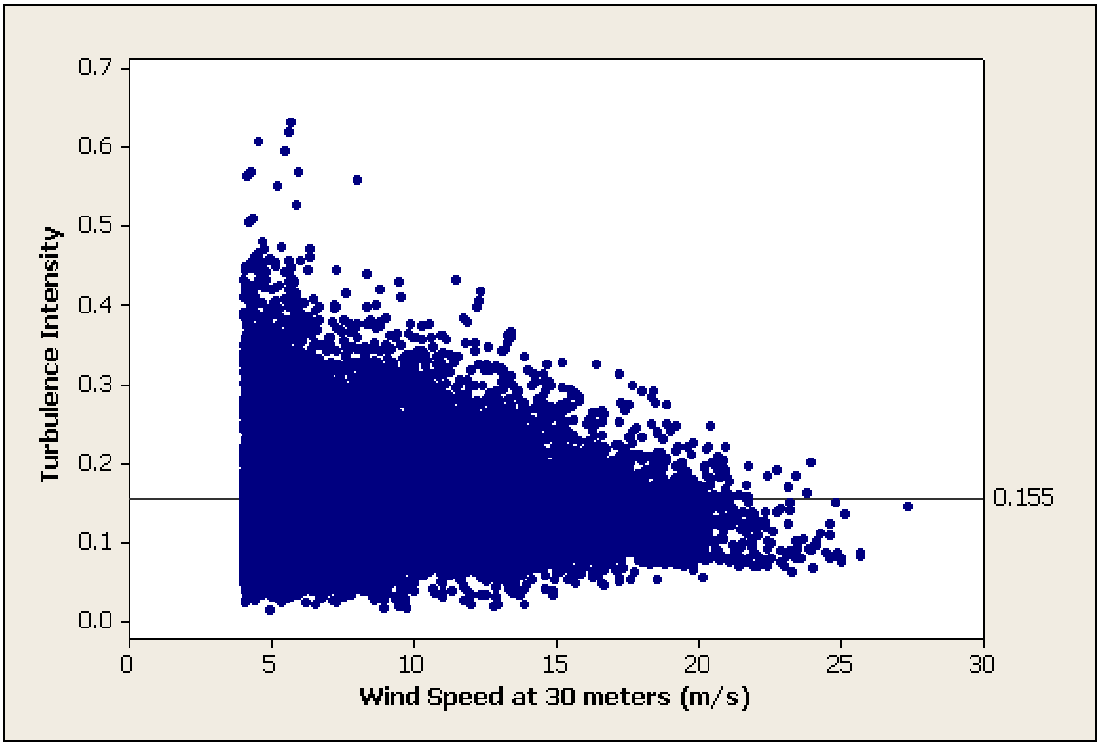


Figure 4. Turbulence Intensity plotted as a function of Wind Speed.

A parameter that is generally not included in wind resource assessments is the standard deviation of the wind direction, or wind direction sigma (WDSig). This parameter identifies the variability of the wind direction within each sampling interval. This is another way to estimate a different character of wind variability. Figure 5 depicts the WDSig as a function of wind speed. Note that there are similar trends to the turbulence intensity and WDSig with scatter decreasing as wind speed increases.

