Podium presentation at the AWEA WINDPOWER Conference, Chicago, May 2009

EFFECTS OF COMPLEX WIND REGIMES ON TURBINE PERFORMANCE

Elisabeth Rareshide, Andrew Tindal[1], Clint Johnson, AnneMarie Graves, Erin Simpson, James Bleeg,
Tracey Harris, Danny Schoborg
Garrad Hassan America, Inc.

1 INTRODUCTION

Wind turbine power performance for the annual energy production calculations of wind farms has traditionally been modeled assuming a set of simple and average input meteorological conditions. Turbine power curve tests are also performed with this assumption, based on criteria defined in the IEC 61400-12-1 [1] standard. While this approach has proven to be adequate for the wind power industry for several years, the increasing size of wind turbines—coupled with an improved awareness of the wind flow variation throughout the boundary layer—has generated concern that the effects of complex meteorological conditions on turbine power performance are not well understood.

In the wind-rich regions of the US Great Plains/Midwest region, diurnal variation in the stability of the atmospheric boundary layer is correlated with large fluctuations in shear (both wind speed and direction), turbulence intensity, and temperature. These complex fluctuations generally do not have the same magnitude in areas where neutral atmospheric conditions prevail, such as in Northern Europe where turbine power performance testing has historically been based.

The frequency and magnitude of variation in the above wind flow parameters have been examined here using measurements from several sites across the Great Plains/Midwest region. The sensitivity of turbine power performance to each of these factors has been analyzed using measured power production and dynamic wind turbine models. Results suggest that while power performance variation due to some parameters, such as turbulence intensity, is generally well understood, further research is needed to clarify the wind shear profile throughout the turbine rotor and its time-varying effects on performance in this region.

In addition, increasing numbers of turbine manufacturers are adding restrictions to their power curve warranties to filter out data for these meteorological conditions. Such filters, which are not included in a standard IEC 61400-12-1 test, increase the amount of time needed for testing and may eliminate data that reflect a site's normal wind conditions. This study examines how power curve warranty restrictions affect guarantee levels and the period of data collection needed to complete power performance tests.

1.1 Great Plains/Midwest wind regime

The interior of North America, particularly the Great Plains/Midwest region, supports one of the most robust wind regimes in the world. While the terrain in this region is generally flat and simple, the region's wind regime can be considered complex. The Great Plains/Midwest region experiences a strongly stable nocturnal boundary layer, which is characterized by a large vertical wind speed gradient and low turbulence intensity. Stable conditions can be enhanced when high pressure aloft remains a dominant weather pattern. The daytime boundary layer can often be unstable, however. During unstable conditions, strong vertical mixing creates a generally homogeneous wind profile with relatively higher magnitudes of turbulence intensity and lower wind shear values. In addition, the Great Plains/Midwest region experiences a phenomenon known as the Low-Level Jet (LLJ). The LLJ is due to the meridional heating differences created by the slope of the terrain to the west. The resulting pressure gradient force pulls wind toward the west. The Coriolis force turns it to the right,

---

[1] Garrad Hassan and Partners Ltd.

and thus creates a southerly flow. This region is therefore an important and useful area for the focus of this study.

A typical diurnal correlation between turbulence intensity and wind shear in the Great Plains/Midwest region is shown in Figure 1. For simplicity in this case, daytime is defined as 7 AM to 7 PM, and nighttime is defined as 7 PM to 7 AM.

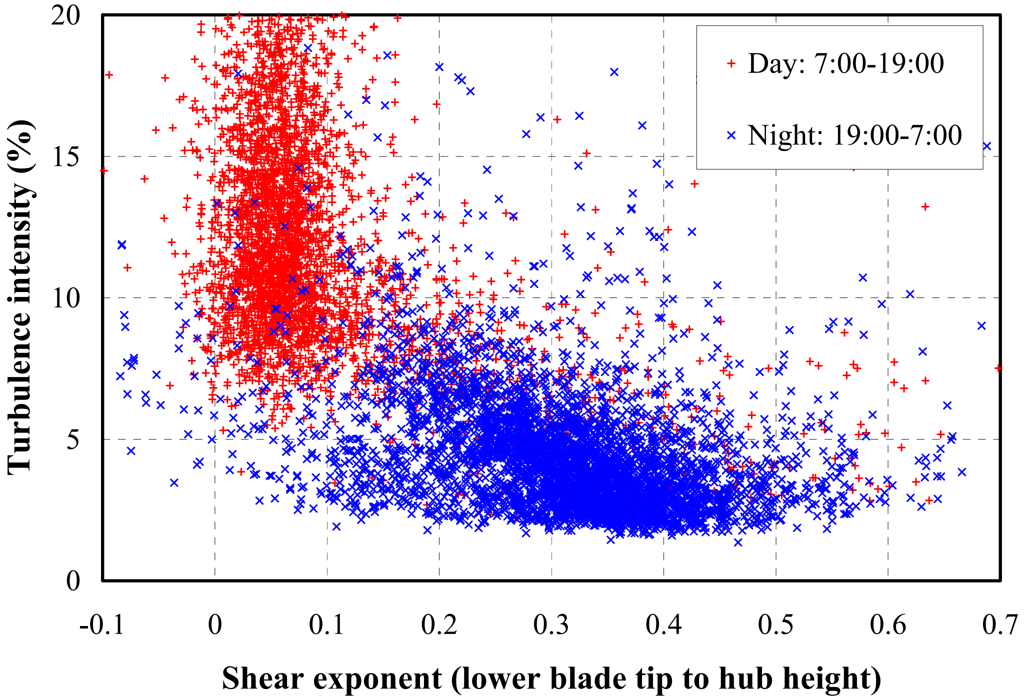

Figure 1 **Turbulence intensity vs. wind shear**

Figure 2 shows the typical seasonal diurnal pattern of wind shear in the Great Plains/Midwest region.

