Green Power Statistics: Local Wind Speed Modeling as Basis for Wind Turbine Performance Prediction

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Abstract
Statistics plays a crucial part in renewable energy research, e.g. building an efficient wind turbine calls for a comprehensive analyzes of the local wind speed distribution. This paper details outcomes of a year-long research by the faculty/student team at LaGuardia Community College, originally presented at the JSM 2017 conference. Our goal of designing a small horizontal axis wind turbine optimized for the wind pattern on the college roof requires a close statistical study of the wind. While collecting and validating short term wind speed measurements at our site for transforming (via. correlation method) long-term data from a nearby airport into a reliable local time series, we determine the best fitting probability distribution model for the airport data in order to gain insight into the wind pattern at our own (similar) location, fine-tune our measurements protocol and make a preliminary estimate of the potential energy output of our turbine. Surprisingly, Weibull distribution with parameters estimated by the Maximum Likelihood method provides an inadequate fit for the data. The Maximum Goodness of Fit and the Quantile methods both fare better in determining parameters of the Weibull model, while Gumbel and Logistic distributions provide a better fit. We apply continuity correction to simulate wind speed data that agrees with, but does not suffer from the deficiencies of, the raw data set. Consequently, Weibull model with parameters estimated by the Maximum Likelihood method provides the best fit. Airport data taken at ground level yields average wind speed estimate insufficient to justify the installation of the turbine. By rescaling the data for the height at which we propose to install the turbine we show sufficient wind speed average. Using the best fitting probability model, we predict the average annual energy output for a proposed turbine.

Key Words: wind speed modeling, parameter estimation, wind turbine energy prediction

1. Project Motivation

Statistics plays a crucial part in renewable energy research, e.g. building an efficient wind turbine calls for detailed analyzes of the local wind speed distribution. Our goal, as a faculty/student research team at LaGuardia Community College, is to design a small horizontal axis wind turbine optimized for the wind pattern on the roof of our campus where we propose to have the turbine installed. Before optimizing the design, it is essential to estimate the potential energy output to justify the costs of production and operation. Once this has been achieved, wind speed distribution plays a crucial role in the selection of an airfoil as well as the blade design. Thus, obtaining an accurate probability model of the wind speed at our site has been a crucial aspect of the research project.

1.1 Similar Projects

Similar research has been conducted at other colleges but none pursued an identical set of objectives. A recent study at MIT was concerned primarily with accurate wind measurements and modeling but had no turbine optimization component, instead the energy output was predicted for an existing commercial turbine. By contrast, CUNY City College project involved designing a wind turbine farm but took a theoretical wind distribution as a starting point. Neither study resulted in the full-scale implementation. Our ambition has been to combine statistical analyses and aerodynamic design calling upon a closer association of the two disciplines.

Our study is further distinguished from MIT project in that the latter limited itself to modeling their local wind data with only Weibull distribution whose parameters were determined by the Maximum Likelihood Method, whereas we embraced a more open approach and considered fitting the data with different distributions (Weibull, Gumbel, Logistic) using different techniques of parameter estimation (including Maximum Likelihood, Maximum Goodness of Fit and Quantile methods). One of the practical reasons behind such a broad approach lies in the fact that we had to obtain a reliable preliminary energy output estimate of our turbine while still in the process or acquiring and validating our own wind measurements.

2. Modeling Local Wind Data

2.1 Raw Data

The original data set was obtained from NOAA records of wind speed at the nearby LaGuardia Airport. The data set met our requirements of being a long-term record of wind readings consisting of validated 10 minute averages of wind speed observations. The proximity to our location justified the assumption of the similarity of the wind patterns. However, there were several drawbacks. First one had to do with the wind pattern itself: the airport data was taken at a ground level whereas our proposed turbine site is at 100 fit elevation. This we proposed to resolve by adjusting parameters once the best fitting model for the original data set has been obtained. Second challenge had to do with the nature of available records: the wind speed readings at the airport have been rounded to the nearest integer values, wind speeds below 3 mi/hr were reported as 0’s, and certain wind speed values (12 mph, 17-19 mph) have been inexplicably omitted from the distribution.

