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Heterogeneous mixture distributions for modeling wind speed, application to the UAE

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ABSTRACT

Heterogeneous mixture distributions (HTM) have not been employed for wind speed modeling of the Arabian Peninsula. In order to improve our understanding of wind energy potential in the Arabian Peninsula, HTM should be tested for the frequency analysis of wind speed. The aim of the current study is to assess the suitability of HTMs and identify the most appropriate probability distribution to model wind speed data in the UAE. Hourly mean wind speed data were used in the current study. Ten homogeneous and heterogeneous mixture distributions were used and constructed by mixing the four following probability distributions: Gamma, Weibull, Extreme value type-one, and Normal distributions. The Weibull and Kappa distributions were also employed as representatives of the conventional non-mixture distributions. Maximum Likelihood, Expectation Maximization algorithm, and Least Squares methods were employed to fit the mixture distributions. Results indicate that mixture distributions give the best fit to wind speed data for all stations. Wind speed data of five stations show strong mixture distributional characteristics. Applications of HTMs show a significant improvement in explaining the whole wind speed regime. The Weibull-Extreme value type-one mixture distribution is considered the most appropriate distribution for wind speed data in the UAE.

1. Introduction

Fossil fuel energy sources such as oil and gas, have been losing economic feasibility due to increasing environmental concerns and the cost of mining [1]. Renewable energy sources are considered as viable alternatives to replace conventional energy sources. Wind energy, in particular, is considered as one of the most promising renewable energy sources. In order to design and operate wind energy conversion systems, it is necessary to estimate wind power potential. Wind power potential can be obtained by integration of the wind power density distribution. The wind power density distribution is a function of the density of the air, the cubic wind speed and the probability density function (pdf) of wind speed [2]. When air density is known and the wind speed distribution is determined, the wind power density distribution can easily be obtained [3].

The application of a suitable distribution model is one of the most important factors to accurately estimate wind power potential. Various probability distribution models have been used and tested to characterize wind speed data in a large number of studies [4-11]. The 2-parameter Weibull (W) and the Rayleigh probability distributions have been most widely used to model wind speed data [12-16]. Wind speed regimes frequently present mixture distributional characteristics such as bimodality and kutotic unimodality [17]. When wind speed regimes show mixture distributional characteristics, non-mixture distribution models such as W, Rayleigh and Gamma (G) distributions cannot explain the whole wind speed regime [18].

Mixture distribution models have been suggested in a number of studies for fitting wind speed data. Most these studies adopted homogeneous mixture distribution models, i.e. models that combine identical types of distributions. Jaramillo and Borja [19] for instance used the W distribution and the Weibull–Weibull (WW) homogeneous mixture distribution model to fit wind speed data in La Ventosa Mexico. The WW distribution led to better fit than the W distribution to describe the bimodal wind speed regime in this

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region.

Heterogeneous mixture distributions are combinations of different types of distributions. Heterogeneous mixture distributions have been adopted in a very limited number of studies in the field of wind modeling, but proved their value. Carta and Ramírez [20] proposed to use the Truncated Normal-W (TNW) heterogeneous mixture distribution, to model wind speed data because it can take into consideration null wind speeds. They concluded that the WW and the TNW mixture distributions lead to a better fit than the W distribution. Akpinar and Akpinar [21] applied the W, the Maximum Entropy Principle (MEP), the WW mixture and the TNW mixture distributions for wind speed analysis. They indicated that mixture distributions, i.e. WW and TNW, lead to better fits than W and MEP to model wind speed data whether showing mixture distributional characteristics or not. Chang [22] investigated the suitability of various mixture distributions to model wind speed data in Taiwan. These results indicated that the Gamma–Weibull (GW) mixture distribution leads to the best fit. Kollu, Rayapudi, Narasimham and Pakkurthi [23] proposed the Generalized Extreme Value (GEV) and the Lognormal distributions for component density modeling of mixture distributions of wind speed data. According to their results, the GEV-W and the GEV-Lognormal mixture distributions provided the best fits.