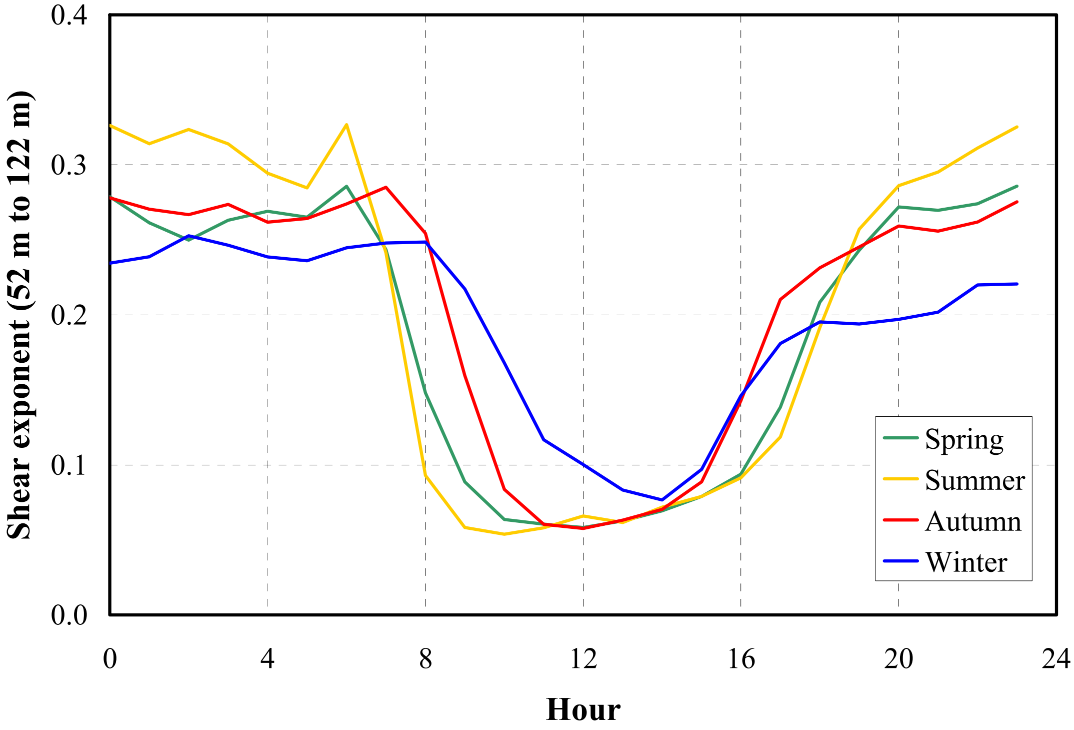

Figure 2 Seasonal diurnal variation in wind shear

Figure 3 shows the typical seasonal diurnal pattern of turbulence intensity in the Great Plains/Midwest region.

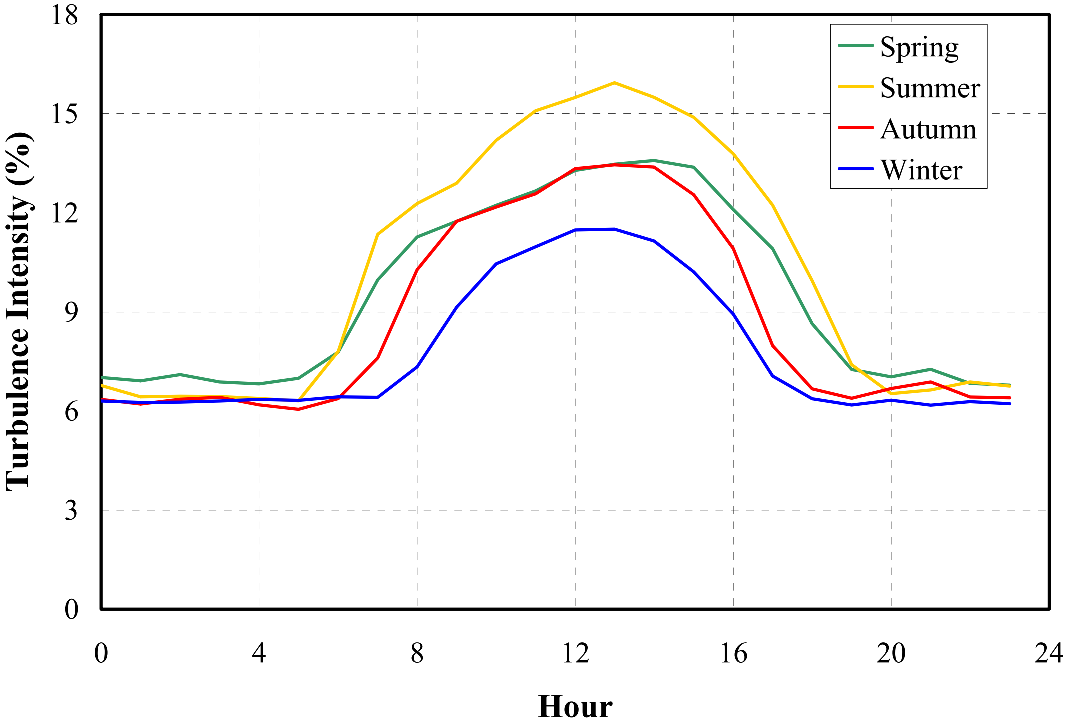

Figure 3 **Seasonal diurnal variation in turbulence intensity**

The Great Plains/Midwest region experiences the nocturnal LLJ particularly in the warm season [2]. Recent studies have suggested that the LLJ might cause significant diurnal variations in performance [3]. Depending on the height and strength of the LLJ, modeling the vertical wind speed profile using the simple power law may provide an inaccurate description of the wind shear profile through the turbine rotor [2]. With the growth of turbine hub heights and rotor diameters, the possibility is increasing that the LLJ can affect turbine performance.

