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Empirical Analysis of Wind Power Potential at Multiple Heights for North Dakota Wind Observation Sites

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Abstract

Wind speed is the most critical factor that determines wind power potential and generation. In this paper, the wind speed data of multiple years from various observation sites in North Dakota, U.S. was analyzed to assess the wind power potential. The study first applied probability density functions (PDFs) to characterize the wind speed data and fit the distributions at various heights for each observation site. The fitted distributions were then used to estimate the wind power potential based on the theoretical cubic power relationship between energy potential and wind speed. Due to the complexity of functions, the numerical integration approach was employed. The following major findings were obtained from this empirical study: (1) Weibull distribution is not always the best function to fit wind speed data, while gamma and lognormal distributions produce better fitting in many occasions; (2) For different height levels at one observation site, the best performing distributions may be different; (3) The estimation accuracies of wind energy potential based on the fitted wind speed distributions range from -4% to 3.8%; (4) The rank of energy potential estimation accuracies is not always consistent with that of goodness-of-fit for wind speed distributions. In addition, a simplified approach that only relies on the hourly mean wind speed to estimate wind power potential is evaluated. Based on the theoretical cubic relationship for wind power estimation, it was found that the simplified approach may provide significantly lower estimates of wind power potential by 42-54%. As such, this approach will become more practical if this amount of difference is to be compensated.

Key words: Wind speed; Distribution; Goodness-of-fit; Wind power potential; North Dakota

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INTRODUCTION

Wind power is a highly attractive renewable energy option for countries and regions with plentiful wind resources like North Dakota, USA. According to the U.S. Department of Energy, North Dakota has the most abundant wind resource of any state in the country (U.S. DOE, 2008). During 1993 to 1997, the North Dakota Division of Community Services facilitated a statewide wind resource assessment, which in 1999 was released to the Division of community Services in the hopes of furthering development of North Dakota's wind energy resources. This particular wind monitoring program was specifically designed to select North Dakota sites with a good potential for wind energy development (ND Division of Community Service, 2000). Effectively exploring wind energy in North Dakota requires a clear analysis of wind characteristics related to wind power potential at various heights and for each observation site. It is essential that residential and industrial wind power developers assess specific geographic sites for wind speeds at specific heights between 10-55 meters if an accurate assessment of a sites potential for electricity production, and economic feasibility of wind power, is to be realized.

Accurately calculating wind distribution at various heights for a particular location is one of the most critical factors in estimating annual electrical production for any wind developer. The probability density function (PDF) of wind speeds basically determines the performance of a wind system in a particular site. This is because the wind power density being proportional to the cubic wind speed directly determines the wind energy output (Celik, 2004). Various types of probability density function have been utilized for the purpose of characterizing wind speed distributions. Zhou *et al*. (2010) investigated a comprehensive evaluation on PDF of 10-meter wind speed for five locations in North Dakota and found that no particular distribution outperformed the other sites. Chang (2011) proposed a mixture of Gamma and Weibull (GW) PDF and mixture normal (NN) PDF to estimate wind power potential at three wind stations in Taiwan, along with applying bimodal Weibull (WW) and truncated Normal Weibull (NW) PDF. With the aim of evaluating the potential wind resources in Rwanda, Safari and Gasore applied Weibull and Rayleigh PDFs to analyze wind speed characteristics and wind power potential at a height of 10 m above ground on five Rwandan meteorological stations. These characteristics were extrapolated for higher levels in altitude using the log law. In this study Safari and Gasore (2010) found that Weibull PDF proved to be the best fit for the empirical distribution. Elamouri and Amar (2008) evaluated wind speed characteristics and wind power potential for 17 synoptic sites in Tunisia at 10 meters above ground level and extrapolated the wind characteristics to 100 meters. They concluded that the annual mean speed increases approximately 80% and the available annual energy potential grows approximately four times while increasing the height of tower from 10 m to 100 m. The existing studies basically explore different PDF models to analyze wind power potential at one height level only. Instead of analyzing multiple heights directly, many authors discussed data collection where wind speeds were collected at only one height and the characteristics extrapolated to various higher and lower levels.

The motivations and contributions of this research are two-folded. Practically, this empirical research is developed to evaluate the wind energy potentials based on the real measurements at multiple heights for the representative sites in the state of North Dakota in the United States. This is important because North Dakota is the state with the greatest wind energy potential. The characteristics of wind speed/potential at different heights for those sites will be critical for wind power development in North Dakota. Theoretically, this research tries to compare the difference of wind power potential at multi heights for each observation site between a simplified mean approach and several theoretical computing results developed by the directly calculated real wind power, Weibull distribution model, Gamma distribution model and Lognormal distribution model. The simplified mean approach could be very useful when detailed wind records are not available, but its performance needs to be thoroughly evaluated.

