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Wind Energy Assessment Using Weibull Distribution with Different Numerical Estimation Methods: A Case Study

Mutaz A. Alanazi [1], Mohammed Aloraini [2*], Muhammad Islam [2], Saleh Alyahya [3], Sheroz Khan [3]

[1] Department of Electrical Engineering, College of Engineering, Qassim University, Buraydah 51452, Saudi Arabia.

[2] Department of Electrical Engineering, College of Engineering, Qassim University, Unaizah 56452, Saudi Arabia.

[3] Department of Electrical Engineering, College of Engineering and Information Technology, Onaizah Colleges, Onaizah 56447, Saudi Arabia.

Abstract

The demand for electrical energy is increasing every day, which is one of the critical challenges facing the world today. Hence, the necessity of turning to clean renewable energy sources that are not harmful to the environment as an alternative to the traditional generation based on fossil fuels has become more important than ever before. Wind power is one of the renewable sources that provides a clean solution to generate electricity. In this context, the Kingdom of Saudi Arabia announces renewable energy projects to generate 9 GW from wind in 2032. Hence, the aim of this paper is to investigate the most suitable method of Weibull parameter estimation in order to predict wind characteristics and employ it for wind energy assessment in the Qassim region located in the center of the country. In this study, wind data is collected from NASA's forecasts of global energy resources for 2010–2015 based on their availability at altitudes of 10m and 50m and analyzed by using six different methods for Weibull parameter estimation: the graphical method (GM), standard deviation method (SDM), energy pattern factor method (EPF), moment method (MM), alternative maximum likelihood method (AMLM), and novel energy pattern factor method (NEPF). The efficiency of each method is tested by calculating the root mean square error (RMSE) and the relative wind power density error (RPDE). The comparison shows that the most appropriate method for estimating wind power density in the country is the Moment Method (MM), with the lowest RPDE ratio equal to 0.2018%. It has been found that the wind power density in the Qassim region falls into the class 1 category, as it is less than 100 W/m^2 at a height of 10m and less than 200 W/m^2 at an altitude of 50m. The results show the region is only suitable for small off-grid projects.

Keywords:

Energy Utilization;
Energy Conversion;
Power Conversion Efficiency;
Weibull Distribution;
Weibull Parameters;
Energy Efficiency.

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1- Introduction

The role of electrical energy is crucial to societal development, and it fosters economic growth. It plays an essential role for industries, human lives, and many applications of human development, such as smart phones and computers. The law of conservation of energy describes transformation in various forms, which has utilization in a variety of applications of commercial and industrial importance, such as in micro-electro-mechanical (MEMS), electrical, and nanomechanical engineering (NEMS) [1]. In most cases, electric energy is produced by converting mechanical energy, and mechanical energy is produced from heat by burning fossil fuels such as oil, coal, and natural gas. With population growth, the demand for electrical energy increases dramatically, making it harder every day for fossil fuels to meet this demand for the reasons of being non-renewable and causing climate change by increasing carbon gas emissions, affecting the fundamental biosynthetic process [2, 3], amounting to 90% of fossil fuels, forcing the governments of emerging and developing economies to offer subsidies.

* **CONTACT**: mo.aloraini@qu.edu.sa

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The developing countries pay more attention to their growth generation policies than to their environmental problems as a consequence. As a result of which weather conditions fluctuate and affect plant growth, yield, and distribution, and accordingly governments around the world have started investing a lot of money in the generation of alternative forms of energy that are clean, renewable, and harmless to the environment. Saudi Arabia ranks seventh among the most competitive economies among the G20 countries, accounting for 85% of global power consumption. This consumption causes fears of air pollution within the Arab peninsula, affecting the export of oil-related products and hence the export deficit.

Figure 1 shows that electricity production and consumption in Saudi Arabia have increased by 49.58% and 42.45% in 2021, which represent almost double the recorded numbers in 2010. The increasing use of electricity consumption is due to an increasing population, rapid growth in industrialization, and heavy investment in agriculture, dairy, and milk products. Poultry farms and local small industry projects require large investment in the field of electricity, which at the moment depends on oil and gas for generation. Oil and gas used locally are thus highly subsidized, which is originally meant for export at world-market prices to earn foreign reserves. The increased consumption of electricity has resulted in an equivalent increase in revenue investment into capacity and related energy transmission infrastructure. Hence, it can be concluded that there is a need to meet the energy demand from environmentally friendly sources rather than invest in the traditional avenues of electrical energy generation. The geographical location of GCC countries, including Saudi Arabia, is described as being associated with a hot and dry desert climate enriched with an abundance of solar energy potential [4].

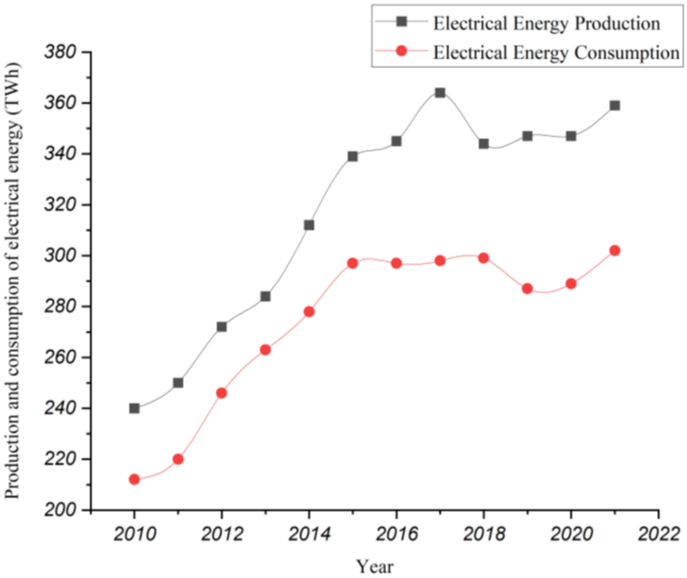

Figure 1. Production and consumption of electricity in Saudi Arabia from 2012 to 2021

The Kingdom of Saudi Arabia is surrounded by the Red Sea to the west and the Arabian Gulf to the east, making it a potential location for generating renewable energy from solar and wind. The KSA announced the formation of the National Renewable Energy Program (NREP) in April 2017 to launch an ambitious renewable energy infrastructure project with the aim of reducing dependence on oil and gas to meet growing domestic and industrial energy needs. This will reduce fossil fuel-based generation of electricity, which will make oil available for export, and it is estimated that a 1% reduction in fossil fuel-based electricity generation per year will save USD 35 billion in oil and gas [5]. There are currently thirteen projects in Saudi Arabia to produce electricity from renewable sources (solar and wind) with a total capacity of 4870 MW. Table 1 shows renewable energy projects in the Kingdom of Saudi Arabia.

Wind energy ranks second after solar energy in the category of renewable energy worldwide, as well as in Saudi Arabia. The Saudi Arabia Vision 2030 demands an initial target of 9.5 GW of renewable energy. Endowed with an impressive solar and wind potential, it is expected to be 30 GW by 2030, when energy consumption becomes three times that of current consumption. Currently, most of the power generation comes from burning oil, while the rest comes from natural gas. Investment in the energy sector is sure to boost oil and gas exports proportionately. However, wind power is the least popular type since it is more susceptible to unpredictable conditions than solar [6]. Since the power generated from the photovoltaic module PV and the wind turbine will vary according to the amount of solar radiation and the wind speed. As a result of the intermittent and unsteady nature of these sources, massive changes are resulting in the generated power, and so a comprehensive study of the region of interest based on historical data is needed. The Weibull distribution is widely used by engineers and researchers to perform statistical analysis of random data such as wind speed variations [7]. The Weibull distribution includes two parameters: the scale parameter (c), which relates to the mean wind speed, and the shape parameter (k), which relates to the variance. Both factors are used to find the probability density function and the cumulative distribution function, in addition to the power and energy density. The wind energy potential of a site is classified according to power density, so the accuracy of the parameter estimation method is an important factor to be considered.