For the purpose of evaluating the impacts on expected Annual Energy Production (AEP) for various scenarios, a generic Great Plains/Midwest wind speed distribution was developed based on met data in the region and scaled to mean wind speeds of 8.5 m/s and 7.5 m/s. Figure 4 shows these distributions.

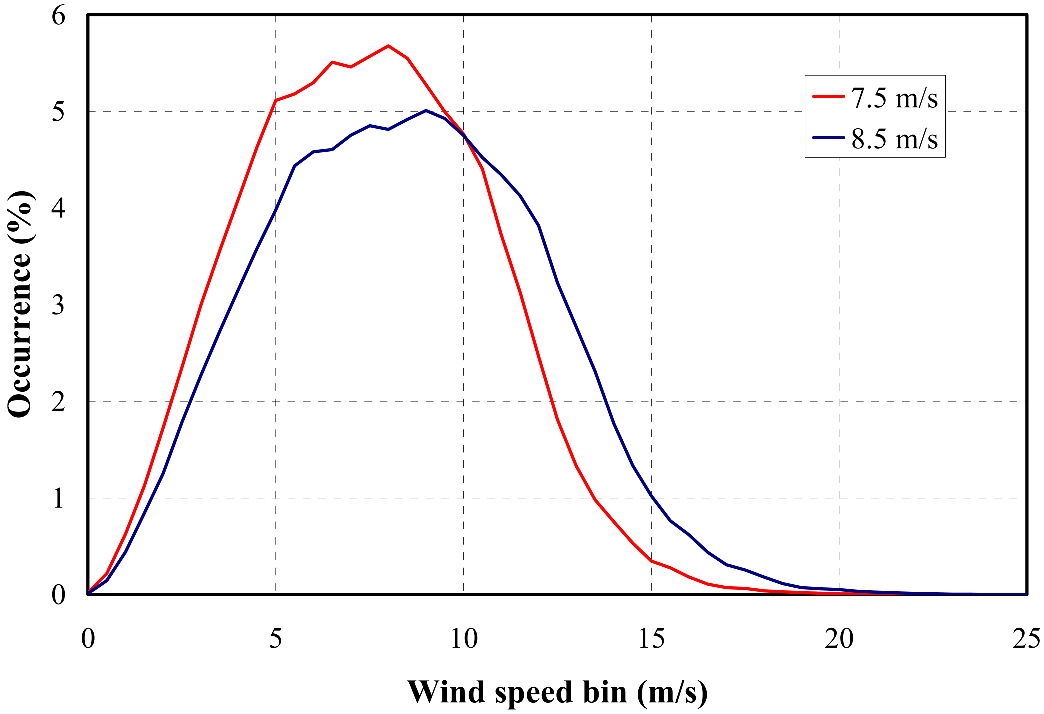

Figure 4 **Generic Great Plains/Midwest wind speed distributions**

2 ANALYSIS OF SENSITIVITY OF TURBINE PERFORMANCE

This analysis broadly followed the IEC 61400-12-1 [1]. Where permanent met masts had been installed in accordance with [1], the data were analyzed per [1]. In the absence of such masts, data from other site met masts or nacelle anemometers were analyzed broadly following the methodology in [1]. Where possible, data from multiple sources at a given site were compared for consistency.

2.1 Sensitivity of turbine performance to turbulence intensity

A number of technical papers, e.g. [4, 5, and 6], discuss how wind turbine power curves are sensitive to turbulence intensity. A typical power curve for a pitch-regulated machine cuts in at about 4 m/s, the power curve is concave between the cut-in wind speed and approximately 10 m/s, and above 10 m/s the power curve becomes convex until rated power is reached. Increasing turbulence intensity increases the machine's power in the concave region of the power curve and decreases the machine's power in the convex region of the power curve. Thus changes in turbulence intensity generally have opposing effects on different parts of the power curve which, depending on the wind speed distribution, may cancel each other out. Most turbine suppliers recognize the potential sensitivity of the power curve to turbulence intensity and associate a supplied power curve with a specific turbulence intensity or turbulence intensity range.

GH has undertaken detailed studies using data both from power curve tests and from ten-minute SCADA data recorded at wind farm sites. To assess the sensitivity of the power curve to turbulence intensity, power curves from these data sets have been derived for unwaked direction sectors binned on turbulence intensity. Some caution must be exercised in the interpretation of these data because other meteorological parameters, such as wind shear, are also varying as turbulence intensity varies. Nevertheless, such data do provide a good indication of the influence of changes in turbulence intensity on the power curve. Furthermore, by combining the binned power curves with realistic wind speed distributions for different wind speeds, the impact of turbulence intensity on annual energy production can be estimated.

Figure 5 below illustrates the power curves that result when the data are binned by turbulence intensity. To reduce the potential effects of wind shear, the data were first filtered for power law shear exponents (α) between 0-0.2. Here low turbulence intensity is defined as approximately 5-11 % and high turbulence intensity is defined as approximately 11-17 %. These definitions were selected in part to include roughly equal amounts of data in each bin, based on the distribution of turbulence intensity and shear in Figure 1.