1. METHODOLOGY

1.1 Statistical Distributions of Wind Speed

There are many PDFs available, but not all of them are suitable for fitting wind speed. The statistical distributions included in this research are Weibull distribution, gamma distribution, and lognormal distribution. They were selected because (1) Weibull distribution is the most popular PDF for wind speed, and (2) gamma and lognormal distributions can often produce comparable performances as Weibull distribution according to the findings in literature (Zhou *et al*., 2010; Celik, 2004, Chang, 2011). Moreover, we consider the general forms (i.e., the 3 parameter versions instead of the simplified 2 parameter versions) of these PDFs, and thus they have the potential to be considered as the underlying statistical distribution for the measured wind speeds. These distributions are listed as follows:

Weibull Distribution: Weibull distribution was originally introduced by Rosin and Rammler and named after Waloddi Weibull (1951). Besides the fact that it is the predominant PDF for wind speed analysis, it also has found diverse application areas such as survival, reliability and failure analysis, and structural analysis (Vogiatzis *et al*., 2004; Al-Abbadi, 2005; Arias *et al*., 2008; Veber, Nagode, & Fajdiga, 2008; Gupta *et al*., 2008). Its capability to mimic exponential and normal distribution through scale and shape parameter contribute to the applicability of this distribution. In our research, the more general form of three-parameter Weibull distribution is considered, with α being the the shape parameter, β the scale parameter and γ the location parameter. It should be noted that Rayleigh distribution is also widely used for wind speed analysis. It is actually a special case of the Weibull distribution, where the shape parameter is equal to 2 and the scale parameter is $1/\sqrt{2}$ times of the scale parameter of the Weibull distribution (Tar, 2008; Stansell, 2004; Zhou *et al*., 2008).

$$f(x)=\begin{cases}\dfrac{\alpha(x-\gamma)^{\alpha-1}}{\beta^{\alpha}}\exp\left(-\dfrac{(x-\gamma)^{\alpha}}{\beta}\right), \gamma < x < \infty \\ 0, \textit{otherwise}\end{cases} \tag{1}$$

Gamma distribution: Gamma distribution is used in diverse fields, such as reliability, economics, material science, etc. (Lu & Tsai, 2009; Jaganathan, Tafreshi & Pourdeyhimi, 2008; Askari & Krichene, 2008). It represents the sum of the exponentially distributed random variables, and it can be identified with three parameters: α, β, and γ being the shape, scale, and the location parameters respectively. Gamma distribution can be transformed to the exponential, chi-squared, or erlang distribution for some conditions imposed on α and β parameters.

$$f(x)=\begin{cases}\dfrac{1}{\beta\,\Gamma(\alpha)}\left(\dfrac{x-\gamma}{\beta}\right)^{\alpha-1}\exp\left(\dfrac{-(x-\gamma)}{\beta}\right), & \gamma<x<\infty\\ 0, \textit{ otherwise}\end{cases}\qquad(2)$$

Lognormal distribution: Lognormal distribution is a special form of normal distribution, where logarithm of the variable is distributed normally. It has been applied to research in various fields, such as meteorology, ecology, and risk management, etc. (Kamarianakis, 2008; Van der Heide, 2008; Annaert, 2007). Along with the Weibull distribution, it is one of the most used statistical distributions in reliability theory as well (Brabady & Kumar, 2008). It is also represented by three parameters, μ, σ, and γ, which are the mean, standard deviation and location parameter, respectively.

$$f(x)=\begin{cases}\dfrac{1}{(x-\gamma)\sigma\sqrt{2\pi}}\exp\left(\left(\dfrac{-1}{2}\right)\left(\dfrac{\ln(x-\gamma)-\mu}{\sigma}\right)^2\right), & \gamma<x<\infty\\ 0, \textit{ otherwise}\end{cases}\qquad(3)$$

1.2 Goodness of Fit Tests

In this research, we applied Anderson-Darling (AD) test to evaluate the goodness-of-fit of the three distributions that are described in the previous section. AD test is a modification of the Kolmogorov-Smirnov test. AD test makes use of the specific information for calculating the critical value for rejection or acceptance of the hypothesis on whether the data follows a specified distribution. This increases the sensitivity of the test, but, on the other hand, bears the necessity of calculating the critical value for each statistical distribution that is tested (NIST/SEMATECH, 2006). The test is based on adding up the two terms. The first term is the natural logarithm of cumulative distribution function calculated at point Y_i (i.e., ln $F(Y_i)$), where Y_i is the ordered set of the observations, i is the index of that particular observation in ascending order, and F is the cumulative distribution function. Similarly, the term $\ln(1\text{-}F(Y_{N+1-i}))$ is calculated, with N denoting the total number of observations. These two terms are added together, and the result is multiplied by the factor (2i-1)/N. These values are summed for every index value from 1 to N of the set of the bins to find the term S. Then, S is subtracted from $-N$ to obtain the test statistics value (i.e., A^2) for the AD test. This test is used in distribution fitting research for wind energy and financial applications (Ramirez & Carta, 2005; Synowiec, 2008). The AD test statistic is defined below,

$$A^2=-N-S\qquad(4)$$

$$S=\sum_{i=1}^{N}\frac{2i-1}{N}\left[\ln F(Y_k)+\ln(1-F(Y_{N+1-k}))\right]\qquad(5)$$

where F is the cumulative distribution function of a specified distribution.

