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Analysis Of Wind Energy Potential By Different Methods Based On Weibull Statistics For A Site In Juja, Kenya

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***Abstract*—Wind energy is a never ending natural resource which has shown its great potential in combating climatic change while ensuring clean and efficient energy. Wind turbine technology has led to significant growth of wind power generation across the world. Wind can be harvested economically if properly selected turbines are installed in a windy area. Its fluctuation demands a necessary model describing its variation thereby estimating the amount of energy as well as to optimize the design of the wind turbine. This paper analyzes the wind speed characteristics for purposes of determining wind energy potential in Juja at heights of 10 m and 30 m for a period of three months. The wind data was recorded in hourly intervals from which mean diurnal and monthly variations were determined. The wind speed averages for 10 m and 30 m were 2.54 m/s and 3.04 m/s, respectively. The shear exponent, α, and roughness parameter, z_0, were found to be 0.1652 and 0.0374 respectively. Weibull scale and shape parameters were obtained using Weibull-fit, Regression and Maximum LikeliHood methods. The wind speed distribution was modeled using the Weibull function. Power densities for different methods were calculated. The wind power densities for heights 10 m and 30 m were 13.73 W/m² and 22.44 W/m² by Weibull-fit, 13.81 W/m² and 18.81 W/m² by Regression and 10.50 W/m² and 20.70 W/m² by Maximum Likelihood, respectively.**

Keywords—Wind speed; Power density; Wind distribution methods; probability Distribution Functions.

Introduction

The rapidly growing global population along with fast depleting reserves of fossil fuels is influencing researchers to search for clean and pollution free sources of energy which are sustainable and cost-effective. These types of energy include; solar, wind, waves, tidal and bio-energies. Wind energy is a never ending natural resource which has shown its great potential in combating climatic change while ensuring clean and efficient energy, yet it is the most under exploited energy. Wind turbine technology has led to significant growth of wind power generation across the world. However, wind energy is more sensitive to variations with topography and wind patterns compared to solar energy. It can be harvested economically if the turbines are installed in a windy area and suitable turbines are selected. Wind speed forecasting is a critical factor in assessing wind energy potential and performance of wind energy conversion systems. Wind fluctuation demands a necessary model describing its variation thereby estimating the amount of energy as well as to optimize the design of the wind turbine [1, 2]. The most suitable wind turbine model which needs to be installed in a wind farm is selected by careful wind energy resource evaluation. It is therefore important to choose an accurate distribution model which closely mimics the wind speed distribution at a particular site [3]. The development and utilization of wind energy in developing countries, particularly Africa, has been hindered by absence of adequate measurements and assessment studies to ascertain its potential viability for power generation [4].

2 Study background

Juja, a semi urban town at 1416 m above sea level (1^0 10' S, 37^0 7' E) and about 35 km from Nairobi, having a rapidly growing population and a major university, Jomo Kenyatta University of Agriculture and Technology (JKUAT), requires an alternative energy source to supplement existing convectional energy. Use of power generators during power outage, is expensive and also leads to air pollution and hence the need for clean, reliable, sustainable and cost effective sources. Wind energy is among the least exploited in Kenya with 25.5 MW from the two Ngong wind farm phases, though there are underway processes of establishing other wind plants in Kenya such as in Kinangop [5] and Turkana [6]. Thorough wind speed analysis is therefore critical.

A study based on different methods brings out a better picture of the state of wind in a site. Several methods and Probability Density Functions (PDFs) have been used in literature to describe wind speed characteristics. The methods include Weibull-fit, Regression, Standard deviation, Maximum likelihood, Chi-square among others while PDFs include Weibull, Rayleigh, bimodal Weibull, lognormal, gamma among others [3]. This paper analyses wind speed using different methods modeled using Weibull statistics for Juja at two different hub heights of 10 m and 30 m.

