Statistical Fitting of Wind Speed Data for Determination of Wind Power Potentials in Saudi Arabia

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***Abstract*—This paper presents a statistical analysis of wind speed data for the Kingdom of Saudi Arabia. The study aims to determine the best probability distribution function for the wind speed data of some selected sites in the Kingdom. This is achieved by analyzing a few parameter distribution functions. The probability distribution functions used in the analyses were Weibull, gamma, and Rayleigh distributions. In order to determine the best fits, a mean annual error was used. Results shows that the Weibull distribution has a 0.000601 annual average error, followed by the gamma distribution with an annual error of 0.362221, and finally, the Rayleigh distribution with an annual distribution error 0.63323. This indicates that the sites under study are suitable for electrical power generation in both grid-connected and off-grid modes. Comparing the annual error of each site shows that the gamma distribution performs better compared to other distributions. The results determined the best site for wind speed and very important for various microgrids designs in the Kingdom of Saudi Arabia.**

Keywords— Wind speed data, Weibull distribution, Gamma distribution, Rayleigh distribution and Pearson type III distribution.

1- Introduction

The objective of this paper is to carry out a statistical analysis of the wind speed data in Saudi Arabia in order to find the best frequency distribution functions that fit the wind speed data most accurately. This analysis could lead to the development of a model for the optimum design of a microgrid capable of supplying grid-connected loads at the lowest cost while guaranteeing a continuous electricity supply. This model can determine the most suitable combination of component sizing and its operational strategies among the available designs.

Using renewable energy resources for electric power generation requires an understanding of the energy potential of the area under consideration. This could be achieved by the use of reliable data. In addition, the prediction and development of a model for the resources requires the use of either historical records or statistical techniques. However, the first method is difficult due to the amount of data needed to carry out the analysis successfully. In order to objectively achieve the analysis using this method, the data for a period of 3 to 30 years is needed. Thus, this method may have many drawbacks including accuracy, technical challenges, cost, and time, among others. Due to these drawbacks, it can be observed that the results of the analysis may not be accurate or realistic. Therefore, statistical methods have gained more popularity due to its cost, time and efficiency compared to the historical method. Therefore, this paper proposes the use of the statistical method for the analysis of the available data. The output of the analysis is expected to be an input into the optimization model that could be used for optimum and realistic planning of renewable energy application.

2- Literature Review

Many studies on analyzing wind speed data are available in the literature. However, these analyses depend on many factors such as site and geographical time factors. Therefore, it becomes necessary to establish the analysis in any site before the installation of wind turbine for electrical power generation. Example of this analysis has been presented in [1], in this paper, two probability distribution functions were used for fitting the wind speed data in Turkey. The study was carried out at Iskenderun located on the Mediterranean coast of the country, which has high wind potential for electrical power generation. in this paper, a time series was used to derive the probability density functions. Eventually, the Weibull and Rayleigh distributions were used for fitting 1-year wind speed data measured hourly. The results revealed that the two mathematical models fit the wind speed data. A similar study was conducted in the same country in [2], in which many probability distributions were used. These include Inverse Weibull (IW), exponentiated Weibull (EW) distributions, Marshall–Olkin extended Lindley (MOEL), extended Lindley (MOEL), extreme value (EV), gamma, inverse gamma (IG), Rayleigh, and burr type iii distribution functions. The data analyzed were obtained from Turkey's Aegean coast. It is observed that Weibull distribution is incapable of fitting all the wind regimes. Eventually, the exponentiated Weibull (EW) distribution showed the best performance compared to others. On the other hand, the Rayleigh distribution was the worst in fitting the wind speed data of all the sites. Finally, it is observed that each station has a different characteristic regardless of the proximity

In Malaysia, a similar study was carried out in [3]. In this paper, the data recorded in the Faculty of Engineering, University of Kebangsaan were used. Weibull and lognormal distributions were used for fitting the wind speed data. In order to estimate the statistical parameters, the maximum likelihood method was proposed. The results revealed that the two probability distributions were found suitable, but the Weibull

distribution was more suitable compared to lognormal distribution for the sites under study.