Table 1. Renewable energy projects in Saudi Arabia [8]

Solar PV Systems Projects		
Project	**Region**	**Capacity (MW)**
Seder	Riyadh	1500
Saad		300
Wadi Al-dawaser		120
Layla		80
Rass	Qassim	700
Al-Shuaiba	Makkah	600
Jeddeh		300
Rabigh		300
Sakaka	Jouf	300
Qurayyat		200
Madinah	Madinah	50
Rafha	Northern Borders	20
Wind Energy Projects		
Project	**Region**	**Capacity (MW)**
Dumat Al-Jandal	Jouf	400

In the literature, several methods have been presented to calculate these two parameters in order to compare different methods to select the best-fit method for the collected data. A comparison of these methods is performed by calculating statistical indicators such as relative power density error (RPDE), root mean square error (RMSE), coefficient of determination (R^2), and chi-square test (χ^2). Salah et al. [9] have conducted an analysis of wind speed characteristics for selected sites in Saudi Arabia using three different parameter estimation methods and found that the moment method (MM) is the best method compared to the least squares method (LSM) and maximum likelihood method (MLM) for estimating wind power density. The paper also shows encouraging wind energy results in Saudi Arabia with a capacity of 1000 MWh per month for several sites, making them ideal for the installation of wind turbines.

Sedliačková et al. [10] have used MLM, which has shown good performance according to root mean square and coefficient of determination values. Another method known as the standard deviation method (SDM) or empirical method of Justus (EMJ) has been used to determine Weibull parameters in Kaplan [11], and it has yielded very good results for estimating the Weibull parameters. Hussain et al. [12] have presented a comprehensive study of solar energy generation in Cameron by estimating Weibull parameters using thirteen numerical methods, and the results have shown that MLM, the Energy Pattern Factor Method (EPF), and EMJ are the most suitable methods compared to the performance of the Empirical Mabchour Method (MABCH), the Rayleigh Distribution Method (RAYL), and the Empirical Method of Lysen (EML). A similar study of wind energy has been carried out in [13], and in this study, according to the results, the graphical method (GM) has been the best method for estimating the cumulative distribution function (CDF). However, GM, EML, MABCH, and RAYL are the worst methods to estimate wind speed distribution and wind power density.

It is noted that the accuracy of the estimation method changes according to the data collected and the location of interest. In this regard, several papers have discussed wind energy at different sites [14] that investigate wind power at six locations: Sharurah, Jeddah South, Al Wajh, Riyadh, Hafar Al Batin, and Al Jouf. Alabbadi et al. [15] have investigated wind power in Madinah using the MLM method, and the authors have found Madinah very suitable for small off-grid applications. AlQdah et al. [16] have performed a feasibility study of the wind energy system in Neom city, which is located in the north-eastern area of Saudi Arabia, and they found that it falls into Class 3, which is suitable for commercial-scale projects.

Alfawzan et al. [17] have presented a study for wind speed characteristics in the city of Jubail, which is located in the eastern region of Saudi Arabia, and found that the mean wind power density is equal to 50.92W/m^2, 116.03W/m^2 and 168.46W/m^2 at 10m, 50m, and 90m heights, respectively. Another study has been performed for Yanbu in the western area of Saudi Arabia, and it has concluded with encouraging results for wind energy systems in that region. However, most of these previous works have not provided a complete comparison of different estimation methods in Saudi Arabia, while the Qassim region has not been included in most recent studies except the study by the authors in Salah et al. [9]. Nevertheless, the authors have only used three methods for the estimation of wind power density. Hence, by considering all of these points mentioned above, the purpose of this work is summarized as follows:

- Investigation of wind power in the Qassim region with different methods for Weibull parameter estimation.

- The techniques used in this paper are explained in detail, which will provide a better understanding for researchers to study other areas around the world.
- This work will contribute to assisting decision-makers in the wind energy sector by providing an assessment of the potential of wind energy in the Qassim region, for which studies in this area are rare.
- Finally, this work will help future project designers determine the cost analysis with high accuracy by choosing the appropriate method for predicting the maximum wind energy.

In this paper, we have collected and analyzed wind data at heights of 10m and 50m above the ground for the Al-Qassim region. Finally, the wind energy potential will be calculated based on the Weibull distribution, which allows us to compare the result with the international wind power classification. The Weibull parameter estimation process will use six different methods, which are: (1) graphical method (GM), (2) standard deviation method (SDM), (3) energy pattern factor method (EPF), (4) moment method (MM), (5) alternative maximum likelihood method (AMLM), and (6) novel energy pattern factor method (NEPF). All methods will be compared by calculating the root mean square error (RMSE) and the relative power density error (RPDE). The organization of this paper is as follows: Section 2 presents energy in Saudi Arabia and the Qassim region; Section 3 discusses Weibull distribution; Section 4 discusses the estimation methods used in this paper; Section 5 will include the results; Section 6 will discuss results and discussion; and Section 7 concludes the paper with a summary of the conclusions achieved.

2- Energy in Saudi Arabia

2-1- History and Future

The Kingdom of Saudi Arabia (KSA) has a long history with oil, and it is one of the largest oil producers in the world while standing as the fourth largest in gas reserves, in addition to a high growth rate of domestic oil consumption due to rapid growth in population, industrialization, agriculture, and urban development [18]. The utilization of renewable energy sources in electric vehicle charging stations is another one of the most prominent areas of research in many developing and developed countries [19]. KSA also depends on generating electricity from carbon-intensive fuels and their products, which may cause air pollution as well as soil and sea pollution as a result of waste disposal through sea water desalination. The number of renewable energy source projects started to increase in the country with the establishment of the NREP program in 2017, since when the production of electricity from renewable sources has been increasing day by day. Figure 2 shows the electricity production from renewable sources over the 2010–2021 period in small proportions, as most projects are under construction at present.

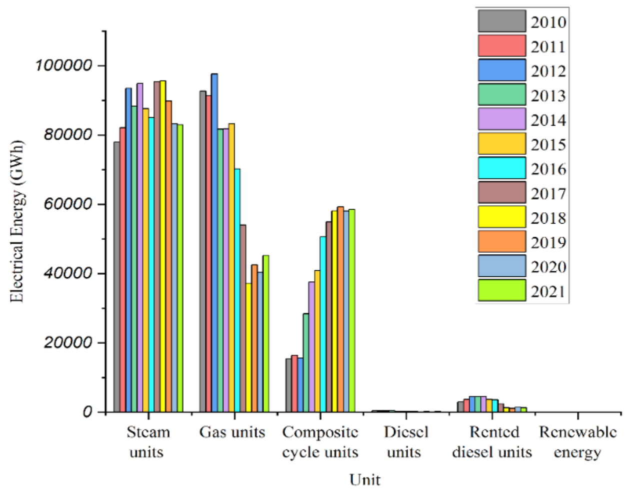

Figure 2. Electrical Energy Produced by Power Plants from 2010-2021

The 2018 saw the maximum production of 3.80 GWh from renewables, which is a small generation compared to that from steam units and gas units. The population growth rate in Saudi Arabia ranges between 1% to 2%, with a population of 33, 413, and 660 (as of 2018), about 80% of which live in major cities. The country has an area of 2.15 million km^2 and is located between the Red Sea and the Arabian Gulf, with mountainous ranges in the region parallel to the Red Sea coast. The GCC countries are critically explored with toxic heavy metals contaminating soil from agriculture perspectives [20]. The KSA, enjoying the geographical advantage of solar and wind energy, is moving forward with plans to develop the renewable energy sector as the use and production of fossil fuels have caused several environmental issues in the form of air and water pollution that have adverse effects on the health and environment. The government plans to produce 50% of its electricity from renewable sources by 2030 and 15 GWh by 2024. One of the projects announced by the government is the city of dreamers in robots and solar power in the form of NEOM, which is located in northern Saudi Arabia and will require between 20 to 40 GW of power. All power is produced from zero-carbon emissions sources of solar and wind [21]. It is known that high efficiency is one of the most important requirements in all systems, and in order to build a renewable energy system with high efficiency, a comprehensive study must be conducted to evaluate and analyze the resources of the specific site [22]. This is one of the many reasons for interest in research in areas related to renewable energy in Saudi Arabia, particularly that of wind energy, which can add a significant share to the RE portfolio if estimated and the project is undertaken holistically similar to that of NEOM. Alternative efforts to maintain the heat balance of buildings' construction while utilizing solar energy.