2.1 Materials and Methods

The study was carried out in Juja at 10 m and 30 m heights in order to measure wind speeds and directions at the two heights above the ground. A mask of required length was constructed using metallic circular tubes. Anemometers (Ultrasonic wind sensors) were clamped on the mask at 10 m and 30 m in order to measure wind speeds and directions at these heights above the ground. The sensors were connected to transmitting devices (clamped on metallic rods) using insulated cords. The transmitters were linked with two Ultrasonic data loggers programmed so as one received data from 10 m and the other from 30 m centers. The data was stored in computer memory (disc) awaiting processing. The averages of wind parameters were obtained daily for three months. The wind shear exponents, α, surface roughness, z_0, Weibull scale parameter, c, shape parameter, k, and power densities were determined. Wind power potential was modeled using Weibull distributions function.

2.2 Theoretical considerations

2.2.1 Power available in the wind

Wind power, P, available from the wind of speed v using wind turbines with blades of cross-section area, A [7], is given by

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

Where;

A is the rotor area; v, wind speed and ρ, the air density given by;

$\rho = \frac{P}{RT}$; Where P is air pressure, R, gas constant and, T, temperature in degrees Kelvin. The wind velocity at the rotor plane is the average of upstream and downstream wind speeds [8].

2.2.2 The power law

Wind speed near the ground changes with height; this involves an equation that forecasts wind speed at different height by using the available wind speed data. The most commonly used equation for the variation of wind speed with height is the power law [9] is;

$$v_2 = v_1 \left(\frac{h_2}{h_1} \right)^{\alpha} \qquad (2)$$

Where v_1 (m/s) is the actual wind speed recorded at height h_1 (m), and v_2 (m/s) is the wind speed at h_2 (m). The exponent, α, depends on the surface roughness and atmospheric stability. Wind shear exponent, a difference in wind speed and direction vertically has been determined for various types of terrains [10].

Roughness length, z_0 which is used to characterize shear and the height above the ground is not constant [11] and thus equation 2 can be modified to yield equation 3.

$$v_2 = v_1 \frac{\ln\left(h_2 / z_0 \right)}{\ln\left(h_1 / z_0 \right)} \qquad (3)$$

2.2.3 Wind probability distribution functions

Two of the commonly used functions for fitting a field data probability distribution in a given location over a certain period of time are the Weibull and Rayleigh distribution models [12]. The Weibull probability density function, $f_R(v)$ is given as;

$$f_R(v) = \frac{k}{c} \left(\frac{v}{c} \right)^{k-1} e^{-\left(\frac{v}{c} \right)^k} \qquad (4)$$

The Rayleigh $f_R(v)$ distribution is a special case of the Weibull distribution in which the shape parameter k=2. The probability density functions of the Rayleigh distribution is therefore given by;

$$f_R(v) = \frac{2v}{c^3} e^{-\left(\frac{v}{c} \right)^2} \qquad (5)$$

2.2.4 Methods of obtaining Weibull parameters

2.2.4.1 Weibull-fit (standard deviation method)

The shape and scale parameters as per Weibull-fit are as follows [13];

$$c = \frac{v_m}{\Gamma\left(1 + \frac{1}{k} \right)} \qquad (6)$$

Where v_m is the mean value of wind speed, v, and Γ is the gamma function given by;

$$\Gamma = \int_0^{\infty} v^{k-1} \exp(-v) dv \qquad (7)$$

$$k = \left(\frac{\sigma_y}{v_m} \right)^{-1.090} \qquad (8)$$

Where σ_y is standard deviation

$$v_m = \left(\frac{\sum_{i=1}^{n} f_i v_i}{\sum_{i=1}^{n} f_i} \right) \qquad (9)$$

$$\sigma_y = \left[\frac{\sum_{i=1}^{n} f_i (v_i - v_m)^2}{\sum_{i=1}^{n} f_i} \right]^{\frac{1}{2}} \qquad \text{.....................10}$$

2.2.4.2 Regression

The cumulative probability function of the Weibull distribution [14] is given by;

$$F(v) = 1 - \exp\left[-\left(\frac{v}{c} \right)^k \right] \qquad \text{...............11}$$

To determine k and c requires a good fit of the equation above to the recorded discrete cumulative frequency function. By taking the natural logarithm of both sides of equation 11 twice gives;

Plotting $\ln\langle -\ln[1 - F(v)] \rangle$ against $\ln(v)$ presents a straight line whose gradient is *k* and the y-intercept is $-k \ln c$ from which c can be calculated.

