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Harnessing Wind Energy in Jalingo for Power Generation

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Abstract

This paper presents an examination of data on wind speed measured at 10 metres altitude by cup anemometer to assess the wind energy potential in Jalingo, located in North-eastern Nigeria. Data for the years 2013 - 2023 was obtained from the Abuja-based Nigerian Meteorological Agency (NIMET). The analysis was conducted using Weibull distribution function, a statistical method commonly applied to evaluate wind energy potential. The findings indicate the average yearly wind speed for Jalingo is within 4.33 – 4.80 m/s which put the station in class 2 (i.e., v: 4.4 – 5.1 m/s; P_d: 100 – 150 Wm^2) – Marginal potential, based on Pacific National Laboratory (PNL) classification. Computed mean wind energy in the station is in the range 2.50 – 3.66 MWh/month, and 29.37 – 44.47 MWh/year. This is considered quite low compared to good sites (> 1000 MWh/year per turbine). It reflects Jalingo's relatively weak average wind speeds – A wind turbine of medium size 10 – 25 m with rating of 10 -150 kW is recommended for economic reasons.

Keywords: Wind data; Weibull distribution function; Wind power potential; Renewable energy; Jalingo.

1. Introduction

Adequate power generation and supply are the driving forces for development of any society. It is widely assumed that energy consumption and economic growth are highly correlated and have a linear, positive relationship [1, 2]. Energy is a crucial tool needed for cultural, social and economic development of countries [3, 1]. In Nigeria, inadequate power generation and supply have persisted despite abundant energy resources. These may be attributed to under-utilization of the abundant natural resources [4]. As the need for energy continues to grow as a result of exponential rise in population, there is also need for energy diversification especially from traditional fossil fuel sources to renewable energy sources. Wind energy has become one of the fastest growing renewable energy sources due to its advantages, including clean nature, sustainability, cost-effectiveness and low environmental impact.

For many centuries, wind power has been harnessed and used by many ancient civilizations. The ancient human histories have revealed how wind energy was discovered and used at different parts of the globe. As early as about 4000, the ancient Chinese became the first to attach sails to their primitive rafts [5]. Chinese junks were developed and used as ocean-going vessels. Multi-masts and multi-sail junks were built in the South Sea, capable of carrying 700 people with 260 tons of cargo [6]. Approximately at 3400, the ancient Egyptians launched their first sailing vessels initially to sail on the Nile River, and later along the coasts of the Mediterranean [5]. Around 1250, Egyptians built fairly sophisticated ships to sail on the Red Sea. The wind-powered ships had dominated water transport for a long time until the invention of steam engines in the 19th century.

About 300, ancient Sinhalese had taken advantage of the strong monsoon winds to provide furnaces with sufficient air for raising the temperatures inside furnaces in excess of 1100 °C in iron smelting processes. This technique was capable of producing high-carbon steel [7]. The double acting piston bellows were invented in China and was widely used in

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metallurgy in the fourth century [8]. This kind of bellows was able to continuously blast air into furnaces, raising the temperature to a point where iron could be melted. The ancient Chinese were reportedly able to cast tons of iron in this manner.

China has long history of using windmills. The unearthed mural paintings from the tombs of the late Eastern Han Dynasty (25–220 AD) at Sandaohao and Liaoyang City, have shown the exquisite images of windmills, evidencing the use of windmills in China for at least approximately 1800 years [9]. The practical vertical axis windmills were built in Sistan (Eastern Persia) for grain grinding and water pumping, as recorded by a Persian geographer in the ninth century [10]. The horizontal axis windmills were invented in northwestern Europe in 1180s [11]. The earlier windmills typically featured four blades and mounted on central posts – known as Post mill. Later, several types of windmills such as Smock mill, Dutch mill, and Fan mill, were developed in the Netherlands and Denmark, based on the improvements on Post mill. The horizontal axis windmills have become dominant in Europe and North America for many centuries due to their higher operation efficiency and technical advantages over vertical axis windmills.

Unlike windmills which are used directly to do work such as water pumping or grain grinding, wind turbines are used to convert wind energy to electricity. The first automatically operated wind turbine in the world was designed and built by Charles Brush in 1888 [5]. This wind turbine was equipped with 144 cedar blades having a rotating diameter of 17 m. It generated a peak power of 12 kW to charge batteries that supply DC current to lamps and electric motors [5]. As a pioneering design for modern wind turbines, the Gedser wind turbine was built in Denmark in the mid-1950s [12]. Today, modern wind turbines in wind farms have typically three blades, operating at relative high wind speeds for the power output up to several megawatts.

