



WASATCH WIND

Tower Systems and Wind Development

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Taller Turbines, and the Effects on Wind Farm Development create a need for greater Height Wind Assessment

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ABSTRACT

An economic feasibility study of the benefits of the Wasatch Wind Space Frame Tower up to 125m heights has been completed. The data indicates that depending on the power rates, average annual wind shear above .11 using the power law is economically beneficial. Since more than 80% of all sites have wind shears exceeding this level and in some cases dramatically, the need for corresponding meteorological measurement takes on additional importance.

Abstract

Wind shear is a meteorological phenomenon in which the wind increases with height above ground. This common characteristic of wind can be used to advantage by wind turbines at increased hub heights to capture more wind, thereby boosting power production. In areas with enhanced wind shear defined as greater than .20, this increase in power production can be substantial, leading to lower cost of energy and turning marginally economic wind farms into compelling projects. Three independent studies show that at least 83% of all sites across the Great Plains have wind shear greater than .2 above 60 meters. In addition, at heights above 60 meters, many sites exhibit wind shear that is greater than exhibited at lower heights thus providing a compelling argument for directly verifying wind speed at 80 meters and higher prior to wind farm development in order to maximize development benefits and reduce economic risk.

Opportunities for Wind Prospecting

Wind shear at 60 to 125 m levels has only recently begun to be evaluated to a substantial degree. The result is that wind shear is turning out to be greater than expected. For example, the average wind shear in Minnesota measured at over 50 tower sites is .27 from 50 to 70 meters.¹ In addition, the U.S. Department of Energy-Electric Power Research Institute (DOE-EPRI) Wind Turbine Verification Program (TVP) has gathered data from several wind energy facilities in the Midwestern United States, including projects in Big Spring, Texas; Algona, Iowa; Springview, Nebraska; Glenmore, Wisconsin; and Fort Davis, Texas in which the average shear is .22 increasing to .32 at

¹ Wind Resource Analysis Program 2002, Minnesota Department of Commerce,
http://www.state.mn.us/mn/externalDocs/WRAP_Report_110702040352_WRAP2002.pdf



night.² Finally, balloon sounding data from 9 sites ranging from Texas to California to Alaska and extrapolated at 10m to 80m reveals an average wind shear of .26.³

Indeed, evidence suggests an opportunity for the wind industry to develop more economical wind farms in more places using Space Frame Towers at greater heights. Several turbine manufacturers have already built development turbines exceeding 100 m with plans to go even higher. This is a substantial increase from 50 meters and sub 1 MW capacities installed just a few years ago. The completion of the companies design work for the Space Frame Tower means a 100+m turbine appears likely in the near future for land based installations.

The power output for all modern wind turbines increases with the square of the wind speed, up to an average of 7.5 m/s wind speed, meaning, if the wind speed doubles, the power output increases four times. See figure 1.

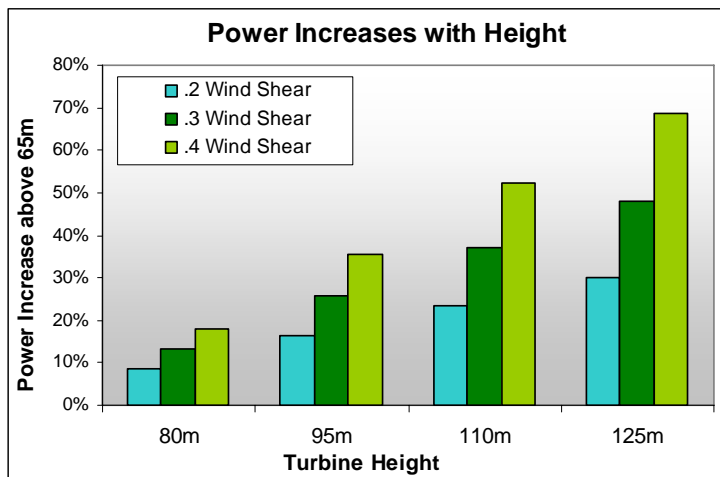


Figure 1: Power output increase for taller turbines vs. wind shear

For a site with a .2 wind shear, power generation increases 9% by moving the turbine from 65 m up to 80 m and increases 23% by moving it to 110 m. For a wind shear of .3, power increases 13% and 37% respectively.