In Nigeria, the areas with high potential wind resources were analyzed for power generation in [4]. Nineteen northern states of the country were analyzed in the study. The wind speed of the areas were fitted by the use of the Weibull, Rayleigh and Gamma models. European charts were used to classify the wind power potential of the country. Further investigations revealed that some sites are suitable for both grid-connected and off-grid modes. In India [5], wind speed data for Marathwada region were obtained and analyzed using Weibull distribution. The data collected were for a one-year period. Efforts were made to fit the data for electrical power generation. Probability distributions used include beta, exponential, gamma, lognormal and uniform distributions. Furthermore, modified Anderson Darling and modified Anderson Darling were used to test the goodness of fit. In Islamabad, Pakistan, a similar investigation was carried out in [6]. The wind speed fitting was achieved using two-parameter distributions (Gamma, Weibull, Lognormal, Rayleigh) as well as three parameter distributions (Burr and Freshets). In addition, the parameter of each probability distribution was determined by applying the method of maximum likelihood estimate. Goodness of Fit (GOF) tests, namely Chi-Squared (CS), Kolmogorov-Smirnov (KS) and Anderson Darling (AD) tests were used to determine the error of estimates. The results of the analysis showed that the Burr, Lognormal and gamma perform better than the Weibull, Freshets and Rayleigh distributions.

A similar study was done in Penjwen region, Iraq [7]. The study, in this case, was based on the use of the Weibull and Rayleigh distribution functions. It was established that the two probabilities fit the available wind speed data for a period of two years. By extension, the Weibull distribution performed excellently in predicting the wind power density of the region compared to the Rayleigh distribution. In the same country of Iraq, authors in [8] used the Weibull distribution throughout. In addition, the maximum likelihood method was used for determining the Weibull parameters. In addition, different wind turbine hub heights were analyzed. It was observed that the characteristics of the wind waves were close to Rayleigh distribution, where the site was proven to be suitable for a small wind turbine installation.

A similar closer site in Palestine was investigated for wind power generation [9]. The analyses were based on daily average wind speed data to fit the Weibull distribution. Contrary to the known method, the parameters of the model were estimated using the graphical method. The study went further to estimate the payback period of the projects in the coastal plains of Palestine. The analysis indicated that the wind power in the site could be suitable for a small scale but was not commercially viable. Other sites analyzed in Palestine includes two sites in the West Bank and one site in Gaza Strip [10]. Specifically, the sites are Nablus, Ramallah, and Gaza. The Weibull distribution was used to fit the wind speed data of the sites. In this case, the parameters of the Weibull distribution were estimated graphically. The output of the study recommended investment in renewable energy in these sites.

3- *Wind Data Analytics*

In the analyses of wind resources for electrical power generation, wind speed is very critical. In this section, the average wind speed for each site is obtained using statistical judgement. In this paper, the mean wind speed was obtained from the data collected over a period of one year and at a one-hour interval. Mathematically, the mean wind speed is obtained using equation (1). Unfortunately, mean wind speed determination using this procedure could lead to erroneous estimate of the wind power density of the site under consideration [4].

$$v_m = \frac{1}{N}\sum_i^N v_i \qquad (1)$$

where v_i is the hourly wind speed-data points over one year observed, and N is the number of data points.

It is important to note that the using equation (1) will introduced significant error. Therefore, researchers proposed the use of root mean cube (RMC) velocity. This velocity will always provide a correct estimate of the average wind power density of a given site. Mathematically it can be determined using equation (2). A typical daily wind speed data of one of the sites (Yanbu) is shown in Figure 1. That is.

$$v_{rmc} = \sqrt[3]{\frac{1}{N}\sum_{i=1} v_i^3} \qquad (2)$$

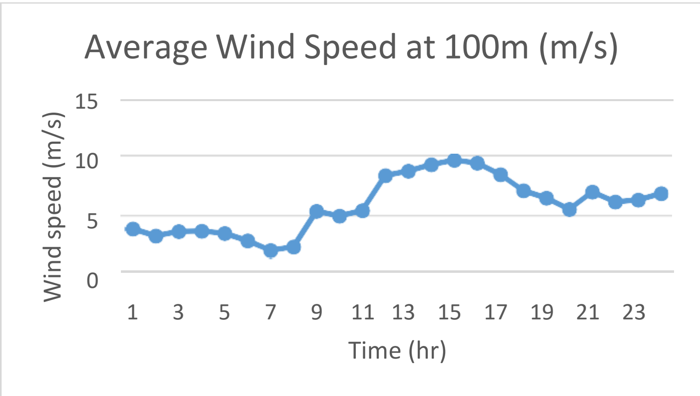

FIG 1: WIND SPEED DATA FOR YANBU SITE, SAUDI ARABIA

4- *Renewable Energy Potential of Different Cities*

This section will allow us to obtain the average power densities of the wind and solar energy sources. It can be achieved with the help of probability density functions. Using error analysis, it will also be possible to determine the best probability distribution function that best fits the renewable energy resources. This could be achieved by using the gamma, Weibull, and Rayleigh distributions. The mathematical expressions of these models are shown in the next section.