The assessment of wind energy potential across Nigeria is crucial for diversifying the energy sector, enhancing energy security, and reducing greenhouse gas emissions. Nigeria’s wind energy potential varies significantly across different regions, influenced by geographical and climatic factors. Research studies have shown that wind speeds are generally higher in the northern regions compared to the southern parts of the country. Sokoto, Katsina, Kano, and Jos Plateau areas, in particular, exhibit higher wind speeds, often reaching above 5 m/s at a height of 10 m, which is considered sufficient for electricity generation [13, 14]. The wind speed in these areas is enhanced by the Sahara Desert's harmattan winds, especially during the dry season.

In contrast, southern Nigeria, with its tropical rainforest climate, generally experiences lower wind speeds. However, coastal areas such as Lagos and Port Harcourt have been identified to have moderate wind speeds due to their proximity to the Atlantic Ocean. According to [15], these regions could still support small- scale wind energy projects for rural electrification and off-grid applications.

Jalingo, the capital city of Taraba State in Nigeria, is located at approximately 8.89’32” N and 11.36’05” E. Like many parts of Nigeria, it faces challenges in meeting its energy demand. The existing electricity infrastructure is often inadequate leading to frequent power outages and reliance on costly and polluting diesel generators. This is the significance of the study, which looks at wind speed statistics and the region's potential for electricity.

Exploring wind energy in Jalingo can position the State capital as a leader in renewable energy and innovation within Nigeria. This can attract research and development initiatives, foster partnerships with universities and technology companies, and encourage the adoption of other renewable technologies.

2. Materials and Method

Monthly mean daily wind speed data for Jalingo, measured at 10 m by cup anemometer were obtained from the Nigeria Meteorology (NIMET) Agency Abuja. The data which covered a full-cycle year 2013 - 2023 were used for analysis and estimation of wind energy potential in Jalingo. Weibull distribution function was employed and used in analyzing the wind speed data. Since wind speed changes rapidly and frequently over time, the statistical function gives better fit to predict wind distribution over a period of time. Researchers have proven that the Weibull distribution function has higher accuracy than other statistical functions to capture the skewness of the wind speed distribution, and it is widely used in research [16].

The probability density function (pdf) is given as equation 1[17]:

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

where v is the wind speed (m/s), c is the Weibull scale parameter (m/s), and k is a dimensionless Weibull shape parameter.

The integral of the probability density function, which is the cumulative distribution function, F(v) is written as [18]:

$$F(v) = 1 - exp - \left(\frac{v}{c}\right)^k \quad (2)$$

The Weibull shape parameter k was computed using equation 3 [16]:

$$\mathrm{k} = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \quad (3)$$

where σ is standard deviation.

The Weibull scale parameter, c (m/s) was computed using equation 4 [16]:

$$\mathrm{c} = \frac{\bar{v}K^{2.6674}}{0.184+0.816k^{2.73855}} \quad (4)$$

where $\bar{v}$ is the mean wind speed in m/s

The mean wind speed and standard deviation, are computed using equation 5 and equation 6 respectively. [16]:

$$\bar{v} = \frac{1}{n}\sum_{i=1}^{n} x_{\mathrm{i}} \quad (5)$$

$$\sigma = \left[\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{v})^2\right]^{\frac{1}{2}} \quad (6)$$

The most probable or frequent wind speed v_F (m/s) is computed using equation 7 [17]:

$$v_F = c\left(\frac{k-1}{k}\right)^{\frac{1}{k}} \quad (7)$$

The wind speed carrying maximum energy, V_E (m/s) is estimated by using equation 8 [19]:

$$v_E = C\left(\frac{k+2}{k}\right)^{\frac{1}{k}} \quad (8)$$

The kinetic energy (KE) of mass of air m, moving at speed v is

$$\mathrm{KE} = \frac{1}{2}\, mv^2 \quad (9)$$

For wind blowing through the swept area A of a wind turbine, the mass flow rate of air is;

$$\mathrm{m} = \rho\mathrm{Av} \quad (10)$$

where ρ is the air density and it is equal to 1.225 kg/m^3; A is swept area of turbine blades (πR^2); v is wind speed (m/s).