2-2- Qassim Region Energy Scenario

The electricity consumption in the Al-Qassim (Figure 3) region is commensurate with its population, which reached 10 TWh in 2021. The region is suitable for an appropriate scale of wind generation as there are no significant deformations of wind speed and direction in this vastly non-mountainous landscape [23], which is sure to reduce higher temperature rises and increased greenhouse gases due to the ongoing conventional electricity generation relying mostly on oil and gas. It has a good renewable source and hosts the second largest solar renewable energy project in Al-Rass, with a total capacity of 700 MW, as listed in Table 1. The Qassim region has been tested with encouraging results for solar power systems [24, 25] based on data on global horizontal irradiance, direct normal irradiance, diffuse irradiance, ambient temperature, humidity, atmospheric pressure, and wind speed for the month of August 2014. In this paper, wind systems will be discussed to study this area for the purpose of building a wind turbine farm to produce electricity. This is a comprehensive study of its kind suitable for the site.

Figure 3. Map of Saudi Arabia with Al-Qassim Region

Most of the electricity in the Qassim region is produced by steam turbines, and there are many projects to convert production to a combined cycle in order to increase efficiency and reduce fuel consumption, which will lead to lowering emissions. The Electricity Company is implementing many projects in the Qassim region, such as the Qassim North Power Plant Project, which will be completed in 2025 with a production capacity of 3,600 MW. This project will save about 15 million barrels of oil [26]. This increasing rate of projects is due to the increased demand for electricity every day and the increased air pollution in the Qassim region due to many factors, such as electricity production and weather conditions [27]. The goal of renewable energy projects is to reduce the use of burning oil and gas to produce electricity because both oil and gas cause high emissions of carbon gases that cause many problems for humans and the environment around them. Carbon dioxide (CO_2) capture and storage (CCS) is one of the critical enabling technologies that would reduce CO_2 emissions significantly while also allowing fossil fuels to meet the world's other pressing energy needs, particularly in the scenario of Middle East and North African (MENA) countries, which account for a sizeable proportion of the world's oil production and trade. Coal-based plants have shown worse results by producing gases (CO_2 0.82 kg/MWh, NO_2 0.07 kg/MWh, SO_2 0.58 kg/MWh, NO_x 0.2, and others 0.1k/MWh [28]). Renewable energy projects in Saudi Arabia seek to reduce nine tons of emissions in 2024, as shown in Figure 4.

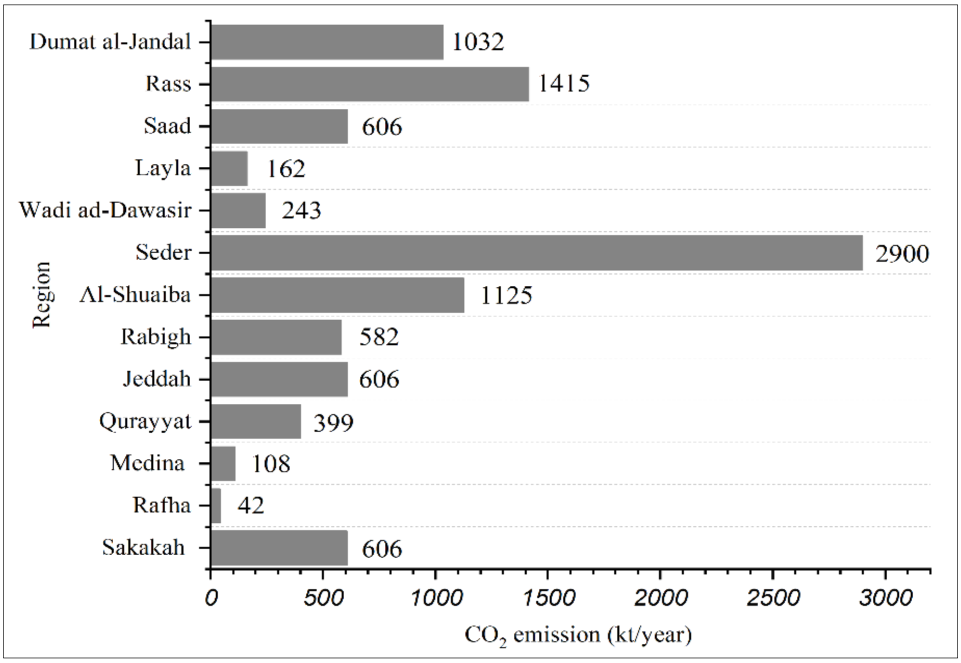

Figure 4. **Reduction in CO_2 Emissions [8]**

3- Weibull Distribution

While the benefits of harnessing wind energy are evident, however the implementation depends on a number of practical challenges due to their intermittent and unsteady nature. Hence, the wind renewable energy projects require complete and extensive site surveys to choose the appropriate location because they depend on the weather conditions at that location. Wind systems similar to those of solar have different potentials in different countries and regions due to site-to-site variability and other essential parameters. Statistical methods should be used to analyze these resources based on recorded data. Since wind speed changes rapidly and frequently over time, the statistical function of the probability distribution function must be used to predict wind behavior over a period of time. Weibull, Gamma, and Rayleigh are types of probability distribution functions for estimating wind power potential using statistical distribution models. Researchers have proven that the Weibull distribution has higher accuracy than other statistical functions to capture the skewness of the wind speed distribution, and it is widely used in research. The Weibull distribution has two parameters that must be estimated to find the two functions, the probability density function and the cumulative distribution function, which appear in Equations 1 and 2. The two parameters are, k, which represents shape factor without a unit and parameter, c, which is scale factor in the units of wind speed in m/s. The shape parameter is important to determine the wind characteristics in the selected region since the wind direction is one of the critical factors to be taken into consideration and scale factor is determining the wind potential [29]. As scale factor increases the wind potential will increase and vice versa.

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{k}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \quad (1)$$

$$F(v) = \int_0^{\infty} f(v)\, dv = 1 - e^{-\left(\frac{v}{c}\right)^k} \quad (2)$$

where v is wind speed, k and c are Weibull parameters, and where $v > 0$; $k, c > 0$.

From the equation above, it is clear that the distribution curve of wind speeds will be affected by the values of shape and scale factors, and hence the estimation of these values with high accuracy is an essential requirement. There are many ways to estimate the *k* and *c* parameters, and it is an important step in determining wind energy and power densities. However, the accuracy of the estimation varies from one method to another. The researchers found that all methods return rough estimates with a different error ratio. Furthermore, one of the interesting results is that the error is different from one place to another, which means that the best method for estimation varies according to the area being tested. Hence, research is increasing in this field to study the best methods and develop new ways for parameter estimation. Table 2 illustrates a group of recent studies comparing estimation methods, and it is clear that the accuracy of estimation methods is a very area-dependent concern.

Table 2. Comparison of estimation methods of Weibull Parameters in recent studies

Ref	Year of study	Area	Methods	Result of comparison
[30]	2021	Istanbul Republic of Turkey	Graphical method (GM) Method of moment (MM) Energy pattern factor (EPF) Mean standard deviation (MSD) Power density (PD) Genetic algorithms (GA)	The best method is GA while the worst is EPF and the accuracy of estimation method is different according to data size and area being tested.
[31]	2022	Eastern Jerusalem Palestine	Maximum likelihood (MLM) Modified maximum likelihood (MMLM) Method of moment (MoM) Energy pattern factor (EPFM) empirical method (EM)	The best methods are EM and MoM while the worst is EPF
[32]	2021	Dar es Salaam Tanzania	Graphical method (GM) Standard Deviation (SD)	SD shows better results compared to GM
[33]	2020	Izmir Institute Republic of Turkey	Empirical Method (EM) Maximum Likelihood (MLM) Modified Maximum Likelihood (MMLM) Least Square Method (LSM) WAsP Weibull Method	The best method is MLM method
[34]	2023	Coastal Areas Pakistan	Graphical method (GM) Empirical Method (EM) Energy pattern factor (EPF) Moment Method (MM) Energy Trend Method (ETM) Least Squares Regression (LSRM) WAsP Algorithm (WAsPA) Maximum Likelihood (MLM)	All method showed good results which are close to the real and actual data except GM and ETM
[35]	2018	Jeju Island South Korea	Empirical Method (EM) Moment Method (MM) Graphical method (GM) Energy pattern factor (EPF) Maximum Likelihood (MLM) Modified Maximum Likelihood (MMLM)	The best method is MM while the worst method is GM
[36]	2023	Khartoum Sudan	Energy pattern factor (EPF) Graphical method (GM) Moment Method (MM) Least Squares Regression (LSRM) Firefly Algorithm (FA)	The best method is FA followed by MM and GM while the worst method is EPM