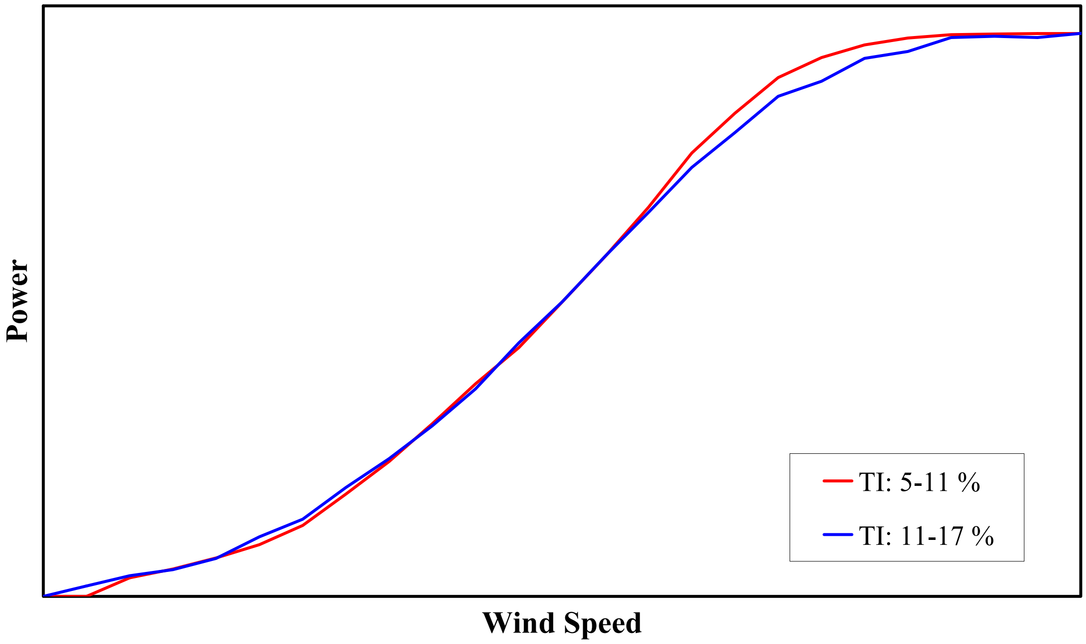

Figure 5 **Power curves binned based on turbulence intensity for wind shear α = 0-0.2**

The effects on AEP of these changes in the power curves are shown in Table 1. The percent change in AEP is based on comparison with all data with shear exponent = 0-0.2.

	Mean wind speed (m/s)			
	7.5		**8.5**	
Turbulence intensity range	Turbine A	Turbine B	Turbine A	Turbine B
5-11 %	0.2 %	0.1	0.3 %	0.2 %
11-17 %	-0.8 %	-0.9	-1.0 %	-1.0 %

Table 1 **Effects on AEP due to turbulence intensity for wind shear α = 0-0.2**

The above results showing how power performance varies as a function turbulence intensity support the adjustment GH adopts when performing pre-construction energy production assessments [6].

2.2 Sensitivity of turbine performance to shear

Most analyses of the wind speeds above measurement height assume the simple power law for the wind shear profile:

$$\left(\frac{U_1}{U_0}\right) = \left(\frac{z_1}{z_0}\right)^{\alpha}$$

where U_1 and U_0 are the wind speeds at heights above ground z_1 and z_0, respectively, and α is the wind shear exponent.

GH has used the GH Bladed wind turbine model to investigate the sensitivity of theoretical power curves to variations in wind shear. Assuming the simple power law for wind shear and a mean wind speed of 10 m/s, Figure 4 shows the theoretical effect of wind shear on power.