1.3 Estimation of Wind Potential

Theoretically, the power available (P_V) at wind speed v can be expressed as

$$P_v=\frac{1}{2}\rho\cdot A\cdot V^3\qquad(6)$$

where A is rotor area, and ρ is air density. Normally, both ρ and A are regarded as constants. As such, the comparison of wind energy potentials is actually about the comparison of the cubes of wind speed. Based on this, the total energy per unit time, contributed by the wind speed at an observation site, can be expressed as,

$$E_v=\int_0^\infty P_v f(v)dv\qquad(7)$$

where f(v) is the probability density distribution (PDF) of wind speed, which can be in many forms such as the three PDF forms mentioned above. Equation (7) could be obtained analytically if the distribution of wind speed follows a simple distribution, such as normal or two-parameter Weibull distributions. However, for more complex PDF forms, numerical methods must be used to obtain the integral as follows,

$$E_v=\sum_{i=1}^{N}P_{vi}f(v_i)\frac{v_{\max}}{N}=\frac{1}{2}\rho A\sum_{i=1}^{N}v_i^3 f(v_i)\frac{v_{\max}}{N}\qquad(8)$$

where $v_i=\dfrac{v_{\max}}{N}\cdot i$, $v_{\max}$ is the maximum wind speed observed, N is the number of intervals for numerical integration.

2. DATA SOURCES

North Dakota is the state with the highest wind energy potential in the U.S. The first large scale wind potential assessment was carried out in 1994-1997 by the state government with regional utility companies. In this period, observation meteorological towers were set up in nine sites across the state which covered most terrain conditions. Wind speed and direction were measured and stored at multiple heights in the format of hourly average and hourly standard deviation. Some towers measured wind up to 40 meters, while some took the measurement at 55 meters as well. Among the nine sites, eight of them have data records covering more than 1.5 years, and thus were selected in this study. The latitude, longitude, and elevation information of the eight sites is shown in Table 1. For the purpose of brevity, Figures 1 and 2 only show the wind speed histograms for sites Alfred and Green River, respectively. It can be seen that the distribution patterns vary between the two sites, and at different heights above ground. This verifies the need to use multiple PDFs to fit the real patterns and find the most suitable one.

Table 1
Geographical Information of 8 North Dakota Sites and the Average Wind Speed

Site	Latitude	Longitude	Elevation
Alfred	46º35'15"	99º00'46"	631 m
Benedict	47º53'20"	101º06'25"	671 m
Green River	47º04'05"	102º55'38"	818 m
Olga	48º46'48"	98º02'16"	475 m
Ray/Wheelock	48º15'57"	103º11'52"	750 m
Petersburg	47º59'13"	98º00'35"	477 m
Valley City	46º58'35"	97º53'22"	457 m
Wilton	47º08'21"	100º42'21"	683 m

