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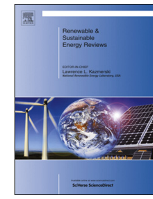

Multi-peak Gaussian fit applicability to wind speed distribution

Jami Hossain [a,*], Suman Sharma [a], V.V.N. Kishore [b]

[a] WinDForce Management Services Private Limited, Gurgaon 122018, India
[b] The Energy and Resources Institute, New Delhi 110003, India

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ABSTRACT

Efforts to harness wind energy on a large scale have gained momentum across the world. By the end of December 2013, a cumulative capacity of more than 300 GW of wind power projects had been installed all over the world. One of the key aspects involved in implementing wind power projects is the analysis of wind speeds distributions observed or recorded and assessment of annual energy output from the wind turbines. The wind speed frequency distribution is generally assumed to follow two-parameter Weibull Distribution. In general, across the world, annual energy generation estimations of a wind turbine at a given site are assessed on the basis of Weibull Distribution. However, in this paper, based on a robust analysis carried out on over 208 measurement sites in India, we show that multi-peak Gaussian distribution functions are a significantly improved representation of observed wind speed distributions.

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1. Introduction

The worldwide installed capacity of wind power was a little more than 300 GW at the end of December 2013 [1]. The electricity generated from these windfarms accounts for more than 3.5% of the global electricity consumption [1]. Geographically, there is now a widespread deployment of modern wind turbine technology across the globe and nearly all the countries are including wind energy in their plans and policies. Over the last 5–10 years, utility-scale wind electricity generation has emerged as a mature mainstream energy technology.

A prerequisite for setting up a windfarm is detailed wind resource assessment at the site, which includes measurement of wind speeds and other climatic conditions for a minimum 3-year period. However, given the pace at which windfarms are being planned and the commensurate speed with which policies, programs and the legal, statutory and regulatory frameworks should

* Corresponding author.
E-mail addresses: jami@windforce-management.com (J. Hossain), suman@windforce-management.com (S. Sharma), vvnk@teri.res.in (V.V.N. Kishore).

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be set in place, the stakeholders and agencies involved are always in a hurry and often try to reduce the development time. An important component in the development time is the wind speed measurement period. Reduction in measurement period can be achieved by means of mathematical modelling of different aspects of wind resource. Some of these aspects are vertical and horizontal extrapolation of wind regimes, regional assessment of large geographical areas, wind distribution modelling, correlations with nearby measurements, etc. With these techniques, it is possible to reduce not only the measurement but also unnecessary expenses.

Here, mathematical modelling of wind speed distributions plays an important role. Assessments of annual energy output (AEO) from wind turbines are often made using mathematical models in which a mathematical function is assumed to represent the actual wind speed frequency distribution. This enables AEO computations to be made by using only a few parameters and the mathematical function mimics the frequency distribution of wind speeds.

Though there are different kinds of functions that could be fitted to wind speeds measured at a site, the two-parameter Weibull distribution has wide acceptance across the world. In spite of scientific improvements, standardization of measurement procedures such as International Electrotechnical Commission (IEC) [2], variance in AEO assessments from actual output of windfarms continues to be an area of major concern in the wind industry. The purpose of the work reported here is to assess the suitability of multi-peak Gaussian function to wind speed distributions in place of Weibull distribution function and to compare the two.

Our analysis with wind speed data from 208 locations, spread all over India, indicates that wind speed distributions have a much better fit with Gaussian multi-peak functions as compared to Weibull distribution.

2. A review of different models

Justus et al. [3] have justified the use of Weibull distribution and its subset, the Rayleigh distribution, which is the Weibull distribution with "$k=2$". Innumerable books and publications [4–7] have used, projected or justified Weibull distribution or Rayleigh distributions as good representation of wind speed distributions. Sedefian [8] has assumed Weibull distribution in his presentation of methods of extrapolating wind distributions to different heights. Pang et al. [9] have reiterated the reasons for using Weibull distribution given by Justus et al. [3]. Pang et al. have estimated three parameters of Weibull distribution using Markov Chain Monte Carlo (MCMC) method and Max Likelihood (ML) methods. They have concluded that for the data analysed by them, there was little evidence that the three-parameter Weibull model was necessary, thus implying that the two-parameter Weibull distribution described above was adequate for approximating wind speed distribution.

Both Lysen and Justus have also mentioned Rayleigh distribution which is a special case of Weibull distribution with $k=2$. The Rayleigh distribution offers additional advantage over Weibull distribution due to the fact that the computations become more simplified as only one variable, i.e., 'mean wind speed', has to be used in the computations. This could have a significant implication on computational time and effort when assessments are being made for a geographical area or at a regional level.

A study on Antarctica has used Rayleigh distribution [10]. In the assessment of California offshore assessment [11] and the Global wind potential assessment also, Rayleigh distribution has been assumed.

In more recent work by Celik and Muneer [12], a critical evaluation of different frequency distributions has been carried out. In addition to two-parameter Weibull and Rayleigh distributions they have also evaluated the applicability of three-parameter Weibull distribution, lognormal distribution and bimodal Weibull distribution. For the data analyzed, they have found bimodal Weibull distribution provides the best fit. However, the shortcoming with this work is that it uses data from only one site and secondly the objective of the paper seems to be development of a method of arriving at a score to figure out which model is best suited to a given wind distribution and not to establish as to which model, in general and for wider applicability, is the appropriate approximation for representing wind speed distributions. Celik [13] assessed the error in energy estimation of small wind power systems using Weibull distribution to be of the order of 2.79%. Kollu et al. [14] have evaluated three mixture probability density functions Weibull-extreme value distribution (GEV), Weibull-lognormal, and GEV-lognormal distributions for their suitability to wind distributions and concluded that mixture distributions are able to provide better fit. Akdag et al. [15] have evaluated two-parameter Weibull distribution and two-component mixture Weibull distribution with five parameters and concluded a mixture of two Weibull distributions is more suitable for the description of such wind conditions and could offer less relative errors in determining the annual mean wind power density.

It is interesting to note that a mixture of distributions turns out to be a better fit than a single Weibull distribution. It is a known fact that wind speed distributions are often multi-modal or bi-modal particularly. Such bi-modal or multipeak distributions will always present difficulties in fitting them to a single Weibull distribution.

With the exception of more recent work of Celik and Muneer [12], Kollu et al. [14] and Akdag et al. [15], who have either carried out a critical evaluation of different frequency distributions w.r.t. wind energy or have attempted mixtures of two or more probability distribution functions, literature search carried out so far continues to point overwhelmingly towards two-parameter Weibull distribution or the Rayleigh distribution as the widely accepted choice for representing wind speed distribution. However, in our analysis presented here, we find that multipeak Gaussian distributions are a significantly better fit than Weibull and Rayleigh distributions.

3. Theory and formulations

3.1. Probability density function

The probability density function (PDF) is a function that can be integrated to obtain the probability of occurrence of the variable having a value in a given class interval. The probability density function is nonnegative everywhere, and its integral over the entire space is equal to one.

A probability density function is most commonly associated with absolutely continuous univariate distributions. A random variable X has density f, where f is a non-negative function [16–18], if

$$P[a \le X \le b] = \int_a^b f(x)dx \tag{1}$$

Hence, if F is the cumulative distribution function of "x", then

$$F(x) = \int_{-\infty}^{x} f(u)du \tag{2}$$