In this paper, six different methods have been used for the estimation of Weibull parameters to study wind energy in the Qassim region. However, before we enter into the details of each method, the relation between wind energy and wind power densities with Weibull parameters needs to be explained. Wind power density describes the amount of wind resources in a particular place, and energy density indicates how much power density exists at a specific time in a site. The available power in wind which is flowing at any speed ‘v’ through a turbine blade with a swept area ‘A’ is calculated by Equation 3.

$$P(v) = \frac{1}{2} \times \rho \times A \times v^3 \tag{3}$$

where ρ is the air density and it is equal to 1.225 kg/m^3, by dividing both sides by swept area A, the power in wind at given speed v per unit area is calculated as power density given in Equation 4.

$$P_d(v) = \frac{P(v)}{A} = \frac{1}{2} \times \rho \times v^3 \quad (4)$$

By applying the integration for the multiplication of Equations 4 and 1 as seen below in Equation 5 and considering standard gamma function shown in equation 6, the wind power density following Weibull distribution for the selected regime is shown in Equation 7. The energy density is calculated by multiplying the power density by the time (T) as seen in Equation 8, and for one year T is equal to 8760 if the time is taken in hourly base.

$$P_d = \int_0^{\infty} P_d(v) \times f(v)\, dv \quad (5)$$

$$\Gamma(t) = \int_0^{\infty} e^{-x} x^{t-1} dx \quad (6)$$

$$P_d = \frac{\rho \times c^3}{2} \times \left(\frac{3}{k}\right) \times \Gamma\left(\frac{3}{k}\right) \quad (7)$$

$$E_d = \frac{\rho \times c^3}{2} \times \left(\frac{3}{k}\right) \times \Gamma\left(\frac{3}{k}\right) \times T \quad (8)$$

Weibull parameters are used also to determine three important factors of the mean wind speed (V_m), most frequent speed in that area (V_F), and the speed which carries the maximum energy to the system (V_E), which are describing the wind characteristics. The mean wind speed that follows Weibull distribution for the selected site is calculated by using Equation 9 that takes into consideration the gamma function as shown in Equation 6, and the Equations 10 and 11 show V_F and V_E. Other factors to determine the suitable turbine are the three different speeds which are V_{in}, V_{rat} and $V_{off.}$

Where V_{in} is the cut-in speed where the wind turbine starts to produce the power, V_{rat} is the rated speed where the wind turbine is producing the rated power, and V_{off} is the cut-out speed where the wind turbine is taken out of service in order to protect its components from the high wind speed, which means that wind turbine will not produce any power below the cut-in speed and beyond the cut-out speed. Figure 5 shows an example for wind power curve illustrating the relation between the wind speed and generated power. The selection of wind turbine rated speed or the speed that generates the rated power will be based on the speed that carries the maximum energy to the system since the maximum efficiency is obtained when the two speeds are almost equal to each other ($V_E \cong V_{rat}$) [16, 30].

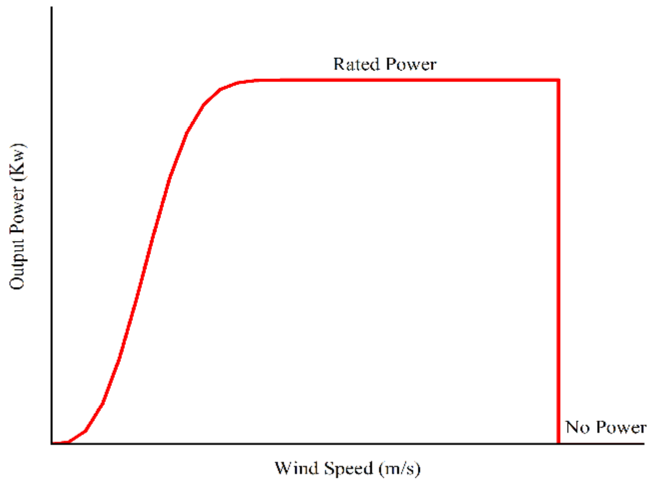

Figure 5. Wind Turbine Power Curve

$$V_m = c \times \Gamma\left(1 + \frac{1}{k}\right) \quad (9)$$

$$V_F = c \left(\frac{k-1}{k}\right)^{\frac{1}{k}} \quad (10)$$

$$V_E = \frac{c\,(k+2)^{\frac{1}{k}}}{k^{\frac{1}{k}}} \quad (11)$$

$$P(v_{in} < v < v_{off}) = e^{-\left(\frac{v_{in}}{c}\right)^K} - e^{-\left(\frac{v_{off}}{c}\right)^K} \quad (12)$$

Furthermore, Weibull parameters are helpful to determine the probability that a wind turbine is in operation since, in most cases, the cut-in speed of wind turbines is between 3 m/s and 4 m/s. The cumulative distribution function is used for this purpose to determine the probability that wind speed will be in the range between the cut-in speed and cut-out speed, as seen in Equation 12. All of these important factors show that the accuracy of the estimation process should be at its highest level.

4- Estimation of Weibull Parameters

The shape and scale parameters can be estimated by using several methods. In this paper, six different methods will be explained and used in the estimation process, and according to the statistical indicators, the method with the highest accuracy will be used to evaluate wind energy in the Qassim region. The methods are graphical method (GM), standard deviation method (SDM), energy pattern factor method (EPFM), moment method (MM), alternative maximum likelihood method (AMLM), and novel energy pattern factor method (NEPFM).

4-1- Graphical Method (GM)

This method (also known as the least squares method) represents the wind data in graphical form, which can be useful to understand the characteristics of wind speed at the selected site to predict future failure since it finds a linear approximation of the observation data by minimizing the distances between the best-fit line and observation points. In this technique, the cumulative distribution function is converted from an exponential function to a linear function by applying a double logarithmic transformation to Equation 2, as seen in Equation 13.

$$\ln[-\ln(1-F(v_i)] = k\ln(v_i) - k\ln(c) \tag{13}$$

Here, a straight line is constructed and drawn by plotting $\ln(v_i)$ on horizontal x-axis and $\ln[-\ln(1-F(v_i))]$ on vertical y-axis. The slope of this line is equal to the shape parameter (k) and scale parameter (c) is calculated by using the intercept on vertical y-axis. The linear approximation of any data is constructed by using the equation below

$$y_i = \alpha + \beta x_i \tag{14}$$

where;

$$\alpha = \bar{y} - \beta\bar{x}$$

$$\beta = \frac{\sum_{i=1}^{n} x_i y_i - n\bar{x}\bar{y}}{\sum_{i=1}^{n} x_i{}^2 - n(\bar{x})^2} \tag{15}$$

By substituting $\ln(v_i)$ and $\ln[-\ln(1-F(v_i))]$ in Equation 14, it is clear the shape parameter is equal to the slope while scale parameter is calculated as shown in Equation 17.

$$k = \beta \tag{16}$$

$$c = e^{-\left(\frac{\alpha}{k}\right)} \tag{17}$$

4-2- Standard Deviation Method (SDM)

This method (also known as empirical method) is widely used in research for Weibull parameters estimation due to its simplicity and the fact that it relies on observation data, which will increase the accuracy and provide a better understanding for the collected data. The mean wind speed and standard deviation of the collected wind data are used to determine the shape parameter k as shown in Equation 18 and once it is estimated, the scale parameter is calculated by using Equation 19. The mean wind speed and standard deviation are calculated by using Equations 20 and 21.

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \tag{18}$$

$$c = \frac{\bar{v}}{\Gamma\left(1+\frac{1}{k}\right)} \tag{19}$$

$$\bar{v} = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{20}$$

$$\sigma = \left[\frac{1}{n-1}\sum_{i=1}^{n}(v_i - \bar{v})^2\right]^{\frac{1}{2}} \tag{21}$$

where $\bar{v}$ is mean wind speed and σ is standard deviation.