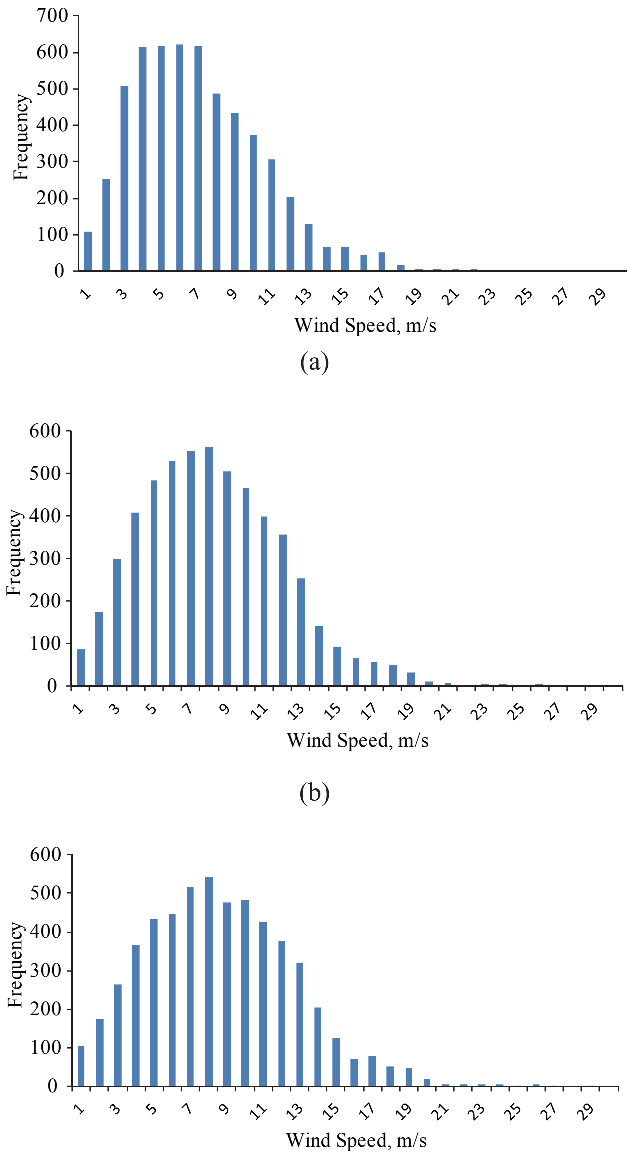

Figure 1
Wind Speed Histograms for Site Alfred at Heights of (a) 10 meters; (b) 25 meters; (c) 40 meters

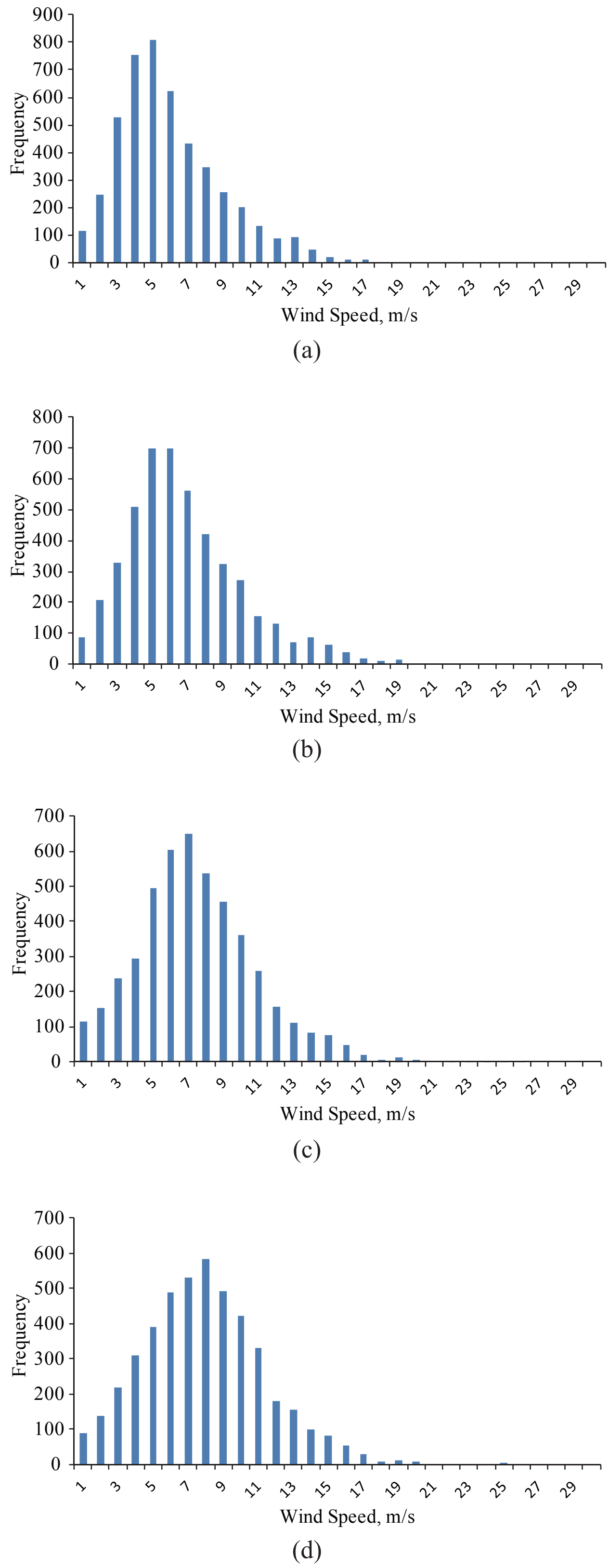

Figure 2
Wind Speed Histograms for Site Green River at Heights of (a) 10 meters; (b) 25 meters; (c) 40 meters; and (d) 55 meters

3. RESULTS AND DISCUSSION

3.1 PDF Parameters of Wind Speed Distributions

MiniTab, a statistical analysis software, was used to perform the analysis to fit the distributions of wind speed at the eight North Dakota sites. The best model parameters were obtained and the corresponding goodness-of-fit values (AD test in this study) were calculated. Tables 2-9 show the results for the eight sites. Note that some AD values may appear to be larger than the typical values encountered in statistics literature. It is actually common for goodness-of-fit statistics when dealing with very large datasets since they tend to be related with the dataset size. In our case, each site has more than 15,000 data points for all the height levels. The overall rule is that the smaller the AD value, the better the model fits. The following findings can be obtained by examining the results in the tables.