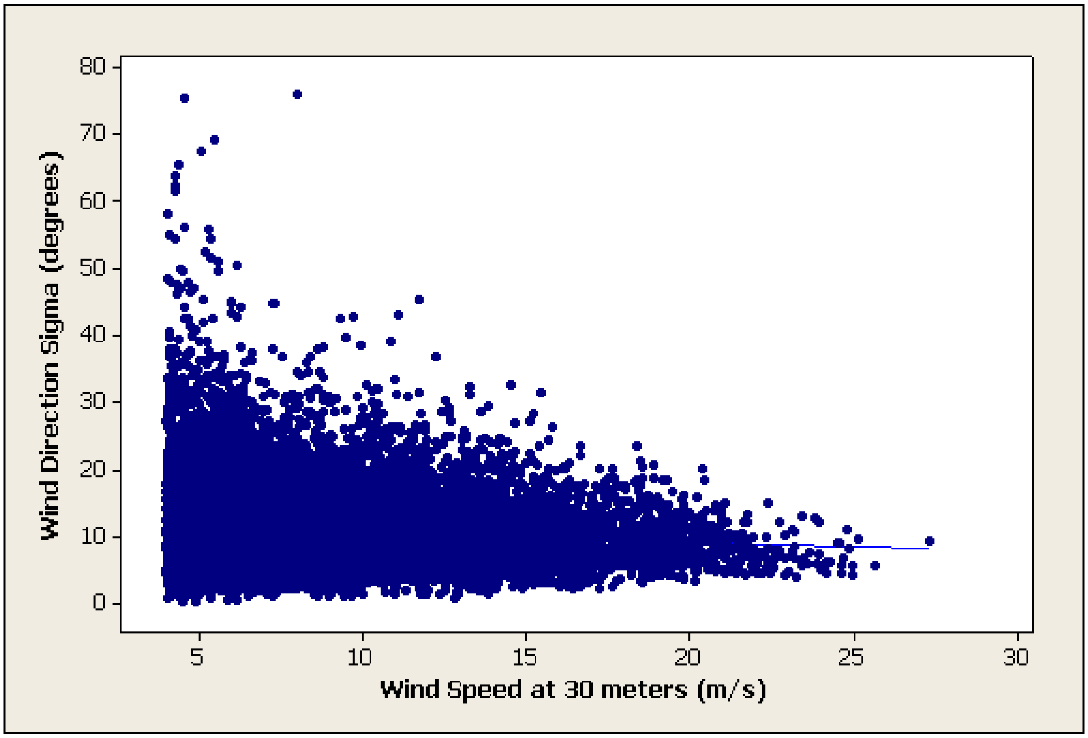


Figure 5. Wind Direction variability (WDSig) plotted as a function of wind speed.

Figure 6 identifies the relationship of the TI and WDSig to each other. There is a general relationship of the turbulence intensity based on speed and the direction variability, though there is quite a bit of scatter to the data. The impact of large variability of wind direction on operations is not well established, and needs more investigation. In general it is anticipated that for a given turbulence intensity and wind speed, adding additional variation in the wind may decrease power produced.

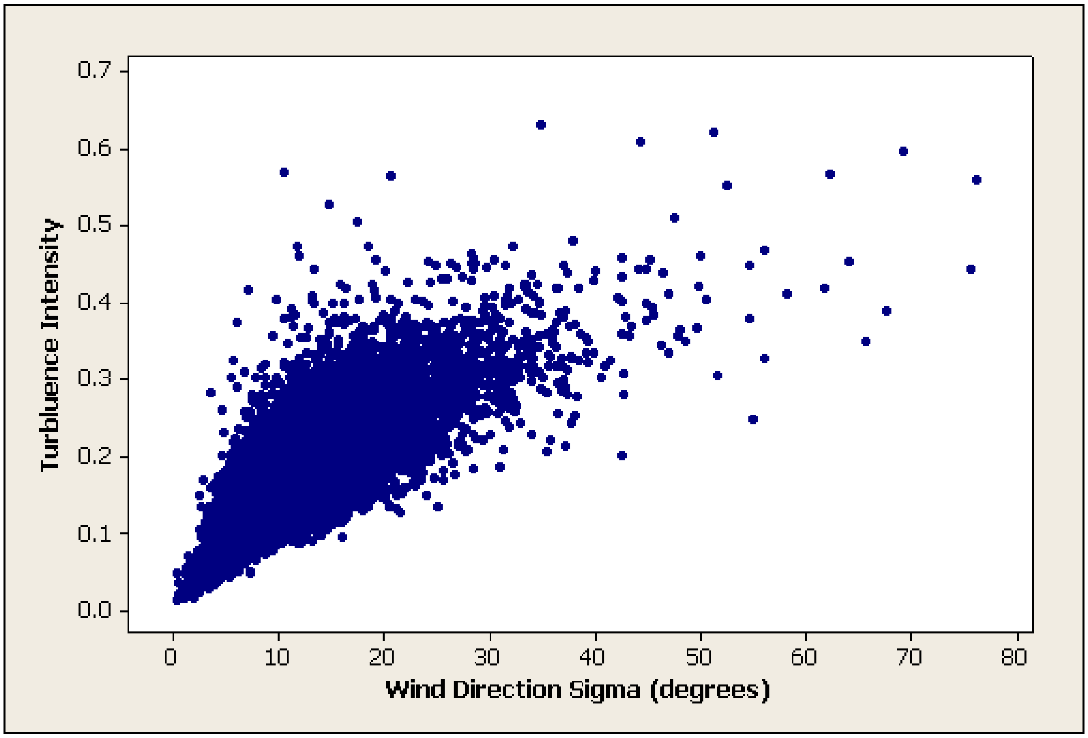


Figure 6. The relation between TI and WDSig parameters at the Cable Site.

4 WIND DIRECTION ANALYSIS

Predominant wind directions in the valley and lower elevation sites in the vicinity of the DOE/KAFB complex are influenced by drainage and slope flows characteristic in mountainous terrain. In addition, some seasonal changes in the wind directions are noted at lower elevations. It is therefore anticipated that seasonal variations may be present at the elevated location of the Cable Site tower. Figure 7 shows the composite windrose for the 7 month data recorded at the cable site. The windrose shows the direction from which the wind is blowing.

The predominant winds are generally from the SW, though there are significant changes in the nature and direction of the wind based on season. These seasonal changes in direction may also include variations in surface roughness and calculated shear exponents. Due to the configuration of the terrain at this site, which includes a drop off in terrain to the canyon below in the northwest and north directions, winds may undergo a speed enhancement when coming from these directions. Speed enhancement generally occurs over a certain height and distance of a given hill or ridge, so the nature of the northwest wind intensity in Figure 7 may not directly transfer to hub height and above for areas located away from this monitoring site. See Appendix 1 for graphic details on the seasonal variations of the wind direction.