4-3- Moment Method (MM)

This method is similar to the previous one and the main advantage of using this technique for Weibull parameters estimation is the simplicity and the capability of providing efficient way to describe the wind speed data in the interest area. Weibull shape and scale parameters can be estimated by substituting mean wind speed and standard deviation shown in Equations 20 and 21 into Equation 22 and once the shape parameter is calculated, and the scale parameter is estimated by using Equation 19.

$$k = \left(\frac{0.9874}{\sigma/\bar{v}}\right)^{1.0983} \tag{22}$$

4-4- Energy Pattern Factor Method (EPF)

This method has been proposed by Akdağ & Dinler [37] and it is simple and direct method because it depends on average wind speed. As the name suggests there is a factor called energy pattern factor (EPF) which represent the ratio between average of cubic speed and cube of average speed as shown in Equation 23.

$$Epf = \frac{\overline{v^3}}{\bar{v}^3} \tag{23}$$

Once energy pattern factor is determined, scale and shape parameters will be estimated by using simple calculations given in Equations 24 and 19.

$$K = 1 + \frac{3.69}{Epf^2} \tag{24}$$

4-5- Alternative Maximum Likelihood Method (AMLM)

The goal of this method is to avoid the iteration of original maximum likelihood method [38]. Iterative methods can provide difficulties during the solution process, and in most cases, software programs such as Matlab are used to solve these types of problems. By using this technique, simple calculations can be performed to estimate k and c values by using Equations 25 and 26.

$$k = \frac{\pi}{6}\left(\frac{n(n-1)}{n\sum_{i=1}^{n}(\ln(v_i))^2 - \left(\sum_{i=1}^{n}\ln(v_i)\right)^2}\right)^{\frac{1}{2}} \tag{25}$$

$$c = \left[\frac{1}{n}\sum_{i=1}^{n} v_i^k\right]^{\frac{1}{k}} \tag{26}$$

4-6- Novel Energy Pattern Factor Method (NEPF)

This method is proposed by Akdaı & Güler [39] and derived from energy pattern factor method (EPF). The method is suggesting specific coefficients for estimation of scale and shape parameters as seen in Equations 27 and 28. The coefficients are presented in Tables 3 and 4.

$$K = \frac{a_4 Epf^4 + a_3 Epf^3 + a_2 Epf^2 + a_1 Epf + a_0}{b_4 Epf^4 + b_3 Epf^3 + b_2 Epf^2 + b_1 Epf + b_0} \tag{27}$$

$$c = \frac{\bar{v}(k^2 + c_1 k + c_0)}{k^2 + d_1 k + d_0} \tag{28}$$

Table 3. Coefficients for calculating shape factor

a_0	-0.220374	b_0	-1.27285
a_1	3.27527	b_1	3.69115
a_2	-5.78961	b_2	-2.60973
a_3	2.15143	b_3	-0.800468
a_4	0.590396	b_4	0.992007

Table 4. Coefficients for calculating scale factor

c_0	0.225761	d_0	-0.35144
c_1	0.134704	d_1	0.711818

5- Error Analysis

The estimation of Weibull parameters is performed by several methods that have different accuracy, and research is developing new methods to reach the highest possible accuracy. The accuracy of all methods can be estimated by calculating statistical indicators. In this paper, two indicators are included to measure accuracy and compare all methods.

The first indicator is root mean square error (RMSE), which provides the inconsistency between recorded data and those obtained by Weibull parameters. RMSE is calculated by using Equation 29, where y_i is the wind speed frequency of observation data and x_i is the frequency found from the Weibull density function. The accuracy of the estimation method will increase as the value of RMSE closes to zero; the results for this indicator are always positive numbers [40].

$$\mathrm{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2\right]^{\frac{1}{2}} \tag{29}$$

Another indicator for testing the accuracy is relative power density error (RPDE), which shows the difference between calculated wind power based on Weibull distribution and those obtained by using measured data [41]. RPDE is calculated with use of Equation 30 where P_d is the power based on Weibull distribution, the results of this indicator could be positive or negative and as the percentage become small, the accuracy of the estimation method will increase.

$$\mathrm{RPDE} = \frac{P_d - P}{P} \times 100 \tag{30}$$

6- Result and Discussion

The daily wind speeds at 10 m and 50 m heights from 2010–2015 have been collected and analyzed using six different methods. All of these methods are compared using the RMSE and RPDE. Tables 5 and 6 show the results of all six methods at both heights. The comparison between the probability density function (PDF) and cumulative distribution function (CDF) gained by each method with the frequency distribution and cumulative frequency obtained by real data is shown in Figure 6 at both heights.

Table 5. Wind Speed Characteristics in Qassim region at 10m height

Method	C (m/s)	K	Vm (m/s)	VF (m/s)	VE (m/s)	Pd (W/m^2)	Pd (W/m^2)	RPDE	RMSE (PDF)	RMSE (CDF)
GM	4.71	3.63	4.24	4.31	5.31	35.81	60.03	0.6762	0.0190	0.0483
SDM	4.29	3.92	3.88	3.98	4.76		44.51	0.2427	0.0256	0.0124
MM	4.29	3.93	3.88	3.98	4.76		44.48	0.2420	0.0256	0.0124
EPF	4.32	3.34	3.88	3.89	4.97		47.55	0.3276	0.0297	0.0183
AMLM	4.39	4.40	4.00	4.14	4.78		46.99	0.3112	0.0205	0.0255
NEPFM	3.50	3.83	3.17	3.24	3.92		24.54	-0.3147	0.0802	0.0767

Table 6. Wind Speed Characteristics in Qassim region at 50m height

Method	C (m/s)	K	Vm (m/s)	VF (m/s)	VE (m/s)	Pd (W/m^2)	Pd (W/m^2)	RPDE	RMSE (PDF)	RMSE (CDF)
GM	6.86	4.46	6.26	6.48	7.45	116.6	178.7	0.5328	0.0115	0.0543
SDM	6.32	4.32	5.75	5.94	6.90		140.2	0.2028	0.0165	0.0095
MM	6.32	4.33	5.75	5.95	6.90		140.1	0.2018	0.0165	0.0095
EPF	6.39	3.53	5.75	5.82	7.26		151.1	0.2960	0.0224	0.0227
AMLM	6.41	4.67	5.86	6.09	6.92		145.2	0.2445	0.0136	0.0193
NEPFM	5.23	4.27	4.76	4.92	5.73		79.8	-0.3153	0.0662	0.0957

According to the comparison of PDF and CDF with the measured data and according to the RMSE value, the best methods for obtaining the PDF are GM with RMSE value equal to 0.0115 followed by AMLM, SDM, MM, EPF and NEPFM. However, the most accurate methods for estimating the CDF are MM and SDM with RMSE value equal to 0.0095 followed by AMLM, EPF, GM and NEPFM. The other factor that can determine the accuracy of the estimation method is the wind power density and by using the RPDE ratio it is clear that the best method for estimating the power density is the MM with RPDE ratio equal to 0.2018% followed by SDM, AMLM, EPF, NEPFM and GM. Although the similar studies for this paper in Saudi Arabia are rare since most of the papers are applying only one method for testing the wind potential at a given site. However, Table 7 shows a group of available studies performed in the region to compare the Weibull parameters estimation methods.