- For site Alfred, Gamma distribution fits the best for 10-meter wind speed, and Weibull distribution fits the best for 25-meter wind speed and 40-meter wind speed.
- For site Benedict, the best PDFs are gamma, lognormal, Weibull for 10-meter wind speed, 25-meter wind speed, and 40-meter wind speed, respectively.
- For site Green River, lognormal distribution is constantly the best PDF for the wind speeds of all height levels (10, 25, 40, and 55-meter), while Weibull distribution generates significantly inferior fits compared with lognormal or gamma distributions.
- For site Olga, the best PDFs are gamma, lognormal, lognormal, and gamma for 10-meter, 25-meter, 40-meter, 55-meter wind speeds, respectively. Similarly, in this case, Weibull distribution does not demonstrate good performances.
- For site Petersburg, the best PDFs are lognormal, lognormal, gamma, and gamma for 10-meter, 25-meter, 40-meter, and 55-meter wind speeds, respectively. Once again, Weibull distribution deviates to a great extent from the observations at all height levels.
- For site Ray/Wheelock, lognormal distribution is again constantly the best PDF for the wind speeds of all height levels (10, 25, 40-meter), while gamma distribution is always the second best option with slightly poorer performances, while Weibull distribution seems to be the worst.
- For site Valley City, gamma distribution is constantly the best PDF for the wind speeds of all height levels (10, 25, 40-meter), while gamma distribution and Weibull distribution show close performances for the three heights.
- For site Wilton, the best PDFs are Weibull, lognormal, Weibull, and Weibull for 10-meter, 25-meter, 40-meter, and 55-meter wind speeds, respectively.

In light of the fact that the commonly used 2-parameter Weibull or Rayleigh PDFs in literature cannot accurately describe the real wind speed distribution patterns, this study adopted the more powerful and general 3-parameter Weibull distribution. However, the results indicate that even the more general 3-paramter version of Weibull distribution cannot prove itself as the dominant PDF for all the heights or all the observation sites. In fact, there are more occasions for gamma or lognormal distribution to claim the crown of goodness-of-fit.

Table 2
PDF Model Parameters and Goodness-of-Fit Values for Site Alfred

		10-meter	25-meter	40-meter
Average wind speed		6.548466	7.760866	8.141619
Parameters (Weibull)	A	1.94831	2.18369	2.25328
	β	7.51428	9.14690	9.82399
	γ	-0.11236	-0.34476	-0.56593
	AD Value	2.743	1.899	2.293
Parameters (Lognormal)	μ	2.31834	2.80845	3.04917
	σ	0.32961	0.22744	0.18906
	γ	-4.17329	-9.25670	-13.33581
	AD Value	4.031	3.105	4.884
Parameters (Gamma)	α	4.53170	8.33878	11.19716
	β	1.69465	1.35908	1.22711
	γ	-1.13116	-3.57217	-5.59851
	AD Value	2.098	2.841	4.925

Table 3
PDF Model Parameters and Goodness-of-Fit Values for Site Benedict

		10-meter	25-meter	40-meter
Average wind speed		6.561719	7.453101	8.320129
Parameters (Weibull)	α	1.99644	2.33313	2.41739
	β	7.64393	9.03895	10.23451
	γ	-0.21478	-0.56522	-0.76122
	AD Value	1.205	5.009	2.331
Parameters (Lognormal)	μ	2.46180	2.95562	3.25017
	σ	0.28774	0.18401	0.15228
	γ	-5.65701	-12.08847	-17.77517
	AD Value	1.443	1.719	2.358
Parameters (Gamma)	α	5.44428	13.10881	17.71254
	β	1.53720	1.00182	0.95073
	γ	-1.80724	-5.67961	-8.51972
	AD Value	1.076	2.044	2.543