The monthly details in Appendix 1 show a significant ESE and SE component of wind direction in August and September. Additional analysis of the fall season data identified these directions were a nocturnal signature. This component to the wind washed out as low sun season approached. The NW component of the wind increased dramatically in November and became the predominant direction in January. The increasing NW trend is expected as synoptic systems and frontal passages driving cold air from the northwest increase and the jet stream sinks south in the low sun season. A notable absence of winds from the NNE sector is present in Figure 7. The direction minima show up in the NNE or NE sector in lower elevation data also, though not quite as pronounced.

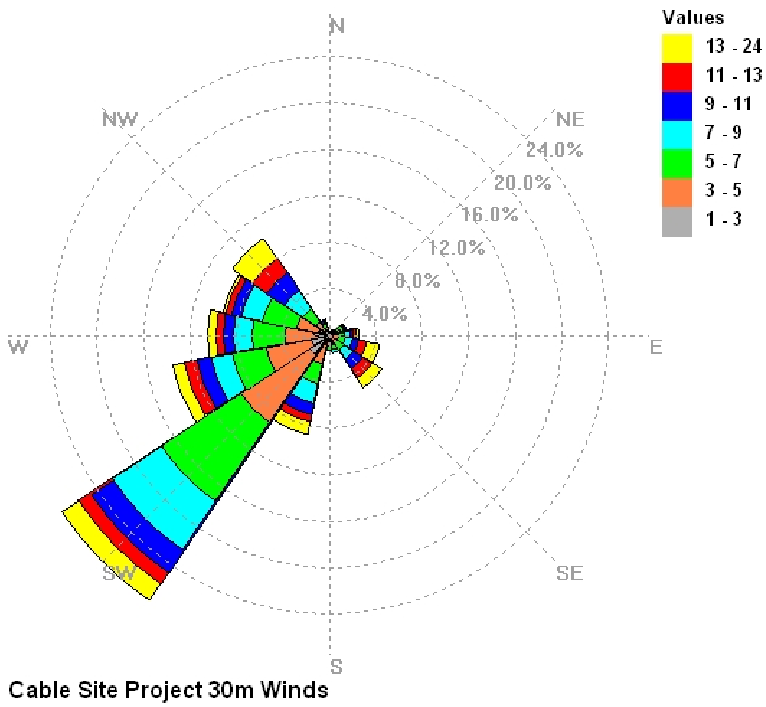


Figure 7. Summary windrose for the cable site tower for August through November 2008 and January through March 2009.

5 ESTIMATES OF WIND SHEAR AND HUB HEIGHT WINDS

Meteorological data for the cable site do not include actual measurements of nominal hub height winds that are generally used for wind resource assessments. Generally, a 30-meter above ground measurement is near the lower tip of the turbine, and most turbine sitings rely on measurements taken at approximate hub heights. However, there are a number of mathematical relationships that may be used to estimate winds above and below measurement heights. The entire dataset was used to develop the estimates in this section.

One estimate that is commonly used in the wind industry is the vertical shear exponent, based on the power law relationship. This estimate needs data at 2 levels of the atmosphere. In the wind industry wind shear is defined as the change in horizontal wind speed with a change in height, and is influenced by site-specific characteristics. This estimate uses the mean of all data, and does not take into account stability or adiabatic influences that affect wind profiles, and thereby wind shears throughout the day. The wind shear exponent at the cable site using all data collected is:

$\alpha = \log\{V2/V1\}/\log\{Z2/Z1\}$ = LOG [7.17/5.61]/ LOG[3]

$\alpha = 0.2233$.

If interest in the vertical shear exponent is refined to only when the blades would actually be turning, the low wind speeds should be omitted from the analysis. Assuming that a 4 m/s WS at 30 meters would be getting close to a 4.5 m/s cut-in speed at 50 meters, and using a dataset where winds < 4.0 were omitted, the a = 0.2319. While the average exponent is of value for approximations, it is recognized shear exponents vary over time. Figure 8 shows the 10-minute shear exponents plotted as a function of wind speed.