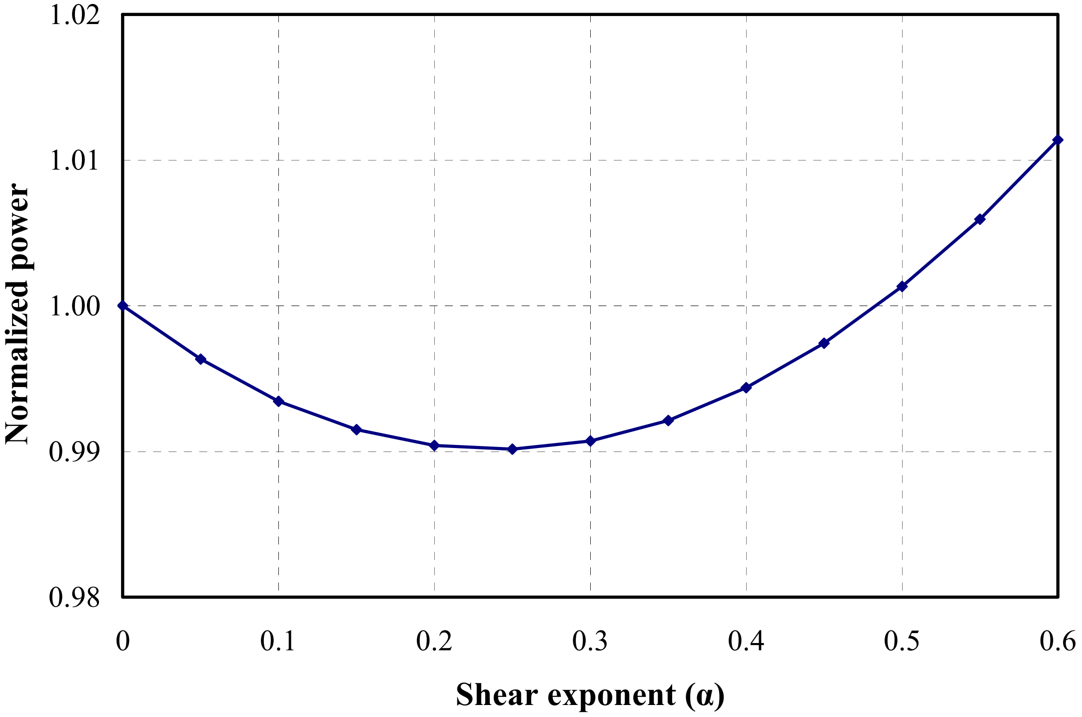

Figure 7 **Theoretical effect of wind shear on power**

The actual variation in power performance with the vertical wind speed profile has not been well studied or documented. Figure 8 shows how the power curve varies with wind shear at a typical site in the Great Plains/Midwest region. To remove the potential effects of turbulence intensity, data were filtered for turbulence intensity between 6-9 %. Wind shear was calculated using the simple power law and wind speeds measured at hub height and the lower blade tip height.

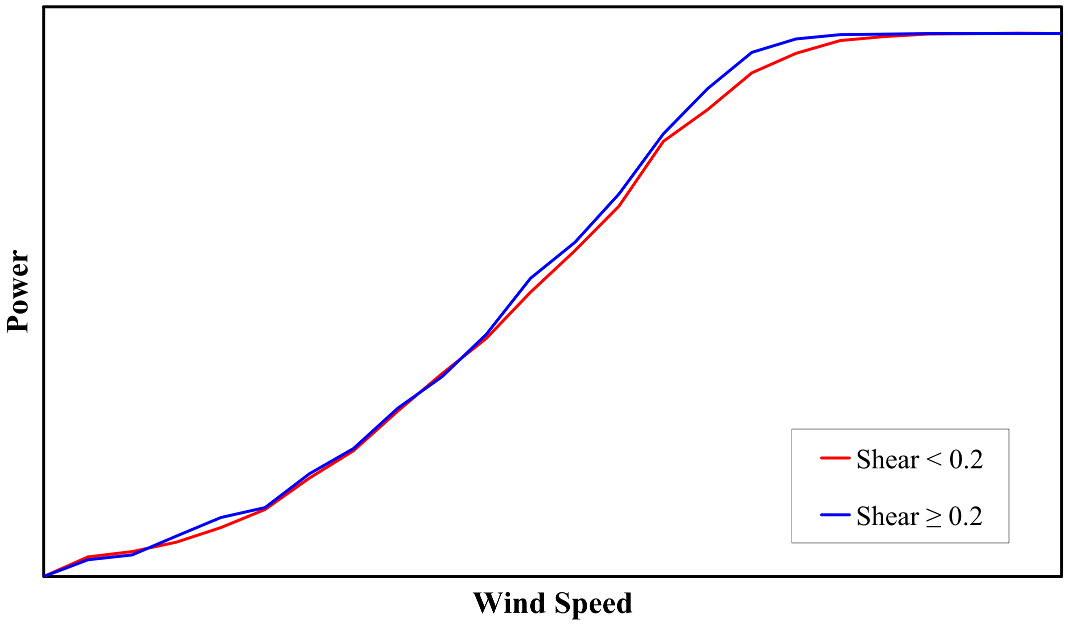

Figure 8 **Power curves binned based on wind shear for turbulence intensity = 6-9 %**

The effects on AEP of these changes in the power curves are shown in Table 3. The percent change in AEP is based on comparison with all data with turbulence intensity = 6-9 %.

	Mean wind speed (m/s)			
	7.5		**8.5**	
Wind shear α range	Turbine A	Turbine B	Turbine A	Turbine B
< 0.2	-1.2 %	-1.2 %	-1.1 %	-1.1 %
≥ 0.2	0.6 %	1.3 %	0.6 %	1.1 %

Table 3 **Effects on AEP due to wind shear for turbulence intensity = 6-9 %**

These results suggest that turbulence intensity may not account for all of the effects on the power curve. However, the apparent effect of wind shear on turbine performance does not match the theoretical effect. If the wind shear profile is influenced by the LLJ or otherwise irregular, the power law could fail to capture the true wind shear profile and therefore not permit accurate calculation of the energy flux across the turbine rotor. Currently there are limited data available to measure the variation of wind speed above the hub height of the machine. This is an area where remote sensing techniques may start to provide robust data to define the detailed wind shear patterns above the turbine hub height.

2.3 Day/night comparison

Since many operational projects do not have direct wind shear measurements on site, especially above hub height, differences in turbine performance between day and night were studied as proxies for the effects of wind shear and turbulence intensity. Because of the strong inverse correlation between wind shear and turbulence intensity in the Great Plains/Midwest region, this method does not separate the effects of these two factors. Since low wind shear and high turbulence intensity are expected during the day while high wind shear and low turbulence intensity are expected at night, turbine performance is expected to be higher during the day than at night for sites with low mean wind speeds. Turbine performance at sites with high mean wind speeds is expected to be higher at night than during the day. Table 4 shows the AEP comparison of day and night for several case studies for a mean wind speed of 8.5 m/s. These results match expectations and support further investigation of day and night turbine performance.