Table 4
PDF Model Parameters and Goodness-of-Fit Values for Site Green River

		10-meter	25-meter	40-meter	55-meter
Average wind speed		5.51577	6.328269	7.029138	7.443142
Parameters (Weibull)	α	1.92221	2.00150	2.31551	2.40564
	β	6.26403	7.24552	8.54282	9.08209
	γ	-0.03430	-0.09183	-0.55324	-0.62024
	AD Value	18.830	18.692	13.487	6.428
Parameters (Lognormal)	μ	2.02296	2.26367	2.82730	2.99180
	σ	0.36428	0.32160	0.19636	0.17319
	γ	-2.56302	-3.80144	-10.20016	-12.77947
	AD Value	2.935	2.922	3.988	1.953
Parameters (Gamma)	α	4.27561	5.22360	12.36570	15.12643
	β	1.44853	1.44966	0.97069	0.90727
	γ	-0.67758	-1.24418	-4.97416	-6.28064
	AD Value	5.405	5.213	4.783	2.240

Table 5
PDF Model Parameters and Goodness-of-Fit Values for Site Olga

		10-meter	25-meter	40-meter	55-meter
Average wind speed		5.358636	6.475487	7.218306	7.664662
Parameters (Weibull)	α	1.92140	2.13436	2.27933	2.25822
	β	6.18681	7.55923	8.64646	9.01786
	γ	-0.12811	-0.22316	-0.44946	-0.32832
	AD Value	7.627	6.606	5.016	2.100
Parameters (Lognormal)	μ	2.09079	2.47170	2.78842	2.82060
	σ	0.34116	0.26392	0.21045	0.21536
	γ	-3.21546	-5.78627	-9.40090	-9.51528
	AD Value	1.714	1.018	0.846	1.104
Parameters (Gamma)	α	4.54536	7.02052	10.40766	9.57887
	β	1.39760	1.23872	1.09551	1.20938
	γ	-0.99398	-2.22096	-4.18334	-3.91980
	AD Value	1.649	1.185	1.013	0.874

Table 6
PDF Model Parameters and Goodness-of-Fit Values for Site Petersburg

		10-meter	25-meter	40-meter	55-meter
Average wind speed		5.855354	6.669572	7.171005	7.975005
Parameters (Weibull)	α	1.85473	2.05776	2.10274	2.17415
	β	6.64635	7.63628	8.29236	9.29574
	γ	-0.04128	-0.09691	-0.17686	-0.26266
	AD Value	14.746	12.089	4.193	2.086
Parameters (Lognormal)	μ	2.07122	2.37908	2.55974	2.80951
	σ	0.37858	0.29694	0.26870	0.23135
	γ	-2.66767	-4.61264	-6.23606	-9.07594
	AD Value	1.195	1.055	1.887	3.675
Parameters (Gamma)	α	3.95729	5.85249	6.52384	8.10076
	β	1.65340	1.40766	1.43346	1.40590
	γ	-0.68762	-1.56878	-2.18065	-3.41385
	AD Value	3.042	2.044	1.669	3.289

Table 7
PDF Model Parameters and Goodness-of-Fit Values for Site Ray/Wheelock

		10-meter	25-meter	40-meter
Average wind speed		5.956467	6.812431	7.744645
Parameters (Weibull)	α	1.92468	2.17754	2.21768
	β	6.82769	8.11115	9.13131
	γ	-0.09779	-0.37752	-0.34935
	AD Value	7.968	6.768	4.908
Parameters (Lognormal)	μ	2.19529	2.65262	2.82016
	σ	0.33898	0.23435	0.22087
	γ	-3.55518	-7.77354	-9.44870
	AD Value	0.510	1.523	1.978
Parameters (Gamma)	α	4.52638	8.44170	9.18714
	β	1.54519	1.19165	1.26820
	γ	-1.03765	-3.24713	-3.90653
	AD Value	1.026	2.025	2.268

Table 8
PDF Model Parameters and Goodness-of-Fit Values for Site Valley City

		10-meter	25-meter	40-meter
Average wind speed		5.812713	6.7097	7.62417
Parameters (Weibull)	α	1.94843	2.08737	2.11661
	β	6.71092	7.78089	8.97345
	γ	-0.13809	-0.18451	-0.32857
	AD Value	1.723	0.927	2.068
Parameters (Lognormal)	μ	2.24560	2.48706	2.73414
	σ	0.31730	0.27341	0.24565
	γ	-4.11796	-5.77295	-8.24261
	AD Value	1.816	0.925	2.067
Parameters (Gamma)	α	4.76961	6.33219	7.31621
	β	1.47302	1.37852	1.46353
	γ	-1.21301	-2.01932	-3.08334
	AD Value	0.890	0.688	1.958