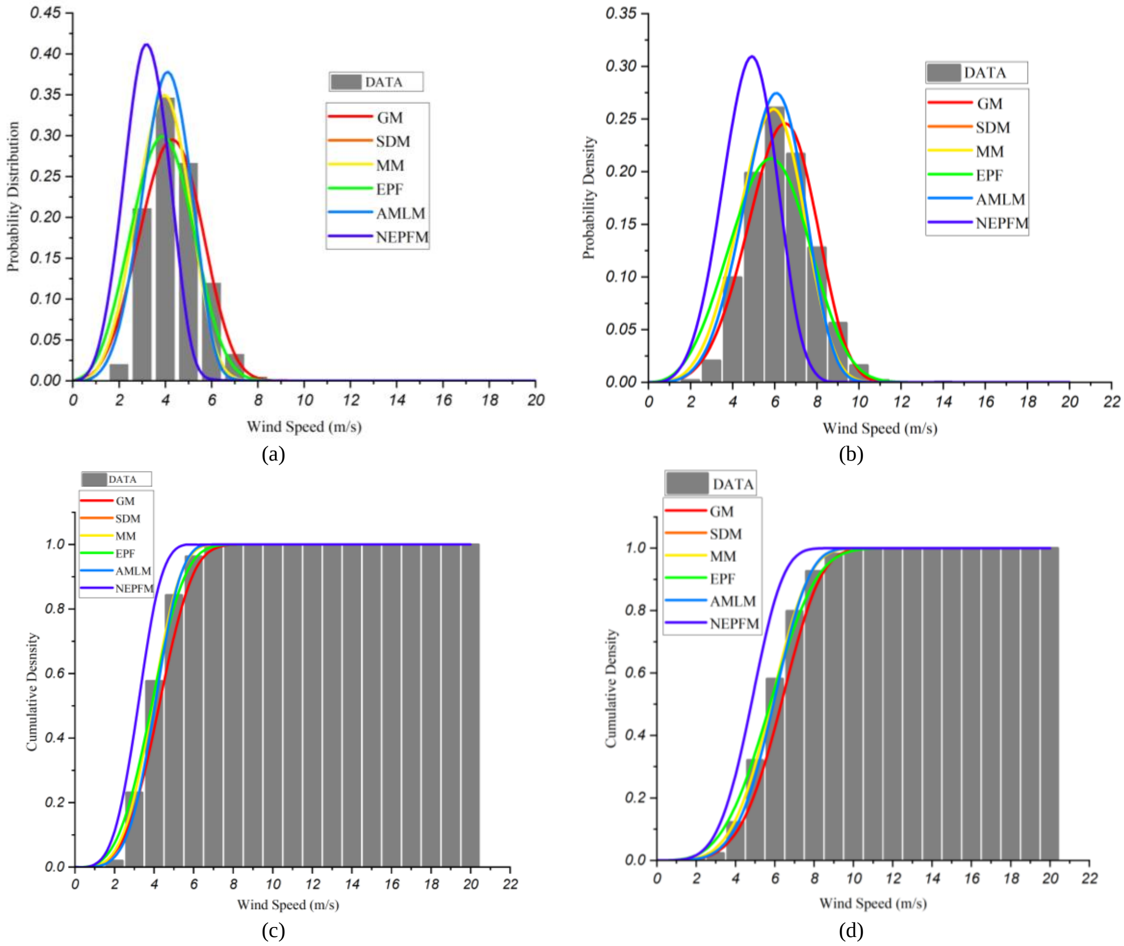

Figure 6. PDF and CDF functions, (a) PDF at 10m height, (b) PDF at 50 m height, (c) CDF at 10m height, (d) CDF at 50 m height

Table 7. Comparison of estimation methods of Weibull Parameters in recent studies performed in Saudi Arabia

Ref	Year of study	Area	Methods	Result	Comparison with this paper
[9]	2021	Riyadh, Qassim, Arar, Aljouf, Dholum, Guriat, Jeddah, Haql, Yanbu, Jezan, Dhahran and Nejran	Graphical Method (GM) Method of Moment (MM) Maximum Likelihood (MLM)	MM is the best method for estimating the wind power density. However, the MLM is showing the best performance compared for estimating wind speed.	This paper is using more methods for Weibull parameters estimation; However, the paper shows that MM method is the best method for wind power density estimation and also the GM is the best method for Qassim region which is supporting the findings.
[42]	2023	Riyadh, Hafer Al Batin and Sharurah	Least Squares Regression (LSR) Maximum Likelihood (MLM) Method of Moment (MM) Empirical Method (EM) Energy Pattern (EPM) Neural Network Algorithm (NNA)	NNA outperform all the methods, However, by comparing the numerical methods, the MLM is the most accurate method for estimating Weibull parameters compared to other numerical methods while the LSM has the worst performance.	This paper uses more methods but does not apply the MLM method or NNA method. However, Qassim region is not included in this study, and the previous study by Salah et al. [9] shows that GM is better than MLM for Weibull parameter estimation in Qassim region and this paper support this finding.
[43]	2017	Jubail	Maximum Likelihood (MLM) Least Squares Regression (LSR) Wasp Algorithm	The best method for Weibull parameter estimation is the MLM followed by LSR method	This paper is studying another area which is Qassim region and the results shows that the LSR or GM have better performance for Weibull parameters estimation compared to other methods. Furthermore, Baseer et al. [44] did not test the power density error which is one of the important factors that shows the accuracy of the estimation method.

The GM technique will be used for the estimation of the probability density function as well as for finding the Weibull parameters of mean wind speed, frequent speed, and the speed that carries the maximum energy to the system. The MM method will be employed for wind power density calculations, which are used for site classification and also for the estimation of the cumulative distribution function (CDF). All wind characteristics will be estimated according to the best method that provides the best results for the assessment of wind potential at the site. Furthermore, the data used in the assessment of the Al-Qassim region are hourly data, providing clearer observation of the wind speed with increased accuracy.

The Weibull parameters are thus calculated by finding the sloop and intercepts as described in Equations 16 and 17 for substituting them into Equation 1. The results are shown in Table 8 at 10m height and Table 9 at 50m height. Table 8 shows the shape parameter (k) is varying between 2.04 (2010) and 3.31 (2013), while the scale parameter (c) is varying from 3.54 (2010) to 5.62 (2015). Table 9 gives values of k that are smaller and c that are larger in most cases than what are seen in Table 8 because the height is different and the speed of wind is increasing with height, and the shape parameter 'k' and scale parameter 'c' are in the range between 2.00 (2011) to 3.06 (2015) and 5.26 (2010) to 7.46 (2015) respectively.

Table 8. Monthly shape parameter K, and scale parameter C, at 10 m height

Year	2010		2011		2012		2013		2014		2015	
Month	**k**	**c**	**k**	**c**	**k**	**c**	**k**	**c**	**k**	**c**	**k**	**c**
JAN	2.83	4.53	2.36	4.33	2.68	4.62	2.97	4.93	2.62	4.41	2.72	4.34
FEB	2.15	4.40	2.44	4.71	2.53	5.09	2.75	4.44	2.74	4.30	2.74	4.62
MAR	2.42	4.54	2.45	4.65	2.72	4.83	2.61	4.67	2.28	4.76	2.69	4.46
APR	2.41	4.71	2.71	5.35	2.48	4.32	2.52	4.85	2.10	5.22	2.55	5.62
MAY	2.36	4.55	2.45	4.53	2.37	5.29	2.64	4.37	2.51	4.44	2.33	4.43
JUN	2.30	4.02	2.37	4.09	2.50	4.52	2.76	5.01	2.92	5.03	2.34	4.35
JUL	2.66	5.02	2.63	4.35	2.72	5.02	2.91	4.99	2.47	4.65	2.89	4.60
AUG	2.57	4.52	2.57	3.89	3.14	3.88	2.79	4.34	2.48	3.94	3.13	5.00
SEP	2.87	3.66	2.21	3.65	3.09	4.13	2.56	3.89	3.00	3.91	2.53	3.68
OCT	2.54	3.54	2.80	4.49	2.47	4.69	2.50	4.57	2.65	4.39	2.19	3.82
NOV	2.97	3.81	2.48	4.94	3.16	4.48	2.52	4.66	2.72	4.52	2.52	4.86
DEC	2.04	4.06	2.97	3.75	2.64	4.52	3.31	4.49	2.62	4.05	2.67	4.59