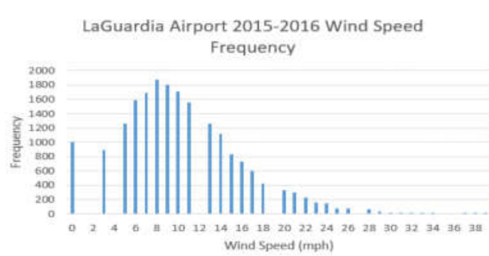
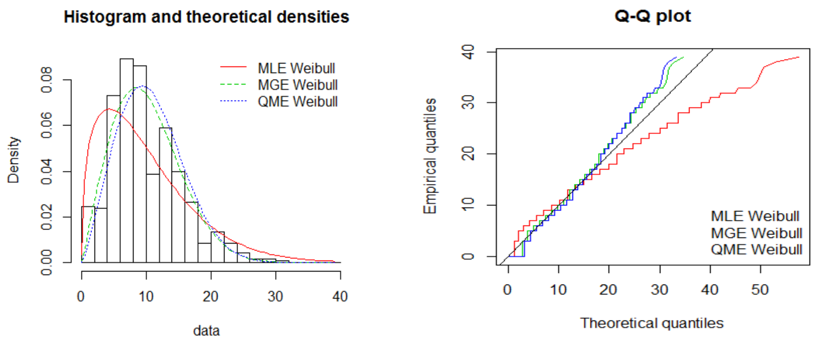


Figure 1: Wind speed distribution at LaGuardia Airport.

2.2 Modeling Raw Data

Our initial analyses produced somewhat unexpected results. The standard fitting of the wind data set with the Weibull distribution using Maximum Likelihood parameter estimations (MLE) resulted in a very inadequate fit. Upon considering Kolmogorov–Smirnov, Cramer–von Mises, and Anderson–Darling statistics, we determined that Maximum Goodness of Fit (MGE) and Quantile Methods (QME) provided better Weibull parameter estimators than MLE. Moreover, both Gumbel and Logistic distributions with parameters estimated by either method resulted in a better model than MLE Weibull, with MGE Logistic being an overall winner (see below).

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Goodness-of-fit statistics
                             MLE Weibull  MGE Weibull QME Weibull
Kolmogorov-Smirnov statistic   0.1933712   0.07472514   0.1195155
Cramer-von Mises statistic    78.7100575   8.80584944  23.6690936
Anderson-Darling statistic   571.1553058 367.82144269 474.6643859
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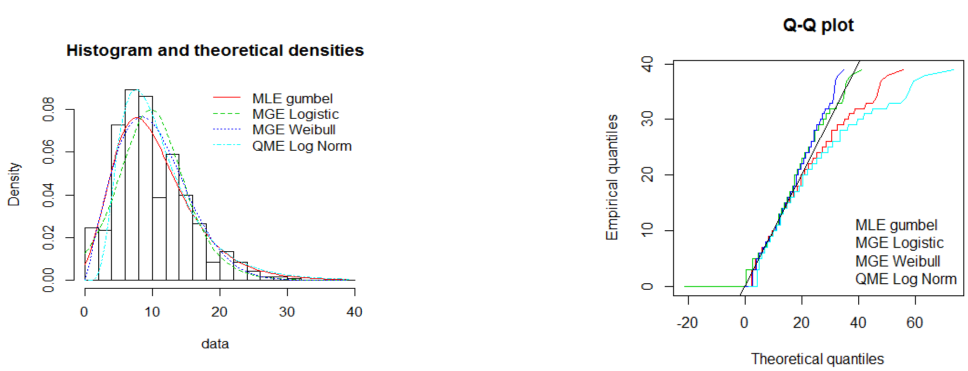
Figure 2: Comparison of Weibull parameter estimation methods

