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Estimation of wind energy potential using finite mixture distribution models

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ABSTRACT

In this paper has been investigated an analysis of wind characteristics of four stations (Elazig, Elazig-Maden, Elazig-Keban, and Elazig-Agin) over a period of 8 years (1998–2005). The probabilistic distributions of wind speed are a critical piece of information needed in the assessment of wind energy potential, and have been conventionally described by various empirical correlations. Among the empirical correlations, there are the Weibull distribution and the Maximum Entropy Principle. These wind speed distributions can not accurately represent all wind regimes observed in that region. However, this study represents a theoretical approach of wind speed frequency distributions observed in that region through applications of a Singly Truncated from below Normal Weibull mixture distribution and a two component mixture Weibull distribution and offer less relative errors in determining the annual mean wind power density. The parameters of the distributions are estimated using the least squares method and Statistica software. The suitability of the distributions is judged from the probability plot correlation coefficient plot R^2, RMSE and χ^2. Based on the results obtained, we conclude that the two mixture distributions proposed here provide very flexible models for wind speed studies.

1. Introduction

The increasing global population and the fast depleting reserves of fossil fuels causing environmental pollution as a result of incomplete combustion have encouraged researchers to research for clean and pollution free sources of energy such as solar, wind and solar-hydrogen energies [1,2]. The rapid development in wind energy technology has made it an alternative to conventional energy systems in recent years. Parallel to this development, wind energy systems have made a significant contribution to daily life in developing countries, where one-third of the world's people live without electricity [3,4].

Most developed countries are facing many challenges as they prepare to meet their energy needs during the 21st century and develop many programs, which support the use and deployment of renewable energy sources. For example, the US Department of Energy's (DOE's) Wind Energy Program recently began charting new directions for its efforts as follows: (i) increasing the viability of wind energy by developing new cost-effective technology for deployment in less-energetic, developing cost-effective distributed, small-scale wind technology; and laying the groundwork for future work to tailor wind turbine technology to the production of hydrogen and (ii) increasing the deployment of wind energy by providing supporting research in power systems integration, resource information, market acceptance, and industry support [5].

Turkey is one of the developing countries. The production of electricity in Turkey is basically focused on hydro-power and thermal-power [6–9]. More than half of the total energy consumption in Turkey is met by imports. Measurements show that Turkey has a reasonable wind potential. It seems that, if the country wants to supply its demand by domestic resources, a shift from conventional energy resources (i.e. fossil fuels, such as hard coal, lignite, oil, and natural gas) to renewable energy resources is essential in the near future. However, the development of wind energy in Turkey started about 3 years ago when some wind plants were installed at several locations in the country. To date, three wind power plants were installed with a total capacity of 18.9 MW. It is projected that the total installed capacity will reach about 504 MW by the end of 2002 [6].

The wind variation for a typical site is usually described using the so-called Weibull distribution that is the most widely used and accepted in the specialized literature on wind energy and other renewable energy sources. In this context, over last decade, various researchers have carried out a number of studies in order to assess wind power around the world [10–18]. In these studies, much consideration has been given to the Weibull two-parameter (k, shape parameter and c, scale parameter) function because it has been found to fit a wide collection of wind data. Recently, Li and Li [19] developed a theoretical approach to analytical determination of wind speed distributions based on the maximum entropy prin-

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ciple. It was shown that this model can describe not only the actual data more accurately than the Weibull distribution but also a much wider range of data types [19–24].

On the other hand, the mixture distributions proposed in this paper were found to provide very flexible models for wind speed studies [25,26]. These mixture distributions can be applied in a widespread manner to represent the wind regimes in the Elazig, Elazig-Maden, Elazig-Keban, and Elazig-Agin with similar characteristics.

The aim of this paper is to compare the Weibull distribution and the maximum entropy principle with the Singly Truncated from below Normal Weibull mixture distribution and the two-component mixture Weibull distribution for regions around Elazig over a period of 8 years. The comparison is centered on the level of fit to the observed wind probability distributions and the ability to describe the experimental mean wind power density.

2. Data validation

The wind speed data in hourly time-series format in the regions around Elazig over a period of 8 years (1998–2005) have been collected and statistically analyzed. Geographic information about these regions is given in elsewhere [15,16]. The wind speed data were recorded at a height of 10 m, continuously by a cup-generator anemometer for the whole stations of the Turkish State Meteorological Service. However, changes on measured and recorded data at the whole meteorological stations have given elsewhere [15,16].

3. Mathematical models

3.1. Weibull distribution (W-pdf)

Many researchers have devoted to develop an adequate statistical model to describe wind speed frequency distribution. The Weibull and Rayleigh functions are commonly used for fitting the measured wind speed probability distribution. Patel [27] claims that the Weibull probability distribution function with two constant parameters is the best one to describe the variation in wind speed.