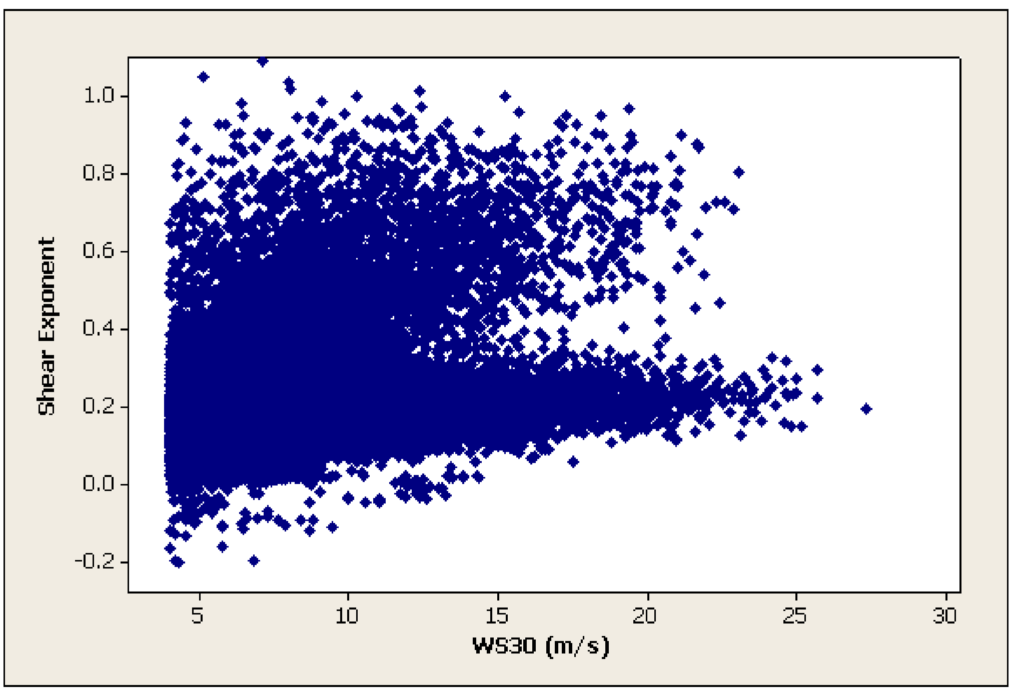


Figure 8. The 10-minute shear exponents plotted as a function of WS.

There is not a strong correlation of shear exponents with wind speed, but Figure 8 does suggest two different distributions, which may be related to time of day or wind direction. It should be noted that with the anchor of the shear exponent at 10 meters, large exponents are calculated when the wind goes nearly calm in the evening. Therefore, the frequency of large shear exponents in Figure 8 should be reviewed with caution.

Figure 9 plots the shear exponent with relation to the time of day. Figure 9 is a box and whiskers plot that includes a mean and quartile ranges. The mean is calculated for each 10-minute interval, and connects all the data. Figure 9 shows an increase in the mean shear in the late afternoon and evening, with slightly smaller average shears and inter-quartile ranges during the middle part of the day when TI is highest. Note the highest variability in the shear exponent occurs from approximately 1800 local time through 2400.