² Evaluation of Wind Shear Patterns at Midwest Wind Energy Facilities, NREL contract, Kevin Smith, Gordon Randall and David Malcolm, Global Energy Concepts, LLC
<http://www.nrel.gov/docs/fy02osti/32492.pdf>

³ Spatial and temporal distributions of U.S. winds and wind power at 80 m derived from measurements, Cristina L. Archer and Mark Z. Jacobson, Department of Civil and Environmental Engineering, Stanford University, Stanford, California, USA, JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. D9, <http://fluid.stanford.edu/~lozej/winds/2002JD002076.pdf>



Of course, a cost is incurred when installing turbines higher; from the increased tower cost, to a requirement for larger and more expensive cranes, to an increase in transportation of the tower over the roads.

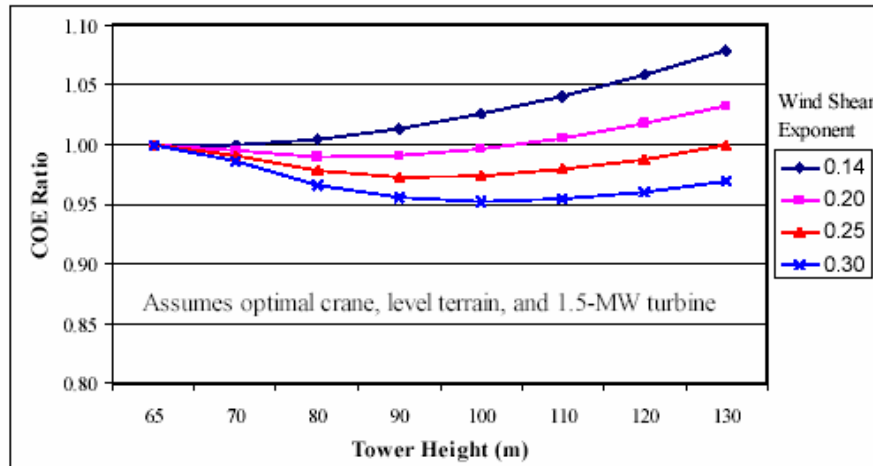


Figure 2: Cost of energy as a function of tower height and wind shear

A study by NREL shows that for sites with high shear, the additional costs of erecting taller turbines are offset by the increase in power production (see figure 2).⁴ The study assumed improvements in turbine tower technology would enable the use of towers above 100m to reduce the cost of energy (COE) in the near future. For example, from the chart, a .3 wind shear would justify a 100m tower for optimum COE. Arguably a reasonable chance exists that more advanced technologies will emerge to further reduce turbine tower cost with height, justifying even taller towers than 100m thus requiring wind measurements at even greater heights.

In Minnesota, 80% of sites exhibit wind shear greater than .2, and 16% of the sites exceed .3. For the NREL funded study, the percentage is 83% and 16.6% respectively across the plains and from the soundings extrapolations of Archer and Jacobson 100% of the sites from Texas to Alaska to California exceeded .2, further indicating that substantial wind shear above 60m is prevalent over large areas.

Prospectors and land owners that educate themselves regarding the impact that wind shear has on wind farm economics combined with an understanding of trends in taller turbines can create advantages for themselves by planning wind monitoring projects appropriately.