Day/Night	
Site A	99.3%
Site B	99.1%
Site C	99.5%

Table 4 Day vs. night comparison of AEP

2.4 Sensitivity of turbine performance to wind direction shear

For this study, wind direction shear, also known as wind veer, is defined as the difference in wind direction with height. Positive direction shear values indicate clockwise change with increasing height, and negative values indicate counterclockwise change with increasing height. Wind direction shear may be caused by the reduction in the force of surface friction on the wind at higher heights. The magnitude of the Coriolis force is inversely proportional to the frictional force. Therefore at higher altitudes in the Northern Hemisphere, wind may turn clockwise, or show positive wind direction shear, if there is very little vertical change in the horizontal pressure gradient. This phenomenon is most prevalent when the atmosphere is strongly stratified, such as at night, and during occurrences of the LLJ, because winds aloft are primarily from the west. Studies of wind direction shear indicate that the effect on power depends on whether the turbine blades are advancing or retreating from the tangential component of the wind [7].

Investigation of data from met towers measuring wind direction at different heights shows positive wind direction shear at night and little wind direction shear during the day, when the lower atmosphere is well-mixed. This observation is theoretically expected in the Great Plains/Midwest region [7], and GH has verified this phenomenon at numerous sites in the region. Figure 9 shows the day and night wind direction shear probabilities of occurrence for a site in the Great Plains/Midwest region that is typical of the frequency and magnitude of direction shear occurrence. Day is defined here as 7 AM to 7 PM, and night is defined as 7 PM to 7 AM.

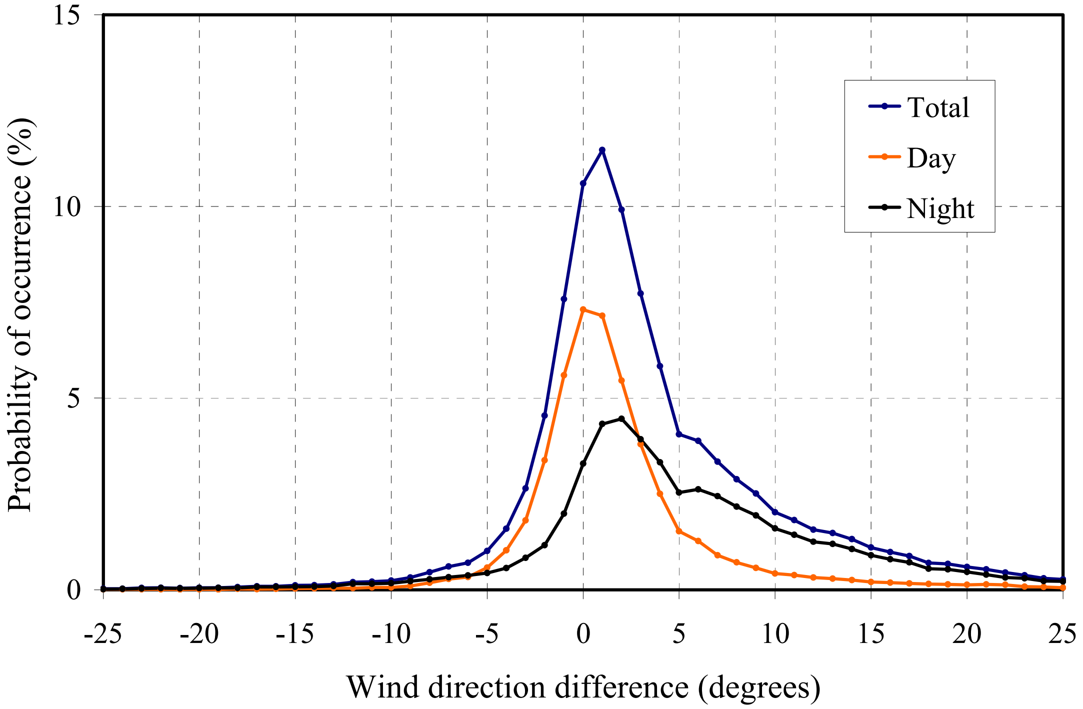

Figure 9 **Probability of occurrence of wind veer measured between 120 m and 50 m agl**

GH has modeled the combined effects of wind direction shear and wind speed shear. As shown in Table 5, the effects of wind direction shear and wind speed shear are not dramatic, except at very large negative direction shear values. By applying the wind direction shear frequency distribution from the site described above, the impact of wind direction shear on AEP at sites in the Great Plains/Midwest region is estimated to be insignificant for current turbine sizes. Further investigation is needed to evaluate the effect of wind direction shear on the actual performance of turbines in the Great Plains/Midwest region. Since wind direction shear is highly correlated with wind speed shear, it may be difficult to separate the effects of wind direction shear and wind speed shear on performance.

Wind Shear exponent	**Wind direction shear (deg/m)**				
	-0.25	**-0.125**	**0**	**0.125**	**0.25**
0.0	0.98	0.99	1.00	1.00	1.00
0.2	0.97	0.98	0.99	1.00	0.99
0.4	0.97	0.99	0.99	1.00	1.00
0.6	1.00	1.01	1.02	1.02	1.02

Table 5 **Effect on power of wind speed shear and wind direction shear normalized to shear α = 0 and wind direction shear = 0 for hub height wind speed of 8 m/s**

4 EFFECTS OF DATA FILTERS ON IEC POWER CURVE TESTS

The IEC 61400-12-1 [1] is the basis for most power curve warranties. In addition to the IEC Standard's requirements to filter out data from waked direction sectors, many power curve warranties now include data filters for environmental conditions such as turbulence intensity, wind shear, and upflow angle. These filters extend the period of data collection for the power performance test. In general, tests with additional filters tend to reflect ideal conditions, whereas tests with fewer filters tend to reflect site-specific conditions. Power curve warranties must be negotiated between the project owner and the turbine manufacturer.