2.2.4.3 Maximum Likelihood (MLH)

The parameters k and c (m/s) can be estimated by using the Maximum Likelihood Method, [15] as;

$$k = \left(\frac{\sum_{i=1}^{n} v_i^k \ln(v_i)}{\sum_{i=1}^{n} v_i^k} - \frac{\sum_{i=1}^{n} \ln(v_i)}{n} \right)^{-1} \qquad \text{..........12}$$

$$c = \left(\frac{1}{2} \sum_{i=1}^{n} v_i^k \right)^{\frac{1}{2}} \qquad \text{............................13}$$

2.2.5 Wind power density function

The evaluation of wind power per unit area P_v is of fundamental importance in assessing wind power projects [16]. The formula for P_v is given by;

$$P_v = \frac{1}{2n} \sum_{i=1}^{n} \rho (v_i^3) \qquad \text{......................14}$$

Where the wind speed at stage i, is v_i, n, the number of non-zero wind data points and ρ, is air density. The ρ depends on altitude, air pressure and temperature and is approximated to be 1.225 kg/m^3 at Juja. The expected monthly or annual wind power density per unit area of a site based on Weibull probability density function P_W [14] can be expressed as follows;

$$P_W = \frac{1}{2} \rho c^3 \Gamma \left(1 + \frac{3}{k} \right) \qquad \text{..........15}$$

Where c is the Weibull scale parameter (m/s) given by equation 6.

3 Results and discussion

3.1: Hourly variation of wind speed

The hourly wind speeds were determined and a graph of wind speed averages against the hour of the day was as shown in figure1.

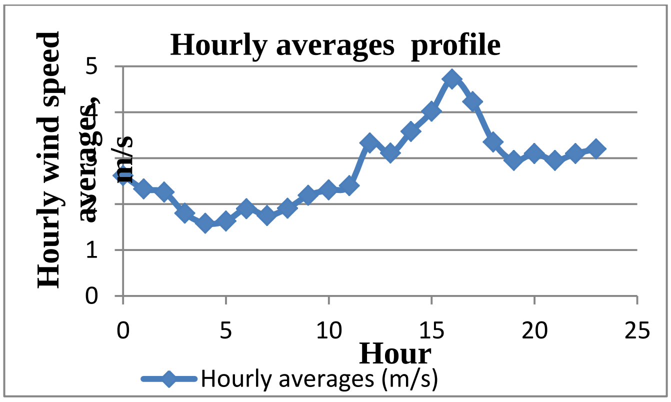

Figure 1: Hourly wind speed averages

Figure1 shows that the highest wind speed values were recorded between 3.00 and 6.00 pm. This is as expected since air in the lower atmosphere is heated from the ground upward. The sunlight warms the ground and air above is warmed by conduction, convection and infrared radiation. Since air is a poor thermal conductor, it takes times for layers of air above the ground to be heated up. The temperature gradient /pressure gradient was greatest within this range and hence the stronger winds [17].

3.2: Wind shear parameters

The **a**verage diurnal wind speeds, wind directions, and temperatures were obtained for the three months. The average wind speeds at 10 m and 30 m heights were 2.54 m/s and 3.04m/s respectively. Wind shear exponent and roughness parameters were 0.1652 and 0.0374 respectively**.** These parameters are in line with [18].

3.3: Diurnal variation of average wind speeds and directions

Figures 2, 3 and 4 show diurnal variation of wind speeds for the months of March through to May, 2015.