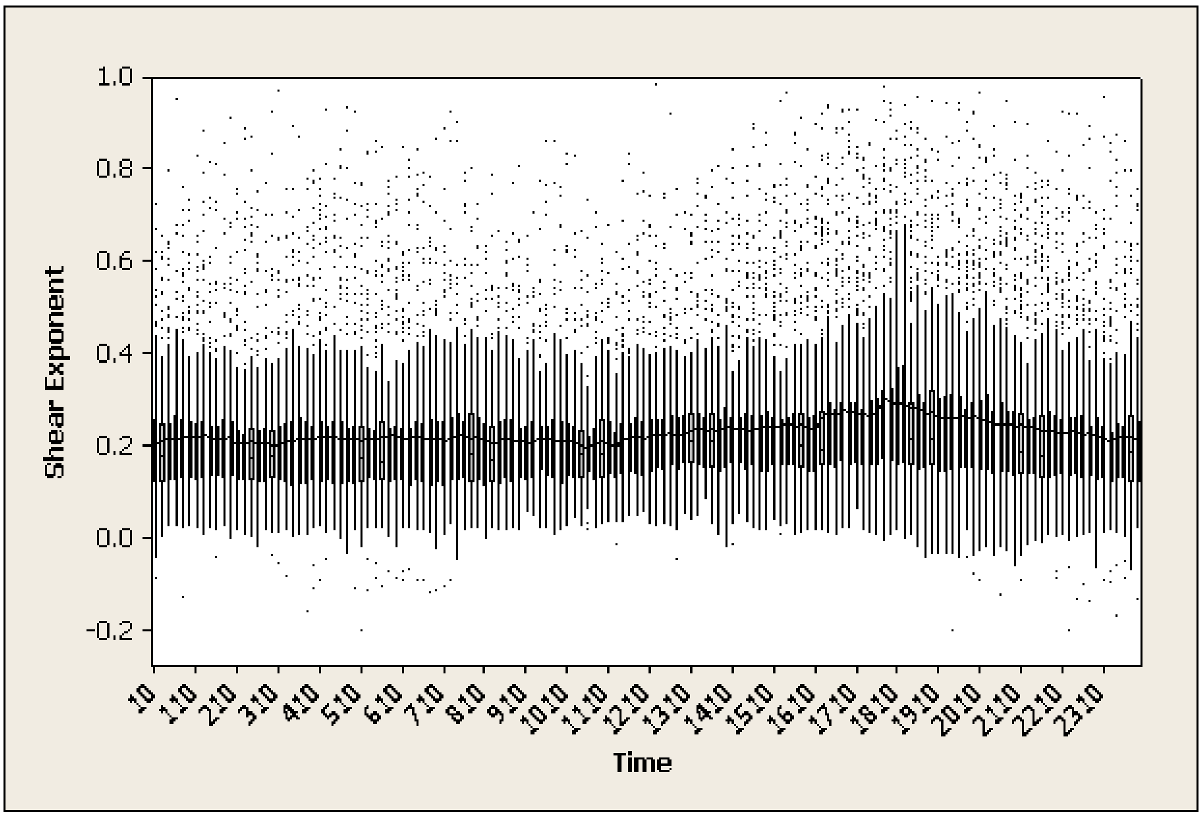


Figure 9. Box and whisker plot of the shear exponent as a function of time of day.

It should be emphasized that the tower is in a clearing, but trees beyond the clearing are 5 to 10 meters in height. The trees may have an effect on surface roughness of the area so that the wind speed at 10 meters may be slightly impacted. The implication of this would be that the measured 10-meter wind speed is slightly lower due to roughness effects, which then produces higher shear exponents. This coupled with potential speed enhancement at 30 meters when the wind comes from the NW may create the large shear exponents, so the shear exponent data should be used with caution. Figure 10 depicts the shear exponent distribution as a function of the wind direction.

Figure 10 shows that, for directions from approximately 90 to 303 degrees (E through WNW), the shear exponents fall predominantly between 0.1 and 0.35 and rapidly escalate approximately by a factor of two for winds from the NW through NE. This plot indicates there is a directional influence to the higher shear exponents. It is possible that speed enhancement of the winds at 30 meters is partially responsible for the large exponents.

These high shear exponents are most likely very site specific. The three factors that influenced the shear exponents reported in this document are the measurement heights in reference to the terrain, not filtering the data for the 10-meter wind speeds < 4.0 m/s, and the hypothesized speed enhancement under NW wind conditions. The lower shear exponent that was calculated with all the data should be used to conservatively estimate hub height winds.

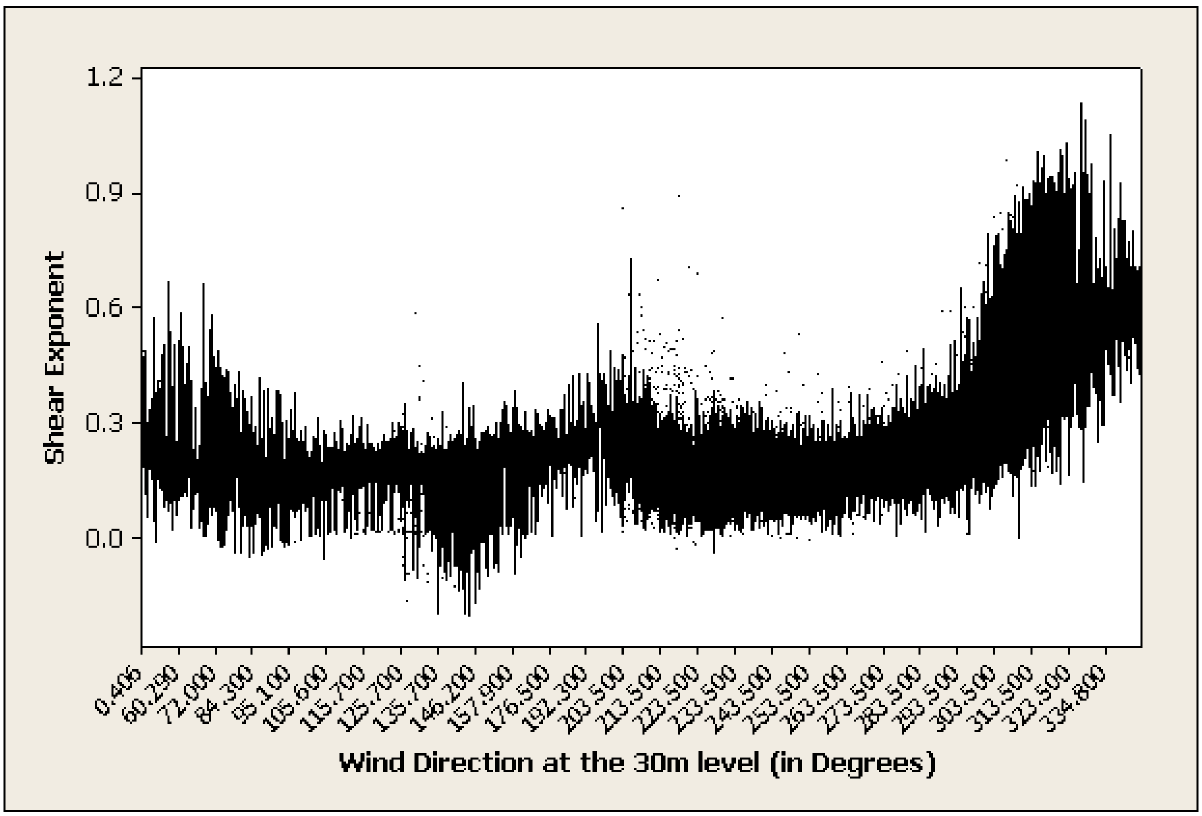


Figure 10. The Shear exponent plotted as a function of the 30-meter wind direction at the cable site.