Table 9. Monthly shape parameter K, and scale parameter C, at 10 m height

Year	2010		2011		2012		2013		2014		2015	
Month	**k**	**c**	**k**	**c**	**k**	**c**	**k**	**c**	**k**	**c**	**k**	**c**
JAN	2.60	6.54	2.21	6.13	2.55	6.42	3.05	6.81	2.52	6.24	2.68	6.22
FEB	2.17	6.25	2.47	6.62	2.51	6.98	2.71	6.63	2.52	6.02	3.06	6.75
MAR	2.35	6.35	2.42	6.49	2.71	6.91	2.45	6.60	2.54	6.55	2.57	6.37
APR	2.58	6.33	2.78	7.21	2.36	6.03	2.55	6.76	2.12	7.00	2.62	7.46
MAY	2.29	6.18	2.54	6.25	2.57	7.21	2.43	6.89	2.51	6.04	2.23	5.97
JUN	2.12	5.63	2.11	5.73	2.22	6.43	2.68	7.05	2.95	7.20	2.18	6.07
JUL	2.53	6.93	2.30	6.32	2.62	6.84	2.68	6.87	2.32	6.66	2.41	6.83
AUG	2.55	6.26	2.30	5.88	2.61	5.73	2.65	6.23	2.33	5.78	2.95	6.99
SEP	2.36	5.47	2.00	5.50	2.42	6.43	2.10	5.77	2.56	5.87	2.19	5.57
OCT	2.11	5.26	2.41	6.50	2.21	6.78	2.23	6.55	2.51	6.39	2.19	5.29
NOV	2.61	5.42	2.49	6.57	2.62	6.32	2.57	6.22	2.56	6.08	2.49	6.62
DEC	2.04	5.64	2.41	5.67	2.52	6.21	2.73	6.35	2.36	5.88	2.50	6.19

Yearly probability density and cumulative distribution functions for the years from 2010 to 2015 at 10m and 50m heights are shown in Figure 7, respectively. These graphs show that at 10m height, the wind speeds range in between 3-5 m/s, the highest values in all years, while the wind speeds ranging in between 4-6 m/s have the highest one at 50m height, which is larger than the speeds at 10 m, and this is normal due to the height increases. Annual wind characteristics are given in Table 10 for 10m height and Table 11 for 50m height, where it is noted that the ranges of the most frequent speed at 10m and 50m height in all years are the same since the peak points in the probability density function refer to the most frequent speed.

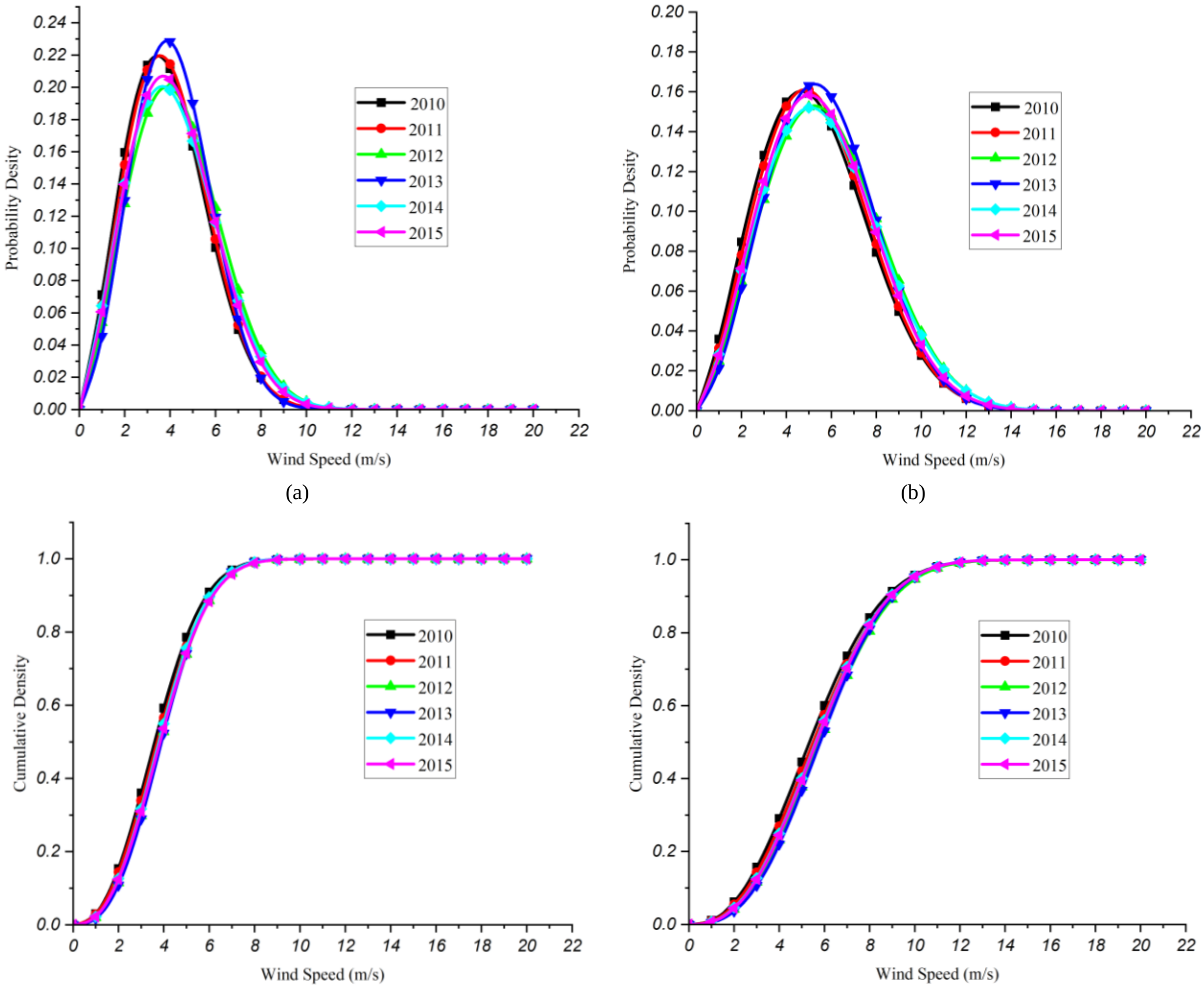

Figure 7. **Yearly PDF and CDF functions, (a) PDF at 10m height, (b) PDF at 50 m height, (c) CDF at 10 m height, (d) CDF at 50 m height**

Table 10. **Yearly wind characteristics at 10 m**

Year	Wind Characteristics (10m height)							
	Vm (m/s)	k	c (m/s)	V_F (m/s)	V_E (m/s)	P_d (W/m^2)	E_d (KWh/m^2)	$V \geq 3$
2010	4.39	2.35	4.37	3.45	5.69	50.37	441.24	0.6397
2011	4.53	2.40	4.45	3.56	5.73	55.28	484.25	0.6596
2012	4.60	2.38	4.85	3.86	6.26	58.36	511.23	0.7010
2013	4.58	2.65	4.62	3.86	5.71	57.63	504.84	0.7102
2014	4.53	2.29	4.70	3.66	6.18	55.42	485.45	0.6826
2015	4.61	2.36	4.66	3.69	6.05	58.33	510.97	0.6911

Table 11. **Yearly wind characteristics at 50 m**

Year	Wind Characteristics (50m height)							
	Vm (m/s)	k	c (m/s)	V_F (m/s)	V_E (m/s)	P_d (W/m^2)	E_d (KWh/m^2)	$V \geq 3$
2010	6.44	2.33	5.96	4.68	7.78	165.63	1450.91	0.8420
2011	6.60	2.40	6.07	4.85	7.81	177.50	1554.90	0.8568
2012	6.77	2.45	6.49	5.24	8.29	191.63	1678.67	0.8836
2013	6.72	2.60	6.35	5.27	7.91	187.90	1646.00	0.8924
2014	6.61	2.38	6.39	5.09	8.26	178.32	1652.08	0.8732
2015	6.63	2.44	6.25	5.03	7.99	180.05	1577.24	0.8764

The other factor is the wind speed, which carries the maximum energy to the system, and it is clear that this speed is higher than the average and the most frequent speed and is also due to the cubic relation between wind speed and power. Since the wind turbine is designed to work at speeds beyond the cut-in speed, which in most cases is between 3-4 m/s [16], the cumulative distribution function is used to find the probability that wind speed is equal to 3 m/s or more. At 10m height the probability of wind speed equal to 3 m/s or more is between 64% and 70%, while at 50m height the probability is in the range between 84% and 89%.

The yearly wind power density shows similar values during the years from 2010 to 2015, which are between 50 W/m^2 and 58 W/m^2 at 10m height and between 165 W/m^2 and 191 W/m^2 at 50 m height. The highest values recorded in 2012 were 58.36 W/m^2 at 10 m height and 191.63 W/m^2 at 50 m height. However, the wind power density has different values during the months of the year due to the seasonal changes that should be considered. In the Qassim region, the largest wind power density is obtained in the period between March and July, as expected since the temperatures begin to rise from March until they reach their maximum values during the summer, which falls between June and August, and most peak loads occur during this period in Saudi Arabia. Figure 8 shows the annual and monthly wind power density at altitudes of 10m and 50m. The largest values of wind power density occur during April in most years, and the highest values were recorded in 2011 and 2015.