A number of studies have investigated wind energy potential in the Arabian Peninsula and neighboring regions [24-26]. All these studies employed the W and Rayleigh distributions in order to model wind speed data. Ouarda, Charron, Shin, Marpu, Al-Mandoos, Al-Tamimi, Ghedira and Al Hosary [27] investigated the suitability of various distributions including non-mixture and one homogeneous mixture distribution, the WW, to model wind speed data in the United Arab Emirates (UAE). No study adopted heterogeneous mixture distributions for wind speed analysis in the Arabian Peninsula. The application of heterogeneous mixture distributions to model wind speed data is promising and may lead to a more accurate estimation of the true wind power potential in the Arabian Peninsula. Heterogeneous mixture distributions have been used with great success for the modeling of other hydro-climate variables (see for instance [28,29]). The aim of the current study is to investigate the applicability of heterogeneous mixture distributions and identify the most appropriate distribution to model wind speed data in the UAE. The Extreme value type-one (E) distribution is also proposed and tested as density component in mixture distributions in the current study.

This paper is organized as follows. In Section 2, the theoretical background of probability distribution models, parameter estimation methods, and goodness-of-fit (GOF) measures is described. Section 3 presents the characteristics of the used wind speed data used in the study. In Section 4, the results of the GOF measures and the estimated frequency of wind speed distributions are presented. In Section 5, the applicability of mixture distributions and the suitability of the employed mixture distributions for wind speed analysis in the UAE are discussed. Finally, conclusions are presented in Section 6.

2. Theoretical background

2.1. Heterogeneous mixture probability distribution model

A mixture distribution $f(v)$ is the weighted sum of g component densities $\pi_i f_i(v;\boldsymbol{\theta}_i)$.

$$f(v|\boldsymbol{\theta}_1,\ldots,\boldsymbol{\theta}_g)=\sum_{i=1}^{g}\pi_i f_i(v|\boldsymbol{\theta}_i) \tag{1}$$

$$\sum_{i=1}^{g}\pi_i=1 \tag{2}$$

where v is a random variable (wind speed), $\boldsymbol{\theta}_i$ is a parameter set of the ith component density, g is the number of mixtures, and π_i is the ith mixing proportion or weight. π_i is a non-negative quantity that is smaller than 1.

Several mixture distributions have been tested in a number of studies for modeling wind speed data [20,22,23,30]. In these previous studies, the G, W, GEV, and Normal (N) distributions were adopted as density components of mixture distributions. The mixture distributions built by these components led to a good fit to wind speed data.

Kollu, Rayapudi, Narasimham and Pakkurthi [23] used the GEV distribution as a density component of mixture distribution and assumed that the value of the location parameter is equal to one. Because the location parameter of the GEV distribution, when modeling wind speed data, cannot always be one, this assumption might lead to a misestimate of wind power potential. Therefore, in the present study, the E distribution is proposed as density component of mixture distribution for wind speed analysis instead of the GEV. The E distribution has already led to a good fit as a density component of mixture distribution for flood frequency analysis in the field of hydrology. Since the W and the E distributions are subfamilies of the GEV distribution, the E distribution might be a good candidate for the density component of mixture distributions to characterize wind speed series [31,32].

In the current study, ten homogeneous and heterogeneous mixture distributions of two components, built by combination of the G, the W, the E, and the N distributions, are employed. A brief description of the density component candidates is presented below. The pdf of the G distribution is given by:

$$f_G(v|a,b)=\frac{1}{b^a\Gamma(a)}v^{(a-1)}\exp\left(-\frac{v}{b}\right) \tag{3}$$

where a and b are the shape and scale parameters, respectively. The domain of the G distribution is $v>0$. The pdf of the two-parameter W distribution is given as follows:

$$f_W(v|c,k)=\frac{k}{c}\left(\frac{v}{c}\right)^{k-1}\exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{4}$$

where c and k are the scale and shape parameters, respectively. The domain of the W distribution is $v>0$. The pdf of the E distribution is defined by:

$$f_E(v|\mu_E,\sigma_E)=\frac{1}{\sigma_E}\exp\left(-\frac{v-\mu_E}{\sigma_E}-\exp\left(-\frac{v-\mu_E}{\sigma_E}\right)\right) \tag{5}$$

where μ_E and σ_E are the location and scale parameters, respectively. The domain of the E distribution is $-\infty\le v\le\infty$. The N pdf is defined by:

$$f_N(v|\mu_N,\sigma_N)=\frac{1}{\sqrt{2\pi\sigma_N^2}}\exp\left[-\frac{(v-\mu_N)^2}{2\sigma_N^2}\right] \tag{6}$$

where μ_N andσ_N are the location and scale parameters, respectively. The domain of the N distribution is $-\infty\le v\le\infty$.

It is important to compare the fit of the proposed mixture distributions with conventional non-mixture distributions in order to investigate the applicability of the employed mixture distributions for wind speed analysis. In the current study, the W and the four-