Another technique used to estimate wind profiles is based on the logarithmic profile and the equation $WS_z = (u_*/k)*LN [Z/Z_o]$. The graphical plotting of the data collected will produce a site specific equation based on natural logarithmic fitting of the collected data and the surface roughness. Figure 11 depicts this technique and data fitting curves.

This technique relies on near-neutral conditions in the atmosphere and is usually applied to estimate surface roughness when wind speeds from two or more points in the surface layer are known. Using a technique that includes surface roughness incorporates some site-specific micro-physics into the wind estimate. In the first estimate, winds < 4.0 m/s were omitted from the data used to develop the profile. The use of the data $\geq$ 4.0 m/s at 30 meters provides a relationship that is close to anticipated operating conditions of a turbine with hub height at 50 or 60 meters and is closer to near-neutral conditions.

The second profile is based on all the data. Graphical interpretation of this technique includes an estimate of surface roughness, and identification of the wind shear through a potential turbine profile.

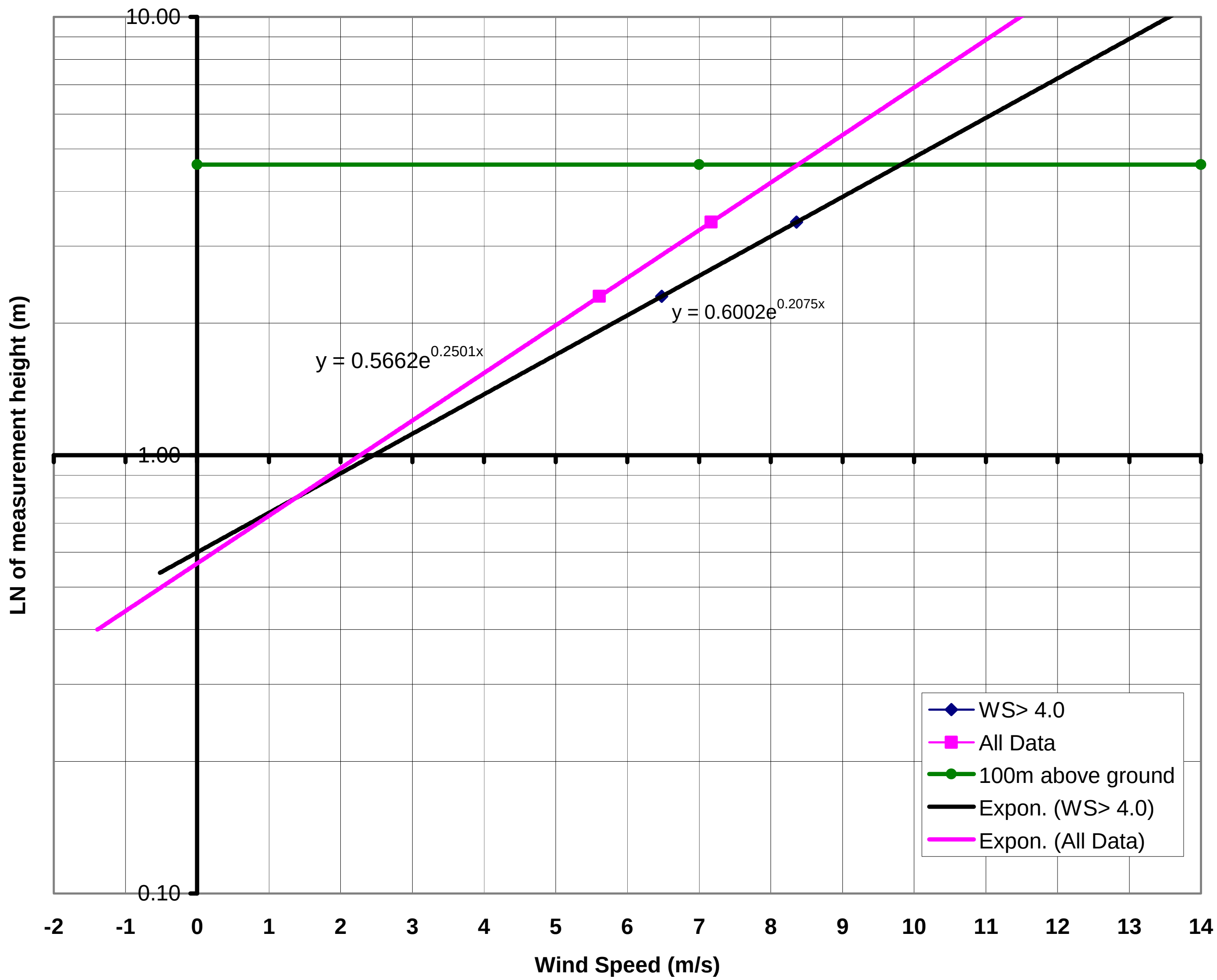


Figure 11. Wind Profile plots and site specific equations.