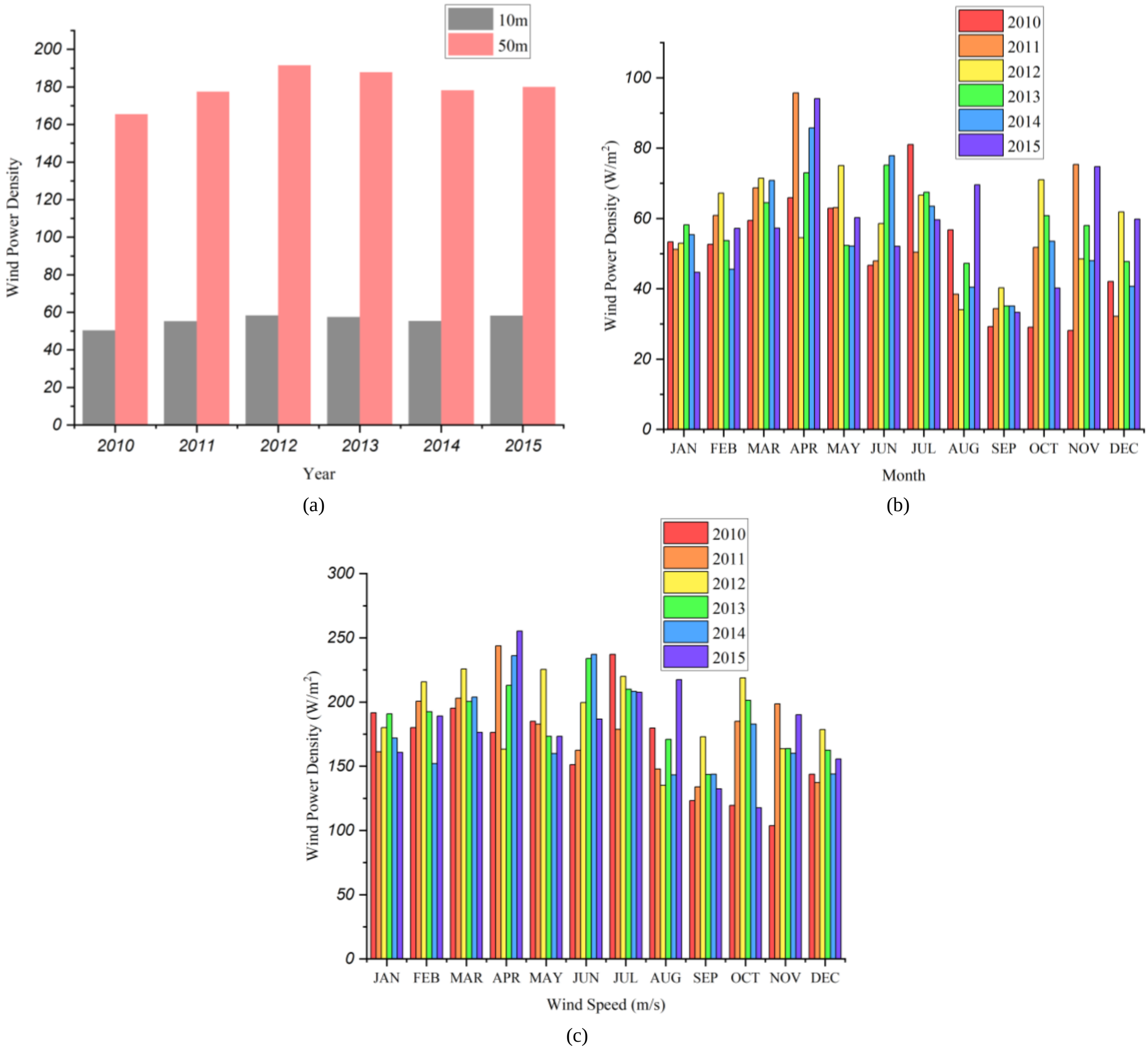

Figure 8. Wind Power density, (a) Yearly at 10m and 50m height, (b) Monthly at 10m height, (c) Monthly at 50m height

To assess the region, there is an international standard classification of wind power generation which evaluates a given region according to speed and power density at different altitudes [36]. Based on the values that show that the power density is less than 100 W/m^2 at 10m height and less than 200 W/m^2 at 50 m height, Al-Qassim region falls in Class 1 most years which means this region is not a suitable for building large-scale projects. However, these values may serve in off-grid projects applications such as battery charging, water pumping, and agricultural applications.

Table 12. Wind power classification

Heights		At 10 m Heights		At 50 m Heights	
#	Class	V (m/s)	Pd (W/m^2)	V (m/s)	Pd (W/m^2)
1	Poor	0-4.4	0-100	0-5.4	0-200
2	Marginal	4.4-5.1	100-150	5.4-6.2	200-300
3	Moderate	5.1-5.6	150-200	6.2-6.9	300-400
4	Good	5.6-6.0	200-250	6.9-7.4	400-500
5	Excellent	6.0-6.4	250-300	7.4-7.8	500-600
6	Excellent	6.4-7.0	300-400	7.8-8.6	600-800
7	Excellent	>7	>400	>8.6	>800

7- Conclusions

In this paper, we have discussed wind energy assessment and how to conduct a study of a region in order to test its wind potential. For this purpose, six different methods have been employed to find Weibull parameters, find the best distribution of wind speeds, and estimate the wind energy density that is classifying the region. The methods used in this paper are the graphical method (GM), the standard deviation method (SDM), the energy pattern factor method (EPF), the moment method (MM), the alternative maximum likelihood method (AMLM), and the novel energy pattern factor method (NEPF). The comparison between these methods has been made on the basis of statistical indicators of root mean square error (RMSE) and wind power density error (RPDE). Based on this study and by comparison with previously available studies, we can draw these conclusions and recommendations:

- The moment method (MM) has been judged as the best method for estimating wind power density with the smallest RPDE ratio, followed by the standard deviation method (SDM) according to the results and in light of already reported studies since these methods depend on real data that give high accuracy.
- The graphical method (GM) has outperformed all other methods in determining the Weibull parameters in the Qassim region since it has the smallest RMSE ratio.
- The moment method (MM) also shows the best performance to obtain the cumulative distribution function, and then the wind speed probability is calculated at a specific speed or through the parameters found by this method.
- By analyzing all the wind data, it is clear that the mean wind speed that follows the Weibull distribution in the Qassim region ranges between 4.39 m/s – 4.61 m/s at an altitude of 10m and between 6.44 m/s to 6.77 m/s at an altitude of 50m, which clearly shows that the wind speed in most years remains the same with no huge difference.
- In the Qassim region, according to the wind power density, it is less than 100 W/m^2 at 10m height and less than 200 W/m^2, and hence the region is not suitable for large-scale projects. However, it can be used for serving loads that are not connected to the electrical grid, such as in agricultural applications.
- In future work, wind speed should be tested at higher altitudes, and the performance of wind turbines for off-grid applications should take into account the potential for wind turbines to produce power. As a result, the turbine will produce energy in 70% of the time per year at 10m height. However, this ratio will increase to about 90% at 50m height. Moreover, after determining the best turbine in terms of performance, future work can study the technical and economic aspects of this type to serve agricultural applications in the region.

8- Declarations

8-1- Author Contributions

Conceptualization, M.A.A. and M.I.; methodology, M.A.A.; software, M.A.A.; validation, M.I., S.A., and S.K.; formal analysis, M.A.; investigation, M.A.A. and M.I.; resources, S.A.; data curation, M.I. and M.A.; writing—original draft preparation, M.A.A.; writing—review and editing, M.I., S.A., S.K., and M.A.; visualization, S.K. and S.A.; supervision, M.I.; project administration, S.A.; funding acquisition, M.A. All authors have read and agreed to the published version of the manuscript.

8-2- Data Availability Statement

The data presented in this study are available in the article.

8-3- Funding and Acknowledgements

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8-4- Institutional Review Board Statement

Not applicable.

8-5- Informed Consent Statement

Not applicable.

8-6- Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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