A. *Weibull distributions*

The Weibull distribution could be regarded as one of the most widely used probability distributions in prediction applications. Many research papers, including [11], have defined the Weibull distribution for renewable-energy analyses. The mathematical expression of the Weibull distribution is presented in Equation (3).

$$f_w = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} e^{\left(-\frac{v}{c}\right)^k} \qquad (3)$$

and the cumulative distribution function is

$$F_W = 1 - e^{(-\frac{v}{c})^k} \quad (4)$$

where c = scale parameter and k = shape parameter.

The probability of the renewable energy prevailing at a given site can be determined by evaluation of c and k parameters. Therefore, accurate modelling using the Weibull distribution is based on the accuracy of the c and k parameters. Several methods exist for the evaluation of these parameters [12]. One of these is the method of mean-standard deviation. c and k parameters can be determined using equations (5) and (6).

$$k = (\frac{\sigma}{V_m})^{-1.086} \quad (5)$$

$$c = \frac{V_m}{\Gamma(1+\frac{1}{k})} \quad (6)$$

where σ is the standard deviation and V_m is the mean. Average power densities can be obtained once the shape and scale parameters are known. In this case, average power densities of the site can be determine using c and k parameters. The Weibull average renewable-power density is calculated using Equation (7).

$$WPD_w = \frac{1}{2} \times \rho \times c^3 \Gamma(1 + \frac{3}{k}) \quad (7)$$

where Γ is the gamma function.

The mean renewable energy of the Weibull distribution in terms of c and k parameters is expressed in Equation (8)

$$V_m = c\Gamma(1 + \frac{1}{k}) \quad (8)$$

B. Rayleigh distribution

The Rayleigh distribution probability density function used in this analysis is defined as [11]

$$f(v) = (\frac{\pi V}{2V_m}) \times exp(-\frac{\pi}{4}) \times (\frac{V}{V_m})^2 \quad (9)$$

where m is the mean, and the cumulative distribution function is given by

$$F(v) = 1 - \text{EXP}(-\frac{\pi}{4}(\frac{V}{V_m})^2) \quad (10)$$

The variance of this distribution function is obtained using Equation (11)

$$\sigma^2 = (4/\pi - 1) \times V_m^2 \quad (11)$$

Using a similar approach, the average-power density is expressed in Equation (12)

$$WDP = 3/\pi \times \rho \times V_m^3 \quad (12)$$

A special case of the Weibull distribution with a value of k =2 is called the Raleigh distribution. Therefore, the mean of this distribution is obtained by

$$V_m = c\sqrt{\frac{\pi}{4}} \quad (13)$$

In the same way, the Rayleigh power density can be defined as

$$WPD_R = 3/\pi \times \rho \times (c\sqrt{\frac{\pi}{4}})^3 \quad (14)$$

C. Gamma distribution

The gamma probability density function is defined by

$$f(x;\, \alpha, \beta) = \frac{x^{\alpha-1}}{\beta^\alpha \Gamma(\alpha)} \text{EXP}[-x/\beta], x > 0, \beta > 0 \quad (13)$$

where α, is the shape and scale β parameters of the renewable energy resources and the cumulative distribution function of gamma distribution is defined as

$$F(x) = \frac{\Gamma(x/\beta)\alpha}{\Gamma(A)} \quad (15)$$

where Γ(x) is the gamma function.

In a similar fashion, the expression for power density for a gamma function in terms of c and k parameter is given by

$$WDP_{Gam} = \frac{1}{2}\rho \times c^3[k(k+1)(k+2)] \quad (16)$$

D. Goodness of fit

Once a prediction is completed, there are several tests to be carried out in order to test the accuracy of the results. Accuracy of the probability density function of the sites is determined using root mean square error (RMSE) [13], chi-square test (x^2), correlation coefficient (R), and coefficient of determination (COD) [14].