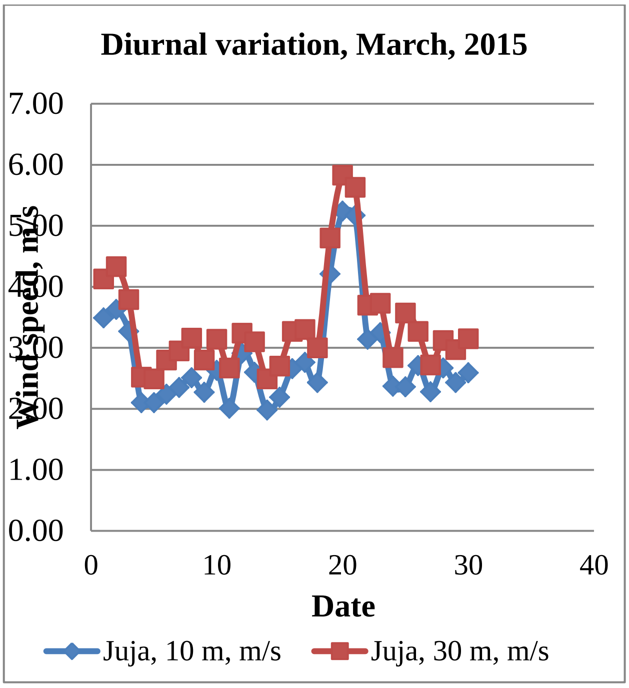

Figure 2: Diurnal wind profile for March, 2015

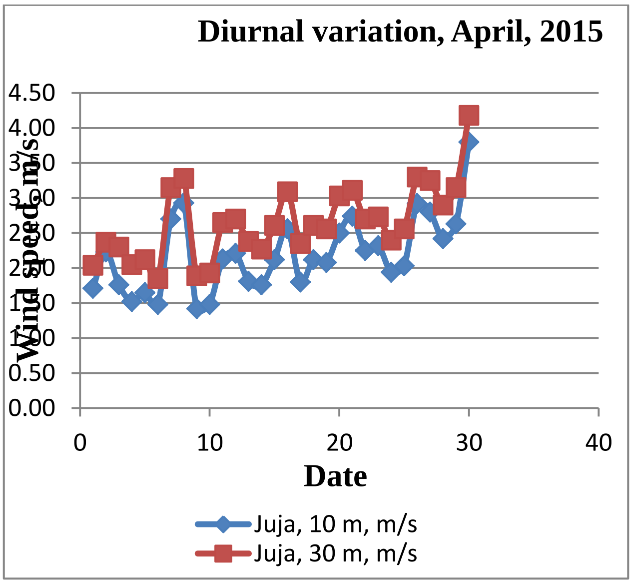

Figure 3: Diurnal profiles April, 2015

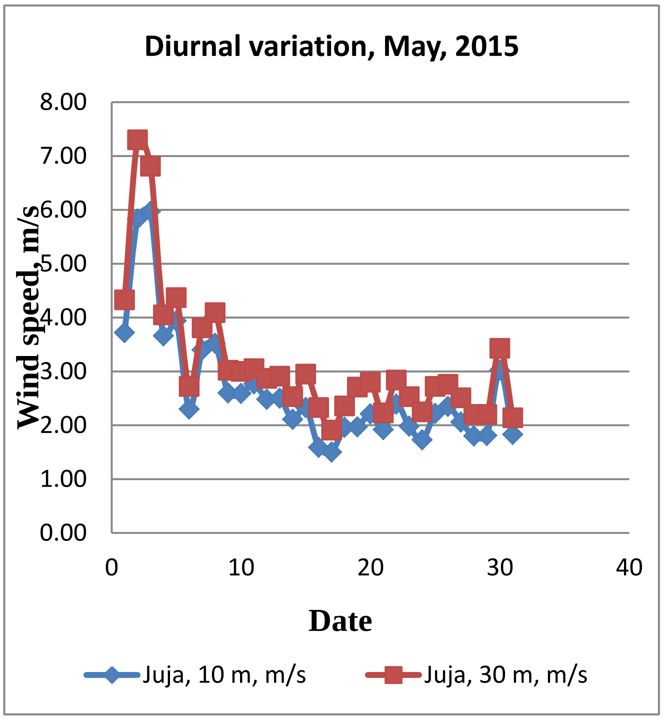

Figure 4: Diurnal wind profile for May, 2015

The site had most wind speed averages below 3.5 m/s, though wind speeds in March and beginning of May were slightly higher. This could be attributed to higher temperatures which led to increase in pressure gradient [19].