A random variable V has a Weibull distribution if its probability density function is defined by Eq. (1). The Weibull distribution with two parameters can be written as

$$f(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} \exp\left[-\left(\frac{V}{c}\right)^{k}\right] \tag{1}$$

where k is the shape parameter (dimensionless) and c is the scale parameter having the dimension of speed. The distributions will take different shapes with different values of k, the shape parameter. The unknown parameters k and c can be determined with several different methods.

3.2. The Maximum Entropy Principle (MEP-pdf)

The Maximum Entropy Principle has been successfully applied to many problems arising in a wide variety of fields. This method can be used to predict the most likely probability distribution, or probability density distribution, for a particular physical problem under a set of constraints expressing the available information related to the distribution sought. When the Maximum Entropy Principle is applied to the wind energy field to determine the wind-speed distribution, the constraint equations imposed must be based on the physical principles, or the conservation of mass, momentum and energy for the air stream flowing with the wind. By maximizing the Shannon's entropy, the probability is derived as [21]

$$P_i = \exp\left(-\alpha_0 - \alpha_1 V_i - \alpha_2 V_i^2 - \alpha_3 V_i^3\right) \tag{2}$$

For continuous variables, such as the wind speed, the subscripts can be dropped and the summation can be replaced by the integrals with the corresponding limits from minimum to maximum. The continuous probability density function can be obtained as [21]:

$$f(V) = \exp\left(-\alpha_0 - \alpha_1 V - \alpha_2 V^2 - \alpha_3 V^3\right) \tag{3}$$

It can be observed that both the theoretical Maximum Entropy Principle distribution derived from the maximization of the Shannon's entropy and all the other empirical distributions used to describe the variation in wind speed are exponential functions. However, the empirical functions always have a pre-exponential term, which is the function of the wind speed to a non-negative power. Considering that this pre-exponential function of wind speed can lower the probabilities in the low speed range, the Maximum Entropy Principle type exponential function is modified by adding the wind speed to r power as the pre-exponential term to the theoretical MEP distribution given in Eq. (3). Therefore, the semi-empirical wind speed distribution can be written as [19],

$$f(V) = V^r \exp\left(-\alpha_0 - \alpha_1 V - \alpha_2 V^2 - \alpha_3 V^3\right) \tag{4}$$

where r may take non-negative values, and $r = 0$ represents the theoretical MEP distribution as shown in Eq. (3). The above equation with non-zero positive r values thus represents the MEP-type exponential family of the distribution functions.

3.3. Singly truncated normal Weibull mixture distribution (TNW-pdf)

A random variable V has a singly truncated from below normal distribution if its probability density function is defined by Eq. (5) [26],

$$\begin{cases} g(v;\xi,\theta) = \frac{1}{I_0(\xi,\theta)\theta} Z(v,\xi,\theta), & v \geqslant 0; \quad \theta > 0 \\ 0, & v < 0 \end{cases} \tag{5}$$

where $Z(v,\xi,\theta)$ and $I_0(\xi,\theta)$ are given by Eqs. (6) and (7), respectively. ξ and θ are parameters with the same units as the random variable. As can be seen in Eq. (5), the density function $g(v,\xi,\theta)$ is defined for $v = 0$, and therefore, unlike the Weibull distribution, it can represent the probabilities of observed periods of null wind speeds

$$Z(v,\xi,\theta) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{(v-\xi)^2}{2\theta^2}\right] \tag{6}$$

$$I_0(\xi,\theta) = \frac{1}{\theta}\int_0^\infty Z(v,\xi,\theta)dv = \frac{1}{\theta\sqrt{2\pi}}\int_0^\infty \exp\left[-\frac{(v-\xi)^2}{2\theta^2}\right]dv \tag{7}$$

The corresponding cumulative distribution function is given by Eq. (8), which cannot be expressed in closed form

$$G(v,\xi,\theta) = \Pr(V \leqslant v) = \frac{1}{\theta\sqrt{2\pi}}\int_0^\infty \exp\left[-\frac{(v-\xi)^2}{2\theta^2}\right]dv \tag{8}$$

V_1 and V_2 are independently distributed as Single Truncated from below normal $g(v;\xi,\theta)$, Eq. (5), and two parameter Weibull $f(v;c,k)$, Eq. (1). Then, a random variable V that is distributed as V_1 and V_2 with mixing weights, mixing proportions or mixing parameters ω_1 and ω_2 (such that $\omega_1 + \omega_2 = 1$) is said to have a Singly Truncated from below Normal Weibull mixture distribution with density function Eq. (9), which depends on five parameters (ξ, θ, c_0, k_0, ω).

$$gf(v;\xi,\theta,c_0,k_0,\omega) = \omega g(v;\xi,\theta) + (1-\omega) f(v;c_0,k_0) \tag{9}$$