In this section, the performance of the model in predicting the average power densities of the sites could be assessed by determining the value of percentage errors as follows [15].

$$monthly\ error(\%) = \frac{PRE-PA}{P_A} \times 100\%, x = W, R, G \quad (17)$$

Similarly, the annual mean of the power density is defined in Equation (17).

$$\%\ ann.error = \frac{1}{12}\sum_{i=1}^{12} \frac{P_{RE}-P_A}{P_A} \times 100\%, x = W, R, G \quad (18)$$

where P_{RE} is the Weibull, Rayleigh and gamma distributions power density and $P_Æ$ is the actual power density of the site determined from the actual renewable energy resources. The comparison can be achieved by quantifying the errors evaluated in Equations (17) and (18). The closer the error is to 0%, the more accurate is the model in predicting the power density of the site.

E. Results obtained from the proposed methodology

The proposed procedure presented in the sections above was tested in the Kingdom of Saudi Arabia. The study analyzed the wind speed in different sites of the Kingdom. This is to enable extending a similar analysis to the rest of the Kingdom by assuming that the rest of the sites could have similar geographical features. Critical examination of the results reveals a good trend. The results presented were for different probability distribution functions. In all the results, a lower value of k less 2 is a clear indication of higher deviation from the mean wind speed of the site. In the same way, k greater than 2 is a sign of little variation about the mean wind speed of the site under consideration. Table 1 shows the analysis of the wind speed using the Weibull distribution function. The results shows that the average wind speed of the Saudi Arabia is 6.74084 m/s and the average standard deviation is 3.116398 m/s. The error due to the Weibull model is a clear indication of how poorly the probability distribution function predicts the wind speed of the different sites in the kingdom. In this case, the average error of the sites is 0.000601. Generally, this means that considering national average, it can be used for wind speed analyses. Unfortunately, considering site by site cases, the results could leads to overestimation of some sites wind power density. Therefore, a cross-examination of each site shows that the distribution function is not suitable for most of the sites analyzed.

TABLE 1: WEIBULL DISTRIBUTION

	WEIBULL DIST							
SITES	**K**	**C**	**MEANW**	**SDW**	**WPDW**	**WPDS**	**ERROR**	**VME**
AL WAJH WADI AL SEEH	2.15804	6.28083	5.56233	2.73938	187.308	186.985	0.00173	8.51143
HAFR AL BATIN	2.24609	8.1935	7.25714	3.44482	401.714	403.04	-0.0033	10.8793
JEDDAH ALJ JAZEERA	2.25141	7.11772	6.30441	2.98607	262.836	265.639	-0.0106	9.43986
KA CARECITY SITE A	2.47836	7.31487	6.48887	2.81332	265.657	267.193	-0.0058	9.28723
K.A.CARE CITY SITE B	2.86057	6.83796	6.09395	2.31522	200.062	200.443	-0.0019	8.23023
SHARURA LATEST	2.48542	8.23887	7.30902	3.16061	378.863	379.296	-0.0011	10.4479
TURAIF-	2.35317	8.44809	7.48658	3.40457	424.496	423.869	0.00148	10.9721
YUNBU	1.75885	6.1699	5.49345	3.26615	223.226	227.345	-0.0181	9.50173
YUNBU NORTH	2.37022	9.78443	8.67183	3.91743	655.963	628.947	0.04295	12.6661
AVERAGE	**2.32912**	**7.59846**	**6.74084**	**3.1164**	**333.347**	**331.417**	**0.0006**	**9.99286**

However, the case is different when analyzing the Rayleigh Distribution presented in table 2. Looking at the error, it can be seen that all the sites have shown a good representation of this distribution function. The average error of the Kingdom is 0.63323. This is higher than the Weibull distribution function. In all the cases, the error observed is very high compared to the Gamma and Weibull distributions. Therefore, it is not suitable for the Kingdom. However, the on-site basis is still better than the Weibull distribution. A similar comparison is displayed in table 3. In this case, the error is less than the Rayleigh Distribution and still higher than the Weibull distribution. Therefore, this distribution is more suitable for the Kingdom.

Critical look at figure 2, it can observed that annual average error for each distribution followed similar trend in all the sites. In addition, Gamma distribution is the best in all the sites compared to Weibull and Rayleigh distributions. Therefore, national average in the kingdom of Saudi Arabia shows that Gamma distribution fits the wind speed data in Saudi Arabia compared to Weibull and Rayleigh distributions.