3.4 Daily number of hours above cut-in speed

The numbers of hours above cut-in speed based on 10 minutes averages were obtained. Statistics showed that 29.39%, 18.87% and 28.30% of daily number of hours had wind speed above 3.5 m/s, for March, April and May respectively, which is sufficient for power generation using variety of wind turbines in the market such as the V90-3.0 MW® IEC IA/IIA. This is a choice for medium wind sites with high turbulence and is designed for easy and cost effective transportation and installation [20].

3.5 Wind Direction

WindRose diagram was used to analyze wind direction as shown in figures 5, 6, 7 and 8. Most Juja wind was between east north east (ENE) and east south east (ESE).

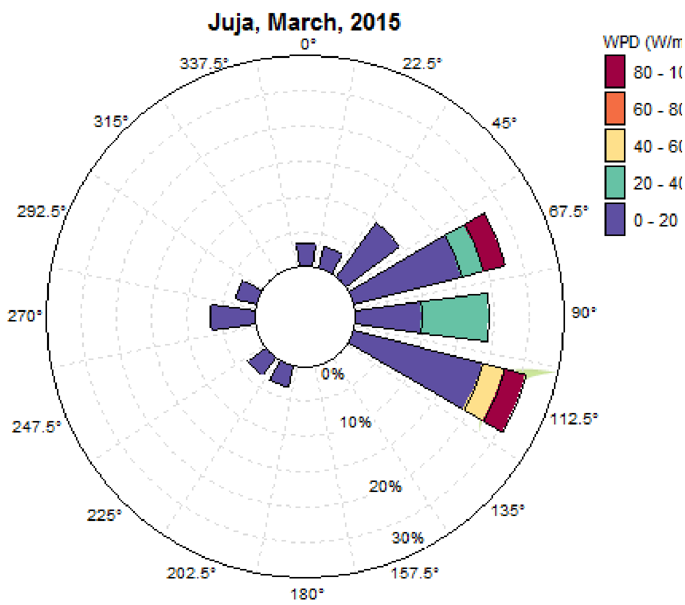

Figure 5: WindRose, March, 2015

Figure 5 shows that wind direction was predominantly from between ESE and SW with modal power density range being 0-60 W/m². This month had the highest wind power density in the three months of study due to high temperature differences [19].

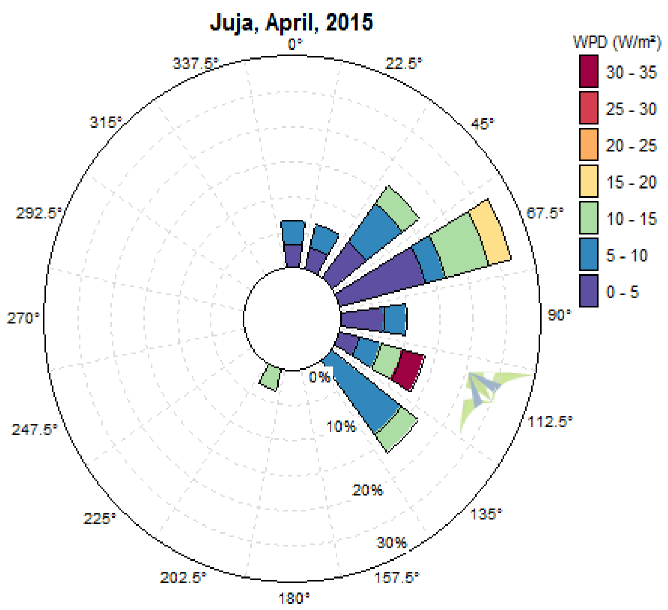

Figure 6: WindRose for April, 2015

Figure 6 shows that wind predominantly blew between NE and SE directions (45-135 degrees) with modal power density range being 5-10 W/m².