NREL's low wind speed web site at http://www.nrel.gov/wind/about_lowspeed.html states one of the problems developers are now facing. "...as more sites are developed, easily accessible prime Class 6 sites are disappearing. In addition, many Class 6 sites are

⁴ Addendum to WIndPact Turbine Design Scaling Studies, Technical Area 3 – Self-Erecting Tower and Nacelle Feasibility, March 2001, Global Energy Concepts. <http://www.nrel.gov/docs/fy03osti/29493A.pdf>



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located in remote areas that do not have easy access to transmission lines. Class 4 wind sites (5.8 meters per second at 10 meter height - 13 mph at 33 feet) cover vast areas of the Great Plains from central and northern Texas to the Canadian border. Class 4 sites are also found along many coastal areas and along the shores of the Great Lakes. While the average distance of Class 6 sites from major load centers is 500 miles, Class 4 sites are significantly closer, with an average distance of 100 miles from load centers. Thus, utility access to the Class 4 sites is more attractive and less costly. Also, Class 4 sites represent almost 20 times the developable wind resource of Class 6 sites.” While the focus at NREL is on new technologies to capture the wind, we postulate and the evidence suggests that much class 5 and even class 6 winds exist over our heads needing to be adequately measured.

A meteorological tower with anemometers placed at anticipated turbine hub height is the optimal solution to directly measure the wind speeds experienced should a wind farm be placed in service at these great heights. This “direct method” is superior to using a shorter tower with anemometers at two lower heights to extrapolate shear for estimating winds above the tower measurement height; called the “extrapolation method”.

Hazards for the Unwary

Studies previously referenced show that wind shear is often very different between 60 to 80 meters than from 30 to 60 meters. In Minnesota, reviewing data from 24 very tall monitoring towers up to 90 m shows that the wind shear above 60 meters is as much as 58% greater to 48% less than the wind shear at lower heights.¹ At 23 of these 24 sites, the actual wind shear is either higher or lower than lower level wind shears i.e. the chance of an error in wind resource prediction would be 96% if wind shear from lower heights is used to predict the wind speeds at heights above 60 m. In 6 of 24 or 25% of the sites, the wind shear would be under-predicted by at least 10% if a shorter tower was used to assess wind shear for a higher turbine. In 8 of 24 or 33% of sites, wind shear extrapolation over-predicts shear by 10%. Combined, the chance of a 10% or greater shear error between 60 to 90 meters exceeds 58%. The magnitude of error at other sites is unknown but the data indicates a significant trend.

In addition, if a 30 m tower was used to evaluate wind resources, at least in Minnesota, the chance of under predicting the wind resource at greater heights is 100% according to measurements on 17 towers at least 40 m tall. In these cases, the average measured wind shear from 10 to 30m is .18 while the shear from 30m to 40m is .33 (see appendix C).

A further data point is available from NREL, see Appendix B. At Big Spring, TX, measured wind shear between lower heights and upper heights indicates that if tower data from 10 to 40 m was used to extrapolate to 80 m., a 17% under prediction of wind shear at night and a 17% over prediction during the day would occur. While the net error sums out, power contracts would be affected as low value off-peak night time resources and higher priced day time rates would be out of sync with contract commitments. In these cases, the error usually favors the purchaser of the power.



These various levels of inaccuracy could have serious consequences for developers. Certainly, erecting a taller tower at the tallest anticipated hub height decreases the possibility of shear measurement error to 0% thereby reducing wind resource risk. Wind projects are usually heavily debt leveraged therefore a small change in overall power production over the life of the debt can have dramatic cash flow affects. When a wind resource is substantially under predicted, the site may not be developed due to underestimates of economics, or the site may be developed but the power contracts and financial terms may cause the developer to leave a substantial amount “on the table”.

Assuming Minnesota is representative of many areas, then in 28% of sites; the additional costs for a taller wind measuring tower may be very small compared to the lost opportunity costs. For over-predicted resources (38% of sites), the economic consequences may be substantial should a project go forward based on extrapolation techniques. If the project is heavily debt leveraged, the cash flow may not be enough to cover operations.

Example of Over-prediction

Near St. Kilian, MN a 90 meter tower was used to assess wind speeds from 1999 through 2001. The average wind speeds for three years along with the capacity factor according to the direct measurement technique are shown in Table 1. This data was from anemometers placed at each of the heights.