TABLE 2: RAYLEIGH DISTRIBUTION

RAYLEIGH DIST.						
SITES	**CR**	**MEAN RAY**	**WPDS**	**WPDW**	**ERROR**	**VME**
AL WAJH WADI AL SEEH	6.27601	7.86632	186.985	289.136	0.5463	8.87561
HAFR AL BATIN	8.18827	10.2631	403.04	642.137	0.59324	11.58
JEDDAH ALJ JAZEERA	7.11331	8.91579	265.639	420.985	0.5848	10.0597
KA CARECITY SITE A	7.32143	9.17665	267.193	459.028	0.71796	10.3541
K.A.CARE CITY SITE B	6.87584	8.61814	200.443	380.214	0.89687	9.7239
SHARURA LATEST	8.24681	10.3365	379.296	656.007	0.72954	11.6628
TURAIF-	8.44716	10.5876	423.869	704.989	0.66322	11.9461
YUNBU	6.19829	7.76891	227.345	278.527	0.22513	8.7657
YUNBU NORTH	9.78447	12.2638	628.947	1095.63	0.74201	13.8373
AVERAGE	7.605731	9.532988	331.417	547.4057	0.63323	10.75613

TABLE 3: GAMMA DISTRIBUTION

GAMMA DIST					
SITES	**C**	**K**	**WPDS**	**WPDG**	**ERROR**
AL WAJH WADI AL SEEH	1.34911	4.122959	186.9851	133.9827	0.395591

HAFR AL BATIN	1.635192	4.438095	403.0396	292.2043	0.379307
JEDDAH ALJ JAZEERA	1.414348	4.45747	265.639	191.3729	0.38807
KA CARECITY SITE A	1.219745	5.319858	267.1931	201.025	0.329154
K.A.CARE CITY SITE B	0.879602	6.928075	200.4426	159.4533	0.257061
SHARURA LATEST	1.366731	5.347807	379.2961	287.0047	0.321567
TURAIF-	1.54825	4.835513	423.8692	314.7116	0.34685
YUNBU	1.941906	2.828894	227.3448	146.4056	0.552842
YUNBU NORTH	1.76967	4.90025	628.9471	487.7282	0.289544
AVERAGE	**1.458284**	**4.797658**	**331.4174**	**245.9876**	**0.362221**

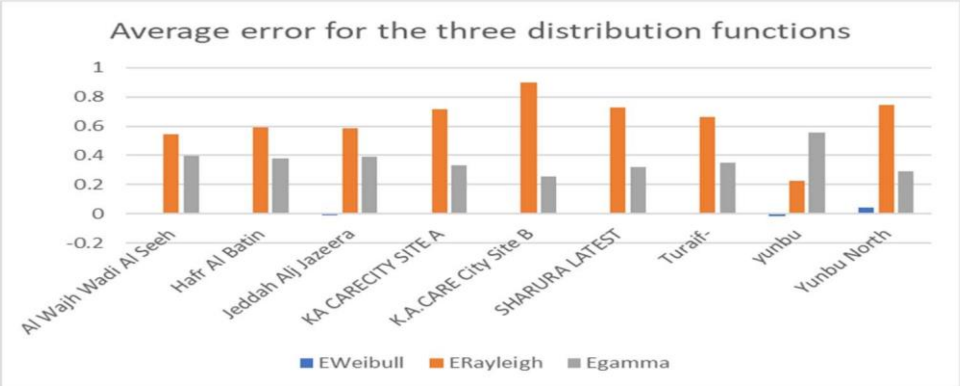

FIG 2: COMPARING ANNUAL AVERAGE ERROR FOR THE THREE DISTRIBUTION FUNCTIONS

F. Classification of Wind Energy Potentials and other wind speed parameter

Normally in this type of wind data analyses, wind-power classification can be based on many standard organizations. One of such is the European classification shown in table 4. Comparing the output of statistical analyses, most of the sites are suitable for electricity production. In addition, taking the average wind power density of each distribution, all the distributions show that the sites fall in the range of good and above. Hence, the sites are suitable for power generation using wind energy. This shows that they are in classes 3 and 4. The classification is that class 1 one is not suitable for power generation. Class 2 is possible if a reasonable tower tall in length is used. On the other hand, class 3 and 4 are suitable for both grid-connected and off-grid power systems [16].