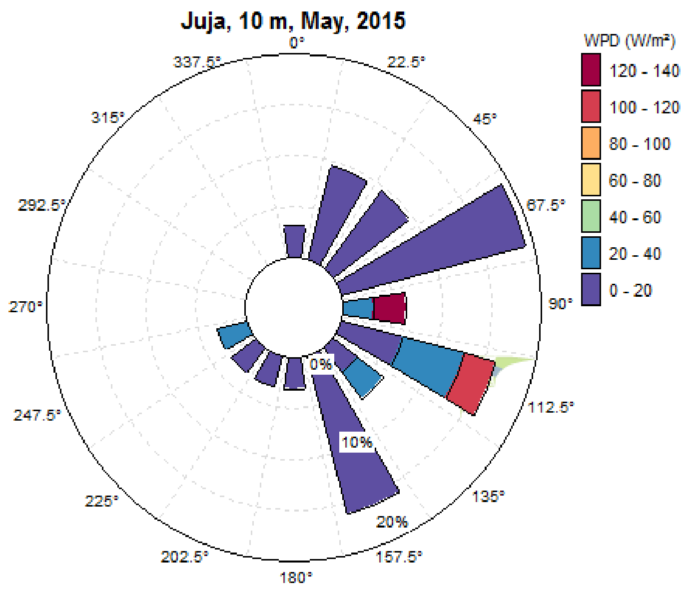

Figure 7: WindRose foe May, 2015

Figure 7 shows that wind predominantly blew between NE and SES directions with modal power density range being 0-20 W/m². This month had highest fluctuations in the three months which was caused by change in weather.

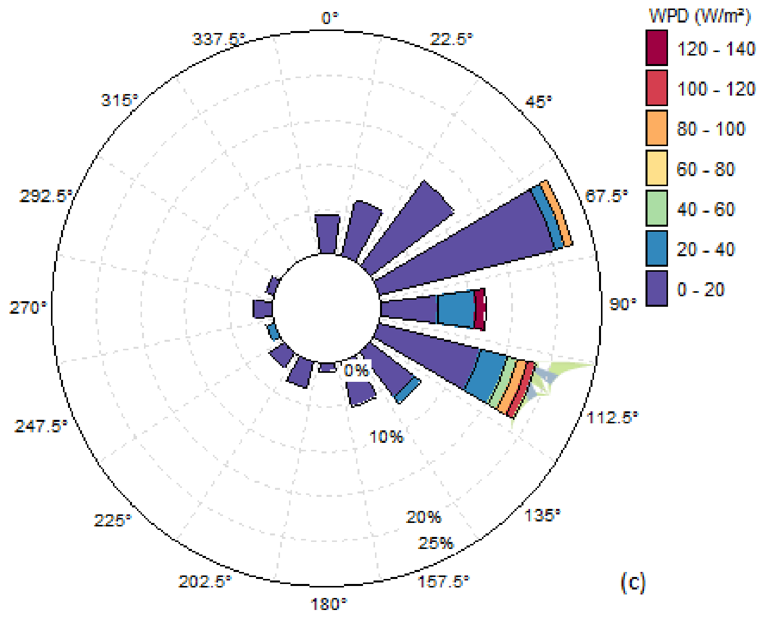

Figure 8: Overall WindRose for Juja

The windRose diagram is almost unidirectional which implies that horizontal axis turbine can be recommended for power generation in the site during that season. This will minimize cost due to absence of a yaw.

3.6: Weibull parameters and power densities

The wind speeds were used to determine Weibull shape parameters (k), scale parameters (c), as shown in table 1 and wind power densities for different methods by table 2. Windographer software and

Microsoft Excel were used to determine and generate the parameters and Probability Distribution Functions (PDFs). Actual power densities for 10 m and 30 m were 14.5 W/m² and 30.9 W/m² respectively. The mean wind power densities were 12.68 W/m² and 20.65 W/m² by Weibull model respectively.

Table1: Weibull parameters for different methods

Method	At a height of 10 m (Juja site)		At a height of 30 m (Juja site)	
	c (m/s)	k	c (m/s)	k
Weibull-fit	2.811	2.937	3.646	3.394
Regression	2.937	2.773	2.937	2.773
MLH	2.394	1.261	2.652	0.943

The Weibull parameters were dependent on method of analysis which was in line with [21].

3.7: Probability Density Functions (PDFs)

The Probability Distribution Functions generated from Weibull parameters obtained from different methods are as per figures 9 and 10.