Table 2 includes the averages plotted in Figure 11. It also includes a summary of shear exponents and surface roughness based on the various data averages.

Table 2. Wind Speed Averages and Shear Exponent Summary.

Data	10m	30m	Exponent	Roughness
WS $\geq$ 4.0	6.48	8.36	0.231872	0.6002 m
All Data	5.61	7.17	0.223332	0.5662 m

Surface roughness is used here as a qualitative measure of the validity of the technique, and can be used in other meteorological relationships. Data in a monthly report show that the technique is a good approximation since the local surface roughness estimate for all data and the estimate using strict method protocol of near-neutral conditions was within 10 percent, and is close to what is expected for the terrain and vegetation. It is a reasonable approximation that the surface roughness for the tower area is between 0.5 and 0.6 meter.

Figure 11 also lists the equations for the logarithmic relationship of wind at this site. For example, the profile equation based on WS > 4.0 is $y = 0.6002e(.2075x)$. The wind speed at any height for this location may be found by X_y = LN[y/.6002]/.2075 where y must be the natural log of the height in meters. A comparison of the estimates using both techniques for the two different averages is listed in Table 3. Table 3 reveals higher wind speeds and shears when using the vertical shear exponent method as compared to the logarithmic profile method for an anticipated rotor blade profile. It is also noted that the difference between the estimates increases in amplitude as elevation increases. While the 50 meter estimates for the "all data" comparison are within 3 % of a mean of the two estimates, the difference grows to 7% for the 100-meter estimate.

Table 3. Estimates of wind speeds at hub heights and beyond using both techniques and average wind speeds.

	10m WS	30m WS	Exponent	50m Estimate	60m Estimate	100m Estimate
Profile WS $\geq$ 4.0	6.48	8.36		9.034	9.253	9.820
Exponent WS $\geq$ 4.0	6.48	8.36	0.2319	9.370	9.760	10.939
Profile All Data	5.61	7.17		7.574	7.752	8.213
Exponent All Data	5.61	7.17	0.2233	8.036	8.370	9.382

From the above table, the estimate for hub height winds at 60 meters using all data is estimated to be 7.8 m/s. For anticipated operating conditions, the estimated average wind speed may approach 9.3 m/s. The profile method was used to identify the potential speeds since it is more conservative in nature, and includes surface roughness effects.

6 WIND POWER DENSITY CALCULATIONS

The wind power density (WPD) was calculated for each 10-minute interval using the 30m wind speed data $\geq$ 4.0 m/s. This assumption turns out to be a fair assumption for power production at a 60-meter hub height when using either mathematical relationship. For example, if using the shear exponent, the WS at 60 meters, based on a 4.0 wind speed at 30 meters, would be:

$WS6_0 = Ws_{30}*(60/30)^{0.2233} = 5.0$ m/s

If using the variations from Table 3, the wind speed at 60 meters from the profile method would be about 8 percent less, or 4.6 m/s.

The WPD was calculated using standard methods [2] where the WPD for each data point is calculated, and an average taken from the sum of all WPDs. Actual pressure and temperature were used to develop the density for each data point. The mean seasonal pressure of 778 Hectopascals was used in the calculations for the 3-week period in August when the actual atmospheric pressure was not available. The calculation is:

$WPD = (\rho WS^3/2)$

The average WPD was calculated from the 24,004 data points that were at or above 4.0 m/s. Note that, from a perspective of time, the turbines are in “power producing mode”, with a cut in speed of ~ 4.5 m/s (at 60 meters), the percentage of time is 24004/30491, or 78 percent.

The WPD using the 30-meter data was 458 watts / m^2. This is most likely an underestimate since the wind speeds used are the 30-meter level wind speeds.

For an increase of 0.5 m/s between the 30m and 60m levels for each data point, which is consistent with the values derived from the most conservative estimate in Table 3, and the data in Figure 11, the estimated WPD for the cable site is 520 watts / m^2 for a turbine with a 60 meter hub height. The estimate for an 80 meter hub height is approximately 560 watts / m^2 as there is a smaller difference between the 60 and 80 meter levels

7 SUMMARY AND CONCLUSIONS

Data from a 30 meter meteorological tower was used to complete analyses applicable to wind resource assessments. The data show promising wind speeds for utility scale wind turbines over the period of data collection. Based on the 30-meter data, which indicates an average wind speed of 7.17 m/s, an average wind speed at 60 meters for that time period is estimated to be a minimum of 7.75 m/s. The estimates developed in this report place the area at a minimum of a Class 4 Wind Power site. The area has the potential to produce power approximately 78% of the time, based on the seven-month collection period that included several months of the windy season, and several months of the low wind season.