	Monitoring Heights		
	30m	60m	90m
Wind Speed	6.4 m/s	7.4 m/s	7.8 m/s
Capacity Factor	26.7%	35.6%	39.2%
Wind Shear	30-60m	0.26	
	60-90m	0.19	

Table 1: St. Kilian average wind speeds and actual capacity factors

Now lets assume we didn't have the hindsight of a 90m tower and rather a 60m tower was used to measure the wind. After gathering a year of data, the wind shear of .26 at 60m would have been determined. This is considered an “above average” shear. This magnitude of shear justified a wind farm using 80 to 90m towers. However, we know that wind shear between 60 and 90 m was actually .19 from our previous wind speed measurement using a taller tower. Extrapolation of wind shear to 90m by using calculations at lower height results in a gross error in power output prediction.

	30-60m
Wind Shear Extrapolation	0.26
Estimated 90 m Wind Speed (m/s)	8.22
Extrapolated Capacity Factor at 90m	43.0%
Overprediction of Power at 90m	9.70%



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Table 2: St. Killian wind shear from 30-60m with calculated capacity factor

Nevertheless, according to Table 2, using the extrapolated wind speed to 90 m yields an estimate of average wind speeds of 8.22 m/s or 5.4% faster than actual measurements from Table 1, thus yielding a capacity factor from power performance charts of 43% rather than the actual value of 39.2%. In this specific case the power output would have been over predicted by an average of 9.7%. This could have prompted the developer to install taller wind turbines, a more expensive proposition. At the least, the additional predicted revenue never materializes and in many cases depending on the PPA, the utility may require purchase of the lost power at market rates.

If a 25 MW wind farm had been commissioned, the amount of power not realized at a typical \$0.03 per kwh amounts to \$249,660 per year or \$3.7 million over a 15 year power purchase contract. This is in addition to the taller turbine tower costs of \$80,000 each x 17 turbines or \$1.36 million. Clearly, precisely measuring the wind resource at hub height is paramount when developing sites with high shear. In this case, the additional cost of a taller MET tower for direct measurement appears to be insignificant compared to the project losses. St. Killian is not atypical in Minnesota, of the 24 sites in the wind survey, 7 would have yielded worse predictions from shear extrapolation.



Appendix A

Wind Shear Overview and Power Output

The wind at any height can theoretically be determined by measuring the wind speed at a lower height and applying a wind shear coefficient “ ∞ ” using the following formula:

$$V_u = V_1 \times (H_l/H_u)^\infty$$

V_u = Estimated upper height wind velocity

V_1 = Measured wind speed at the lower height

H_l = Lower height where V_1 is measured

H_u = Upper height (typically turbine hub height)

∞ = Wind shear coefficient

To look at an example, a 50m meteorological tower measured 12 mph average wind speed at the 20m height. Using a second anemometer at the 50m height, the winds were measured at 14.4 mph. Since the winds are greater at taller heights, wind shear is present. Using a simple mathematical formula, the wind shear between 20 and 50m height is calculated to be .2. With this data, the wind shear can then be used in the above formula to estimate the wind speed at any height. Let's estimate the wind speed for a wind farm to be built at this site with 65m turbines. This hub height is typical for 1.5 MW capacities.

$$V_1 = 14.4 \text{ mph}$$

$$H_l = 50 \text{ meters}$$

$$H_u = 65 \text{ meters}$$

$$\infty = .2$$

$$V_{65m} = 14.4 \times (65/50)^{.2} = 15.2 \text{ mph}$$

Since the winds are increasing with height, estimating the wind speed at even taller heights seems to make sense too. Again using a 1.5 MW size, the tallest steel turbine towers available are 80m:

$$V_{80m} = 14.4 \times (80/50)^{.2} = 15.8 \text{ mph}$$

The difference in wind speed between the two heights at first glance doesn't seem to be significant. However, because the power extraction by a wind turbine increases with the square of the wind speed, wind turbines can be very sensitive to even small differences in wind speed. Because we know that turbines up to 125m are going to be built in the future, let's estimate the wind speeds at that height.



$$V_{110m} = 14.4 \times (125/50)^2 = 17.3 \text{ mph}$$

Using typical turbine power performance charts at sea level, capacity factor and the net present value of the increased energy output was then calculated to verify the output increases.