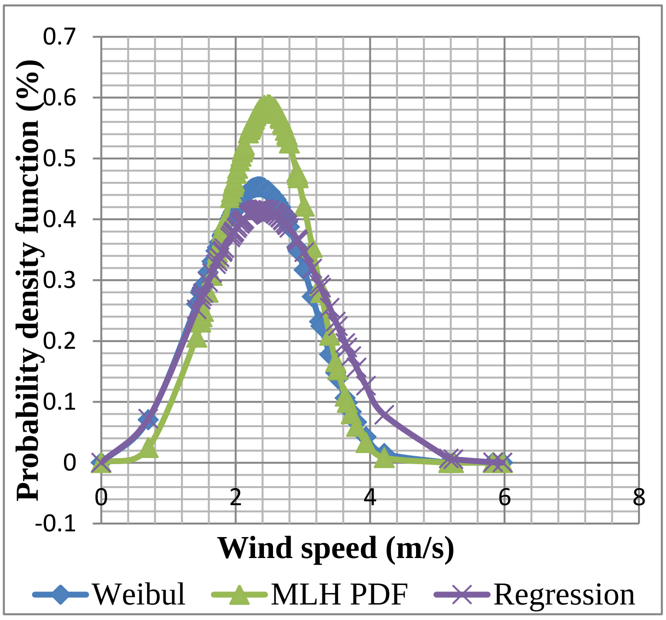

Figure 9: Probability Distribution Function (PDF), 10 m, Juja

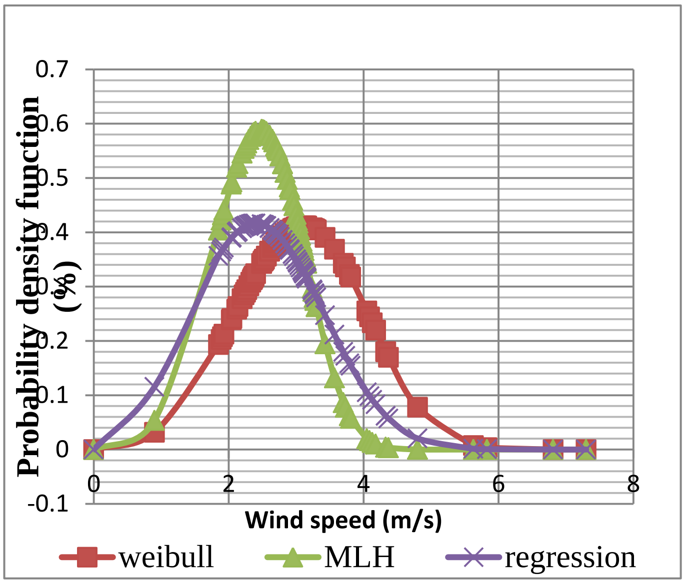

Figure 10: Probability Distribution Function (PDF), 30 m, Juja

The area under each PDF curves is equivalent to power density obtained from each method.

Table 2: Wind power densities

Method	Power density (W/m²)	
	At 10 m	At 30 m
Weibull-fit	13.73	22.44
Regression	13.81	18.81
MLH	10.50	20.70

The results on power density showed Regression being the method of best fit for 10 m and Weibull-fit for 30 m. This implies that power density for any selected height should be obtained using different methods in order determine the actual state of the wind at selected hub height.

4 Conclusion

Juja had low wind speed averages which resulted to low power density of wind class 1. The Weibull scale parameters c and shape parameters k ranged from 2.394 m/s to 4.209 m/s and 0.943 to 2.937 respectively.. The mean wind power densities for 10 m and 30 m were 12.68 W/m² and 20.65 W/m². The results indicated that different methods of analysis yield slightly different values of power densities, which can be attributed to conditions under which they were established. The method of best-fit was dependent on position. From the wind rose analysis, most winds for Juja were found to be in the North East and East South East directions. The site was found capable of power generation by use of small horizontal axis wind turbines such as HAWT upwind with three blades of diameter 1.7 m^2 and cut-in speed of 1.3 m/s [20]. The generated power can be used for activities such as ventilation, water pumping and battery charging.

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