Table 9
PDF Model Parameters and Goodness-of-Fit Values for Site Wilton

		10-meter	25-meter	40-meter	55-meter
Average wind speed		6.267108	7.036658	7.615265	8.006467
Parameters (Weibull)	α	2.32390	2.34670	2.51564	2.59628
	β	7.53342	8.49106	9.67697	10.47500
	γ	-0.41273	-0.49467	-0.97829	-1.30022
	AD Value	1.372	2.226	2.924	4.496
Parameters (Lognormal)	μ	2.76042	2.94117	3.39316	3.73311
	σ	0.18776	0.17540	0.12142	0.09180
	γ	-9.82009	-12.19455	-22.36454	-33.97874
	AD Value	1.459	1.847	3.015	5.215
Parameters (Gamma)	α	12.06254	13.73337	27.17712	43.25869
	β	0.87815	0.91816	0.70149	0.58795
	γ	-4.32560	-5.57279	-11.44924	-17.42793
	AD Value	1.434	1.988	3.237	5.602

3.2 Wind Power Potential Estimation

Based on the PDFs obtained from the previous section, wind power potentials were computed according to Equation (7) or (8). For comparison purpose, we normalized the computations by removing the constant terms (i.e., ρ and A) in these equations. At the same time, since mean wind speed is a popular statistic for gauging the wind potential, we applied Equation (6) (without the constant terms) to compute the wind potential by directly plugging in the mean wind speed. The estimated wind potentials were all compared with the theoretical real power outputs per unit time, which is the average of the wind power outputs from individual observed hourly wind speeds computed by Equation (6). Tables 10-17 show the results and comparison between different methods. Note that the "normed energy" in the tables refers to normalized energy potential.

It can be seen that using the mean wind speed to compute wind potential will significantly lessen the real wind potential between 42-54%, with the average error of -46.64%. This basically makes this simplified approach doubtful. The problem can certainly be examined from the opposite perspective. That is, if no detailed wind speed observations are available, the wind potential estimation using the mean wind speed should be compensated by this error amount. This compensation rule should be particularly useful and effective for small-medium wind developers or residential wind turbine installations when resources are limited.

Also, several observations can be made regarding the potentials estimated by Weibull, lognormal, and gamma wind speed distributions. First, none of the potential estimations show universal superiority over others. This again confirms the need for testing multiple wind speed distributions and finding the best one after rigorous testing in order to accurately estimate the wind potential for any site or any height. Secondly, the overall performances in terms of potential estimation accuracy are in agreement with the goodness-of-fit results of wind speed distributions discussed in the previous section. In particular, for the cases where a PDF function has a large goodness-of-fit value, it usually also shows poor performance in estimating the wind power potential. For instance, for site Green River, the goodness-of-fit values of Weibull distribution are significantly larger than those of gamma or lognormal distribution, and the wind power potential estimations based on Weibull distribution are generally less accurate than those of other distributions. Thirdly, it needs to be pointed out that the performance ranking of wind power potential estimation based on the three PDF functions is actually not always consistent with that of wind speed goodness-of-fit. For instance, gamma distribution fits the best for 10-meter wind speed for site Alfred, but the wind potential estimated by Weibull distribution has the smallest error.

Table 10
Wind Energy Potential Estimates for Site Alfred

		10 m	**25 m**	**40 m**
Estimation based on average speed	Nomed energy	280.81	467.45	539.68
	Error	-50.72%	-45.55%	-44.86%
Weibull	Nomed energy	561.25	853.81	978.79
	Error	-1.51%	-0.55%	0.01%
Lognormal	Nomed energy	591.51	868.15	989.77
	Error	3.80%	1.12%	1.13%
Gamma	Nomed energy	580.60	867.93	992.89
	Error	1.89%	1.10%	1.45%

Table 11
Wind Energy Potential Estimates for Site Benidict

		10 m	**25 m**	**40 m**
Estimation based on average speed	Nomed energy	282.52	414.01	575.96
	Error	-49.64%	-43.57%	-42.38%
Weibull	Nomed energy	558.10	730.56	999.13
	Error	-0.53%	-0.43%	-0.05%
Lognormal	Nomed energy	578.77	734.96	1004.40
	Error	3.16%	0.17%	0.48%
Gamma	Nomed energy	575.32	734.54	1006.00
	Error	2.54%	0.11%	0.64%

Table 12
Wind Energy Potential Estimates for Site Green River

		10 m	**25 m**	**40 m**	**55 m**
Estimation based on average speed	Nomed energy	167.81	253.43	347.30	412.35
	Error	-51.95%	-50.00%	-44.34%	-42.44%
Weibull	Nomed energy	337.20	490.95	617.21	712.1145
	Error	-3.46%	-3.14%	-1.09%	-0.60%
Lognormal	Nomed energy	354.52	503.88	617.28	713.6297
	Error	1.50%	-0.59%	-1.08%	-0.39%
Gamma	Nomed energy	342.25	493.66	615.62	712.972
	Error	-2.01%	-2.61%	-1.34%	-0.48%