.2 Wind Shear

Height (m)	mph	Capacity Factor	Annual Revenue per MW	Yearly Revenue Increase	NPV 20 yr life
65	15.2	30.2%	\$ 79,366		
80	15.8	32.6%	\$ 85,673	\$ 6,307	\$117,892
125	17.3	38.6%	\$101,441	\$ 22,075	\$412,621

Table 3: Annual revenue increases from taller turbines

The annual turbine power revenue was determined based on \$0.03 per kwh. For an 80m tower the increased revenue amounts to \$6307 per year per MW of capacity. The present value of this savings over the life of the wind farm is \$117,892 per MW assuming 7% cost of funds. If the additional crane, transportation, and tower costs are less, then in general going taller makes sense. The amount of increased lifetime revenue for a 125m turbine is even larger at \$412,621 but the turbine costs increase rapidly with height.

What happens to the economics if the wind shear predicted at .2 per Table 3 was actually at .15, a 25% difference. At the taller heights as verified by direct measurement from a tall MET tower, output is as follows:

.15 Wind Shear

Height (m)	mph	Capacity Factor	Annual Revenue per MW	Yearly Revenue Increase	NPV 20 yr life	Economic Difference
65	15.2	30.2%	\$ 79,366			
80	15.8	31.3%	\$ 82,125	\$ 2,759	\$51,578	-44%
125	17.3	35.5%	\$ 93,294	\$ 13,928	\$260,344	-63%

Table 4: Annual revenue differences from errors in wind shear extrapolation

Per this example, a small difference in wind shear error leads to large differences in economics, as much as 63% less.



Appendix B

Under and Over Predictions of Day vs Night Wind Shear

Quoted from:

Evaluation of Wind Shear Patterns at Midwest Wind Energy Facilities, NREL contract, Kevin Smith, Gordon Randall and David Malcolm, Global Energy Concepts, LLC

<http://www.nrel.gov/docs/fy02osti/32492.pdf>

“Wind shear is quantified as the exponent in the Power Law equation that relates wind speeds at two different heights. At some projects, the annual average shear peaks above 0.5 during early morning hours, with 10-minute and hourly average shear measurements frequently exceeding 0.75.

“...shear could benefit wind generated energy production by providing a source of greater hub-height wind speeds, particularly for multi-megawatt turbines that utilize tall towers. Sites that were characterized as possessing low wind speeds based on 40-m or 50-m (131-ft or 164-ft) meteorological data may be more productive than previously believed. Harnessing the high wind shear effects offers an opportunity to increase energy production and possibly lower the cost of energy...”

Most wind resource assessment activities utilize 40-m or 50-m towers with sensors installed at intermediate levels (10 m, 20 m, or 26 m for example). Shear observed over these lower heights is commonly extrapolated up to estimate hub-height wind speeds. This assumption may be reasonable in the case of sub-megawatt turbines, such as those with rotor diameters between 44 m and 52 m and installed with hub heights of 50 m to 65 m. However, this extrapolation may not be appropriate for multi-megawatt turbines (with rotor diameters greater than 52 m) and installed with hub heights greater than 65 m. Figure 3 illustrates an example of this situation using diurnal wind speed data at different measurement intervals on the same met tower from Big Spring, Texas.