A case study in the Great Plains/Midwest region shows the effects of generic power curve warranty filters indicative of those in current power curve warranties. Figure 10 shows the effects of a turbulence intensity filter removing all ten-minute data records that have turbulence intensity greater than 12 %. In this case study, this filter retains 77 % of the total valid data and removes a large amount of daytime data. Therefore this test would more heavily weight the night data than the daytime data.

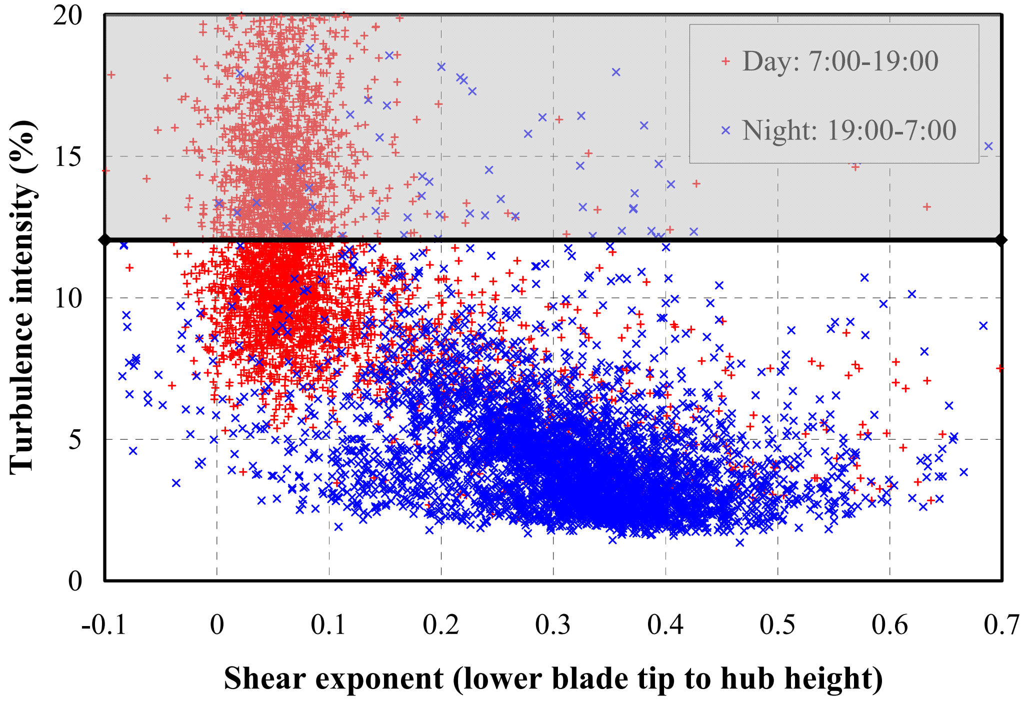

Figure 10 Data filter excluding ten-minute records for turbulence intensity > 12 %

Figure 11 shows the effects of a wind shear filter removing all ten-minute data records that have a wind shear exponent greater than 0.2. In this case study, this filter retains 49 % of the total valid data and removes a large amount of night data. Therefore this test would more heavily weight the daytime data than the night data.

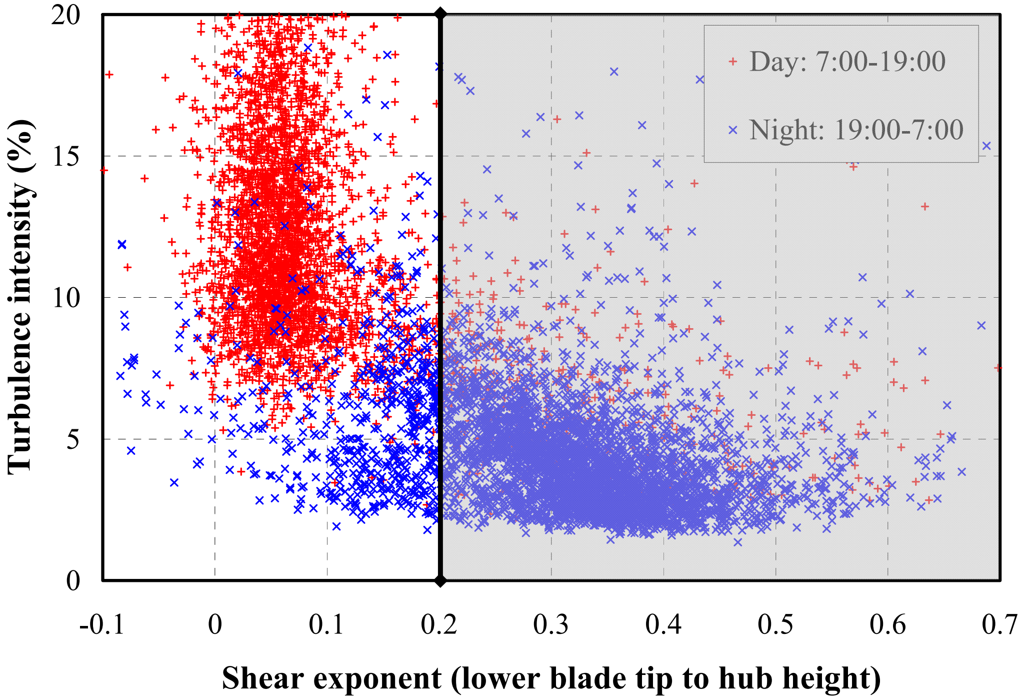

Figure 11 Data filter excluding ten-minute records for wind shear exponent > 0.2

Figure 12 shows the effect of combining these data filters. Because of the inverse correlation between turbulence intensity and wind shear at this site, the combined filters retain 27 % of the total valid data. Data collection for a typical power performance test following the IEC Standard is expected to last approximately 3-6 months. The addition of data filters is expected to increase the time needed for data collection, in some cases longer than a year.