Table 13
Wind Energy Potential Estimates for Site Olga

		10 m	**25 m**	**40 m**	**55 m**
Estimation based on average speed	Nomed energy	153.87	271.53	376.10	450.28
	Error	-52.17%	-46.74%	-44.34%	-43.77%
Weibull	Nomed energy	314.27	502.20	669.95	796.443
	Error	-2.32%	-1.50%	-0.85%	-0.54%
Lognormal	Nomed energy	330.07	511.80	675.64	807.4975
	Error	2.59%	0.38%	0.00%	0.84%
Gamma	Nomed energy	321.42	507.49	673.97	806.3186
	Error	-0.10%	-0.46%	-0.25%	0.70%

Table 14
Wind Energy Potential Estimates for Site Petersburg

		10 m	**25 m**	**40 m**	**55 m**
Estimation based on average speed	Nomed energy	200.75	296.68	368.76	507.22
	Error	-54.07%	-48.32%	-47.08%	-45.27%
Weibull	Nomed energy	419.67	558.36	685.81	920.56
	Error	-3.98%	-2.73%	-1.58%	-0.67%
Lognormal	Nomed energy	443.95	569.03	700.01	935.77
	Error	1.58%	-0.87%	0.45%	0.97%
Gamma	Nomed energy	426.56	561.36	695.58	935.32
	Error	-2.40%	-2.21%	-0.18%	0.93%

Table 15
Wind Energy Potential Estimates for Site Ray/Wheelock

		10 m	25 m	40 m
Estimation based on average speed	Nomed energy	211.33	316.16	464.52
	Error	-51.63%	-46.41%	-44.84%
Weibull	Nomed energy	427.57	584.25	836.38
	Error	-2.13%	-0.97%	-0.68%
Lognormal	Nomed energy	448.44	591.93	846.77
	Error	2.65%	0.33%	0.55%
Gamma	Nomed energy	437.85	589.72	845.29
	Error	0.22%	-0.04%	0.38%

Table 16
Wind Energy Potential Estimates for Site Valley City

		10 m	25 m	40 m
Estimation based on average speed	Nomed energy	196.40	302.07	443.18
	Error	-50.87%	-47.46%	-47.17%
Weibull	Nomed energy	394.77	567.51	832.77
	Error	-1.24%	-1.30%	-0.73%
Lognormal	Nomed energy	413.24	581.84	849.05
	Error	3.38%	1.19%	1.21%
Gamma	Nomed energy	407.36	577.47	847.47
	Error	1.91%	0.43%	1.02%

Table 17
Wind Energy Potential Estimates for Site Wilton

		10 m	25 m	40 m	55 m
Estimation based on average speed	Nomed energy	246.15	348.42	441.63	513.24
	Error	-43.28%	-42.96%	-42.03%	-41.94%
Weibull	Nomed energy	432.78	609.29	762.52	886.37
	Error	-0.28%	-0.25%	0.10%	0.26%
Lognormal	Nomed energy	437.09	613.47	764.59	887.64
	Error	0.72%	0.44%	0.37%	0.40%
Gamma	Nomed energy	437.38	614.08	765.93	889.95
	Error	0.78%	0.53%	0.54%	0.67%

CONCLUSION

This paper presents an empirical study on estimating wind power potential in the state of North Dakota, USA. Based on the comprehensive efforts on wind speed data collection at eight observation sites, we analyzed the wind speed distribution and energy potential at multiple heights of measurement for each site. Overall, the observation sites of Alfred and Benedict have the most abundant wind energy resources, while Green River and Olga have the least potentials. Based on the theoretical estimation, the wind potentials at Benedict are higher than those of Green River by about 68%, 49%, 63% for the height of 10m, 25m, and 40m, respectively.

Three probability density functions, namely, Weibull, gamma, and lognormal PDFs, were adopted to fit wind speed distributions. It was found that the best functions for wind speed distributions can vary with the change of height and/or observation sites, and the popular Weibull distribution does not always outperform gamma or lognormal distributions. Thereafter, we compared the performances of the fitted distributions in estimating wind power potential. In this regard, we discovered once more that no single distribution is the universal top performer, and the rank of estimation accuracy may not always be consistent with that of goodness-of-fit for wind speed distributions. Furthermore, we evaluated the performance when directly applying the mean wind speed to compute wind power potential. It was found that this method tends to be of less value to theoretically real wind power potential by 42-54%. Thus in practice, if no detailed wind speed data or distributions are provided, the estimation based on mean wind speed should be compensated for by the amount of difference.

It should be noted that this study employed the theoretical wind potential equation, which regards the energy potential is a cubic function of wind speed. The estimation may be improved based on the specific power curves of wind turbines since the power curves control the actual wind energy production. However, power curves vary with the selection of wind turbines and there are numerous wind turbines available on the market. As such, the current results have shed enough light for wind energy developers.

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