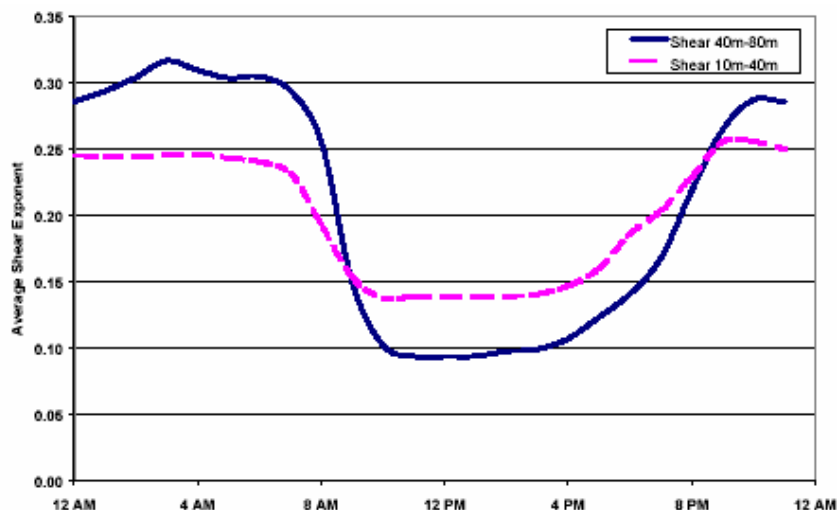


Figure 3: Diurnal wind speed data



In Figure 3, the annual average wind shear between 10 m–40 m and 40 m–80 m was approximately 0.2 for each interval. However, the magnitude of the diurnal variation between high nighttime shear and low daytime shear between 40 m and 80 m was greater than between 10 m and 40 m. Consequently, the site conditions characterized by data obtained between 10 m and 40 m do not resemble the actual conditions encountered by the rotor.

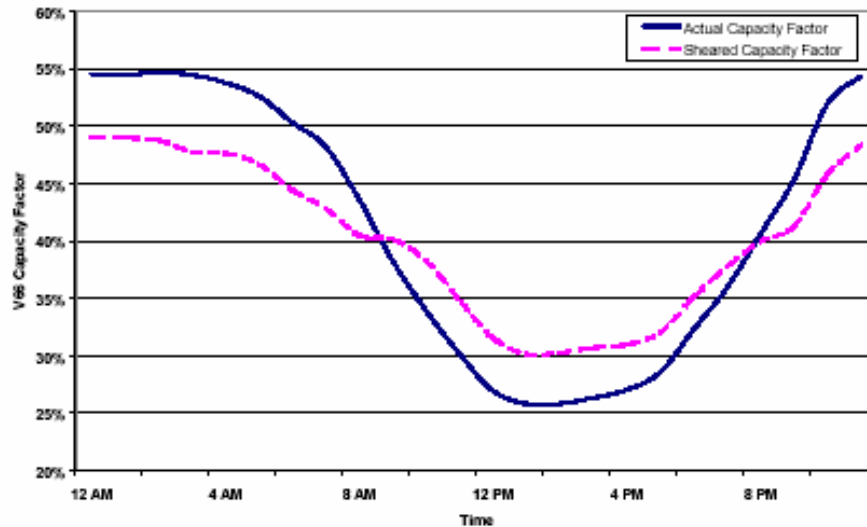


Figure 4. Calculated Versus Actual Diurnal Capacity Factors at Big Spring, Texas

Another example illustrating the differences between wind data collected for development purposes and wind data collected at the rotor is associated with prediction of energy delivery. In Figure 4, the 40-m diurnal wind speed pattern from Big Spring was adjusted to a hub height of 80 m by applying the annual average wind shear value of 0.2. Diurnal annual average capacity factors for a typical wind turbine were then calculated. The resulting values are shown in Figure 4 as sheared capacity factors. The actual diurnal average capacity factor calculated from 80-m wind speed data is also shown for comparison. The sheared capacity factor values under-predicted peak power output at night and over-predicted low power output during the day, both by about 5% of capacity. In this case, if a power marketer or utility grid manager were using the 10 m–40 m wind speed data to schedule project output, the predicted daytime output (when Texas utilities experience peak loads) would be overestimated while the nighttime output (corresponding to off-peak grid load) would be underestimated. This could result in the need for additional unplanned reserve energy sources to make up for the shortfall during daytime peak load hours. “



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TVP Projects	Sensor Heights	Duration of Data	Annual Shear	Day/Night Range +/-
Big Spring, Texas	40 m – 80 m	September 1999 – August 2000	0.21	0.1
Ft. Davis, Texas	25 m – 40 m	July 1998 – June 1999	0.11	0.05
Iowa	25 m – 50 m	January 1999 – March 2001	0.33	0.12
Nebraska	40 m – 65 m	October 1999 – March 2001	0.22	0.08
Wisconsin	37 m – 123 m	December 1999 – Sept. 2001	0.28	0.1
NREL, Lamar, CO	52 m – 113 m	October 2001 – March 2002	0.2	
			0.225	0.09