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Goodness-of-fit statistics
                              MLE Gumbel MGE Logistic
Kolmogorov-Smirnov statistic  0.08235356   0.08154128
Cramer-von Mises statistic    9.76369340  12.95508087
Anderson-Darling statistic   73.33426389  94.18903026
                             MGE Weibull QME Log Norm
Kolmogorov-Smirnov statistic   0.07472514    0.1327818
Cramer-von Mises statistic     8.80584944   29.8989383
Anderson-Darling statistic   367.82144269  142.1964101
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Figure 3: Comparison of best fitting models

2.3 Modeling Adjusted Data

As this was not what we have expected, we re-examined our data set and decided to simulate continuous distribution by replacing an existing integer value with a measurement, specified up to 2 decimal points, randomly chosen with uniform probability from an appropriate range of values. The resulting simulated data set has changed the outcome drastically and continued to do so consistently throughout a series of simulations. The best fit for a simulated continuous data set would invariably turn out to be Weibull with parameters estimated by the MLE method! In fact, MLE Weibull post-simulation was significantly better than the best pre-simulation model (MGE Logistic), based on all three error estimators.

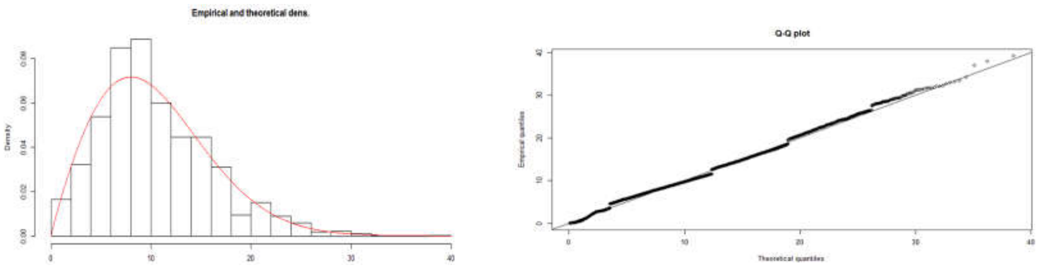

Figure 3: MLE Weibull fit (Post-Simulation)

Goodness-of-fit Statistic	MGE Logistic (Pre-Simulation)	MLE Weibull (Post-Simulation)
Kolmogorov-Smirnov	0.082	0.051
Cramer-von Mises	12.955	6.288
Anderson-Darling	94.189	37.474

Table 1: Comparison of GOF statistics for best models

2.1.1 Proposed model

Thus, we have determined the desired accuracy of measurements for our local data set and hypothesized that the wind pattern at our site (at the elevation of 11 ft equivalent to that of LaGuardia Airport) is indeed most closely matched by the Weibull distribution with the following parameters (estimated by MLE): shape 1.928 and scale 11.694 mi/hr. Since we plan to install our turbine at the height of 100 ft, we have used the wind Profile Power Law to determine that the Weibull shape parameter is independent of the elevation while the scale parameter increases logarithmically with height resulting in the value of 16.028 mi/hr. The resulting model predicted an average wind speed at our site equal to 14.3 mi/hr or 6.3m/s which is deemed sufficient for the installation of a small wind turbine.

Weibull Parameter	At 11 ft	At 100 ft	Std. Error
Shape (k)	1.928	1.928	0.014
Scale (c)	11.694 mi/hr	16.028 mi/hr	0.062

Table 2: Parameters of the Weibull distribution

2.1.1 Power estimation

We have then calculated the energy output estimate for our proposed wind turbine based on our wind distribution model and the turbine's Power Curve estimate (measure of efficiency at a given wind speed) obtained by methods of Blade Element Momentum Theory. The resulting value of annual energy output was close to 19000 kWh, which is sufficient to justify costs of production and upkeep given the turbine's educational as well as economical value.

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