TABLE 4: WIND-ENERGY POWER CLASSIFICATION

CATEGORISATIONS	POWER(W/M^2)	CLASS
POOR OUTPUT POWER	P <100	1
FAIRLY GOOD OUTPUT POWER	100≤ P < 300	2
GOOD OUTPUT POWER	300≤ P < 700	3
VERY GOOD OUTPUT POWER	P≥ 800	4

5- THE MOST PROBABLE WIND SPEEDS AND THE MAXIMUM ENERGY-CARRYING WIND SPEEDS.

Once the classification is known for a given site, it is in the interest of the system designer to know the wind speed carrying maximum energy (V_{emax}) and probable wind speed (V_{mp}) of the site under study. For example, the first one is used to determine the wind speed carrying the maximum energy for the determination of the rated speed. In addition, the peak of the peak wind speed is called the probable wind speed. Therefore, the probable wind speed and speed carrying maximum energy parameters can be estimated using c and k parameters of the site as defined in equations (19) and (20)[17]. That is

$$VEMAX = c\,\left(\frac{k+2}{k}\right)^{\frac{1}{k}} \quad (19)$$

$$V_{MP} = c\,\left(\frac{k-1}{k}\right)^{\frac{1}{k}} \quad (20)$$

Parameters presented in the equations above were obtained by considering all the sites and the results are shown in figures 3 and 4. A critical observation of the maximum energy-carrying wind speed shows that Yanbu has the highest maximum energy-carrying wind speed of 4.3333 m/s. This is followed immediately by K.A. Care Site B, which has 2.35700 m/s. On the other hand, the site with most probable wind speed is Yanbu north, and the corresponding wind speed is 2.0772 m/s in a similar manner. The site with the least probable wind speed is K.A. Care Site B and the corresponding wind speed is 1.6848 m/s.

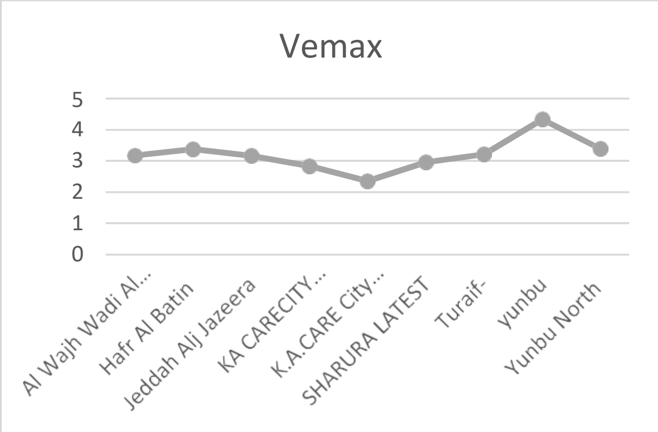

FIG 3: THE MAXIMUM ENERGY-CARRYING WIND SPEEDS.

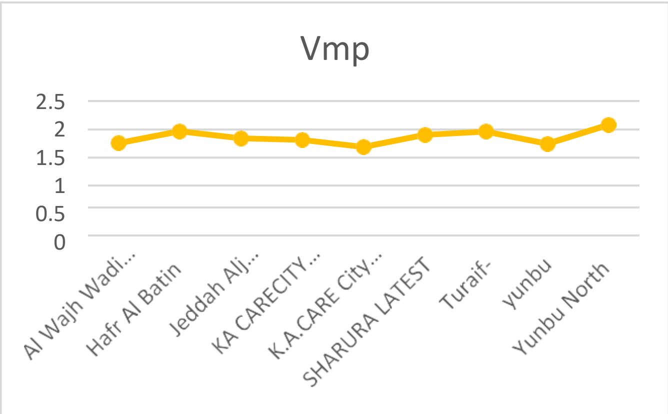

FIG 4: THE MOST PROBABLE WIND SPEEDS

6- CONCLUSION

The paper was able to compare different probability distribution models at different sites in Saudi Arabia to determine the best fits for wind speed data. It was stablished that the Weibull distribution records the least error compared to the Gamma and Rayleigh distributions. In a similar manner, all the sites are suitable for electrical power generation from wind energy in both grid and standalone modes.

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