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Appendix C:

Tall Tower Data from Minnesota Wind Resource Measurements

Excerpted from: Wind Resource Analysis Program 2002, Minnesota Department of Commerce,
http://www.state.mn.us/mn/externalDocs/WRAP_Report_110702040352_WRAP2002.pdf

Minnesota	30-50m	50-70m	Diff.
Alberta	0.37	0.26	-30%
Brewster	0.25	0.23	-8%
Brownston	0.32	0.26	-19%
Crockston	0.22	0.2	-9%
Currie	0.17	0.18	6%
Hallock	0.19	0.21	11%
Isabella	0.54	0.45	-17%
Lucan	0.24	0.25	4%
Luverne	0.27	0.14	-48%
Montevideo	0.28	0.29	4%
Mountain Lake	0.24	0.26	8%
Nerstrand	0.24	0.24	0%
Rochester	0.19	0.3	58%
Sabin	0.29	0.28	-3%
Winnebago	0.26	0.24	-8%
Avg	0.27	0.25	
	30-60m	60-90m	Diff.
Currie	0.19	0.13	-32%
Hatfield	0.29	0.25	-14%
Hillman	0.36	0.56	56%
Marshall	0.19	0.2	5%
St. Killian	0.26	0.19	-27%
Avg	0.26	0.27	

Minnesota	10-30m	30-40m	40-50m	50-60m	60-70m	Diff.
Breckinridge	0.17	0.23	0.26	0.27	0.3	11%
Chandler	0.19	0.2	0.2	0.22	0.33	50%
Clarks Grove	0.19	0.25	0.3	0.11	0.25	127%
Marshall	0.19	0.22	0.16	0.29	0.25	-14%
Avg	0.19	0.23	0.23	0.22	0.28	27%

Minnesota	10-30m	30-40m	Diff.
Lac Qui Parie	0.26	0.31	19%
Bejou	0.16	0.4	150%
Bigelow	0.2	0.4	100%
Current Lake	0.19	0.35	84%
Hadley	0.17	0.53	212%
Heron Lake	0.11	0.29	164%
Jeffers	0.19	0.2	5%
Trosky	0.22	0.23	5%
Wilno	0.16	0.22	38%
Wabasso	0.23	0.35	52%
Callaway	0.16	0.25	56%
Elizabeth	0.19	0.27	42%
Greenbush	0.2	0.36	80%
Kensington	0.19	0.24	26%
Rollag	0.17	0.23	35%
Syre	0.17	0.33	94%
Thief River Falls	0.14	0.72	414%
Avg	0.18	0.33	93%

Negative indicates an overprediction of wind shear if extrapolated from a lower height
Positive indicates an under prediction of wind resources



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Appendix D

Further Literature Review of Wind Shear

Spatial and temporal distributions of U.S. winds and wind power at 80 m derived from measurements, Cristina L. Archer and Mark Z. Jacobson, Department of Civil and Environmental Engineering, Stanford University, Stanford, California, USA, JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. D9, <http://fluid.stanford.edu/~lozej/winds/2002JD002076.pdf>

Soundings Data 10-80m	Night Shear	Day Shear	Average	Range
Amarillo, TX	0.33	0.11	0.22	0.11
Pine Spring, TX	0.36	0.11	0.24	0.13
Clayton, NM	0.36	0.16	0.26	0.10
Cold Bay, Alaska	0.42	0.13	0.28	0.15
Dodge City, KS	0.36	0.16	0.26	0.10
Russell, KS	0.36	0.16	0.26	0.10
Garden City, KS	0.36	0.16	0.26	0.10
Hobart, OK	0.39	0.16	0.28	0.12
Sandberg, CA	0.36	0.16	0.26	0.10
			0.26	0.11