There seemed to be site specific influences that enhanced the speed and shear exponent data for approximately 10 percent of the data collection time period. This mostly occurred during low sun season when there was a larger component of NW winds. This highlights the importance of site location and various flow factors in complex terrain. The frequency of exponents above 0.4 may have been a function of multiple factors including speed enhancement with Northwest wind directions, and the 10-meter level sampling height, and may not be representative of the exponents for the general area.

The calculated average wind power density for this 2270 meters MSL site for the 7-month duration of the project was 458 watts/m2 using site specific density and temperatures for the 30-meter tower. Using a conservative estimate of 60-meter winds increasing only 0.5 m/s higher than the 30-meter speed, the WPD may be closer to 520 watts/m^2.

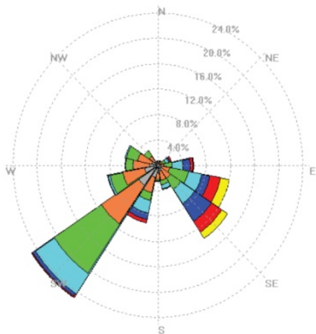
The data show that the effort to place a tall meteorological mast or a remote sensing device to better characterize the site is warranted. It should be emphasized that characterization through the anticipated rotor plane of the turbine should be performed rather than just the lowest layers through hub height due to the complex terrain of this area. Characterization of the entire rotor plane may be completed using remote sensing technology used in tandem with a meteorological tower that extends to the anticipated hub height. Particular attention to seasonal patterns should be included in the planning if the remote sensing campaign will be of short duration.

8 REFERENCES

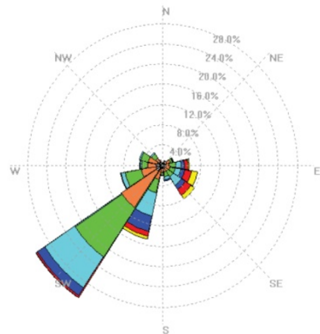
1. Michael Brower, *Wind Resource Maps of New Mexico*, Prepared for State of New Mexico Energy, Minerals, and Natural Resource Department, May 2003.

2. AWS Scientific Inc, *Wind Resource Assessment Handbook*, Fundamentals for Conducting a Successful Monitoring Program, Prepared for The National Renewable Energy Laboratory, April, 1997.

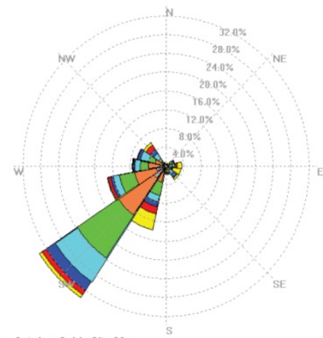
APPENDIX A: MONTHLY WIND ROSES



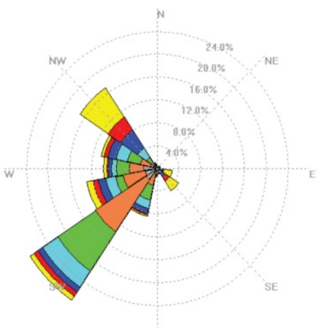
August Cable Site 30m



September Cable Site 30m



October Cable Site 30m



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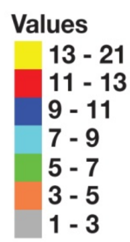

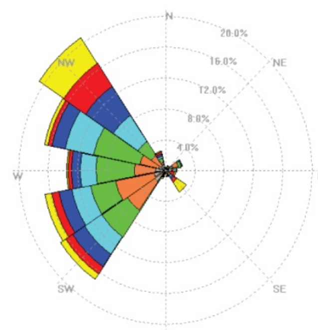

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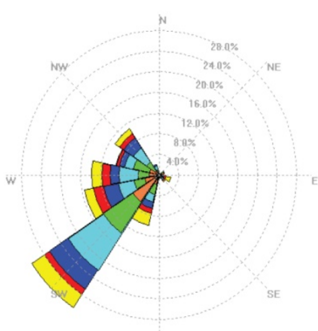
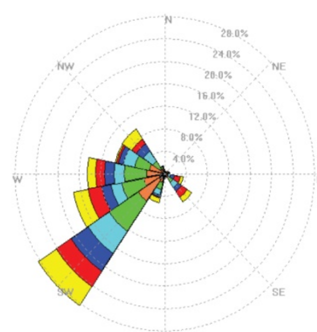


February Cable Site 30m



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