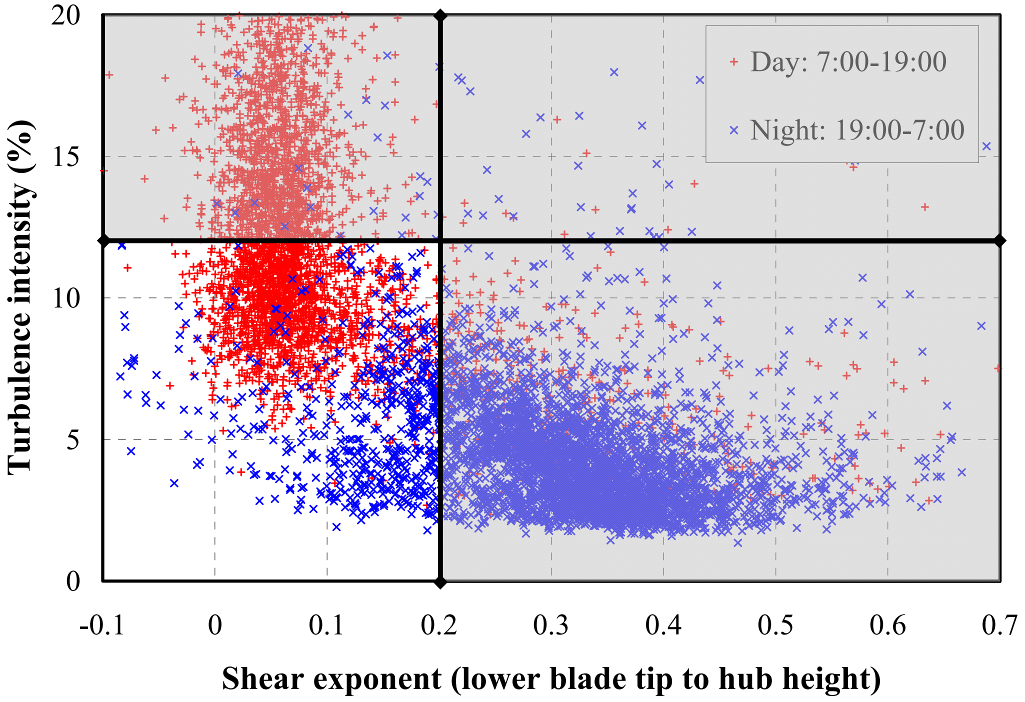

Figure 12 **Data filters excluding ten-minute records for turbulence intensity > 12 % or wind shear exponent > 0.2**

Table 6 shows the effects of these filters on AEP. In general, the effects on this case study are within the uncertainty range of a typical IEC test.

Percent change in AEP	
Shear exponent < 0.2	-0.7%
Turbulence intensity < 12 %	0.0%
Shear exponent < 0.2 and Turbulence intensity < 12 %	-0.4%

Table 6 **Case study effects of data filters on AEP**

3 CONCLUSIONS

The effects of the complex wind regime of the Great Plains/Midwest region on turbine power performance have been analyzed. The sensitivity of power performance to wind speed shear, wind direction shear, and turbulence intensity has been investigated. The key findings from this study are summarized below:

- Analysis of relevant data sets has demonstrated that for sites with particularly high turbulence levels, there is potential for reduction of the energy production of the wind farm when compared with lower turbulence sites.
- In the Great Plains/Midwest region, the effects of wind shear on power performance are inconclusive, and no consistent material impact due to varying wind shear has been found.
- The Great Plains/Midwest wind regime is characterized by strong diurnal trends in meteorology. For the case studies investigated in this research, only modest diurnal differences in AEP were observed.
- Although observations from Great Plains/Midwest sites show significant periods of large clockwise direction shear, the expected theoretical impact of such fluctuations on turbine power performance are estimated to be minimal.
- Power performance testing data filters will likely extend the time required to complete an IEC power curve test. Depending on the site conditions and the data filters, approximately 75 % of the data can be removed at some sites in the Great Plains/Midwest region. The case study results suggest that the data filters have a small effect on the measured AEP.

REFERENCES

1 *Wind turbines – Part 12: Power performance measurements of electricity producing wind turbines*, IEC 61400-12-1, 2005.

2 Earth System Research Laboratory, National Oceanic and Atmospheric Administration, *Lamar Low-Level Jet Program*, http://www.esrl.noaa.gov/csd/projects/lamar/

3 Antoniou I, Pedersen S and Enevoldsen P, *Wind shear and uncertainties in power curve measurement and resources*, Siemens Wind Power A/S, 2009.

4 Kaiser K, Hohlen H and Langreder W, *Turbulence correction for power curves*, Proceedings of European Wind Energy Conference, EWEC, Madrid, 2003.

5 S Honhoff, *Power Curves – The effect of environmental conditions*, GE Wind, AWEA Wind Speed and Energy Workshop, Portland, September 2007.

6 Tindal A, et al, *Site-specific adjustments to wind turbine power curves*, Proceedings of AWEA WINDPOWER Conference, Houston, 2008.

7 Walter K, Weiss, C, Swift A, Chapman J, Tall Tower Wind Shear Observations in the Stable Nocturnal Boundary Layer, American Institute of Aeronautics and Astronautics, 2009.