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 11 [16]:

$$\mathrm{P} = \frac{1}{2} \times \rho \times A \times v^3 \quad (11)$$

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 12 [16]:

$$P_D = \frac{P(v)}{A} = \frac{1}{2} \times \rho \times v^3 \quad (12)$$

Where P(V) is the wind power in watt.

Thus, mechanical power extracted:

$$P_{mech} = C_p \frac{1}{2}\rho A v^3 \quad (13)$$

where C_p, the power coefficient = $\frac{16}{17}$ ≅ 0.593; A is the rotor swept area.

From mechanical power to electrical power (efficiencies):

$$P_{elect} = \eta_{sys}\, P_{mech} = \eta_{sys} C_p \frac{1}{2}\, \rho A V^3 \quad (14)$$

Energy density indicates how much power density exists at a specific time in a site. The mean energy density, E_D over a given period of time, T is computed using the expression 15 [18]:

$$E_D = \frac{1}{2}\rho C^3 \Gamma\left(1 + \frac{3}{k}\right) T \quad (15)$$

T is 720 hours/month; equals 8760/year if the time is taken in hourly base.

For new technology wind turbines, the wind energy output is dependent on the turbine efficiency, η, the height of the wind turbine (usually 25 m), the cut-in and cut-out wind speeds, the rated wind speeds [usually (1.8-2.2) V_m] and the duration of each wind speed regime, T [27]. Thus, the total energy generated by the turbine (kWh or MWh) is determined using the relation [31, 32]:

$$E = \frac{1}{2}\rho A C_p\, \eta c^3 \Gamma\left(1 + \frac{3}{k}\right) T\ kWh/m^2/month \quad (16)$$

Where ρ is air density (kg/m^3), A is rotor swept area (m^2), C_p is power coefficient (turbine efficiency in capturing wind energy), η is overall mechanical and electrical efficiency, c is Weibull scale parameter (m/s), k is Weibull shape parameter, $\Gamma\left(1 + \frac{3}{k}\right)$ is gamma function term from Weibull statistics, T is time period considered (hours in month/year).

3. Results and Discussion

The wind speeds at 10 m height from 2013-2023 have been gathered and examined utilizing Weibull distribution function. Table 1 shows yearly wind speed characteristics of Jalingo station for the periods under consideration. The wind speed range for the station is 4.33 – 4.80 m/s which falls within the range of (2.2 – 10.1 m/s) reported for moderate region of Nigeria [33]. Table 1 also shows other wind speed characteristics like power density (P_d) and energy density (E_d) which are the determinants of wind energy of turbines. The graph of yearly mean speed variation in Jalingo is presented in Figure 1. The peak of the graph is 4.80 m/s and the lowest is at 4.33 m/s. These mean wind speeds were above the minimum values (3.0–4.0 m/s) required for most wind turbines to operate. The wind energy estimates for Jalingo station are presented in Table 2. From the table, efficiency is taken to be 0.30 %, power coefficient Cp is 0.405, the corresponding duration of the wind speed in hours (T) in the interval for one month is 720 h, and it is 8760 h for a whole year [27]. The wind speed frequency distribution shows that Jalingo station is generally a low wind speed region.

Table 1 Yearly wind characteristics of Jalingo at 10 m height (2013 – 2023).

Year	V_m (m/s)	SD	k	C (m/s)	V_f (m/s)	V_E (m/s)	P_D (w/m^2)	E_D (kWh/m^2)
2013	4.45	1.21	4.60	5.24	4.96	5.66	122.84	88.70
2014	4.60	1.35	4.87	5.30	4.11	5-00	132.00	95.30
2015	4.75	1.50	4.90	5.90	4.03	5.30	140.92	103.43
2016	4.35	1.10	4.20	5.20	4.26	5.63	153.32	111.05
2017	4.33	1.09	4.60	5.49	4.18	5.08	90.04	65.32

2018	4.77	1.67	4.75	5.99	4.40	5.65	80.79	58.45
2019	4.80	1.79	4.04	5.49	4.30	5.78	85.70	61.90
2020	4.55	1.30	4.55	5.33	4.11	5.97	74.99	53.20
2021	4.40	1.19	4.49	5.28	4.97	5.60	46.49	33.60
2022	4.79	1.70	4.98	5.49	4.18	5.66	32.50	23.90
2023	4.61	1.36	4.90	5.56	4.12	5.74	32.45	23.60

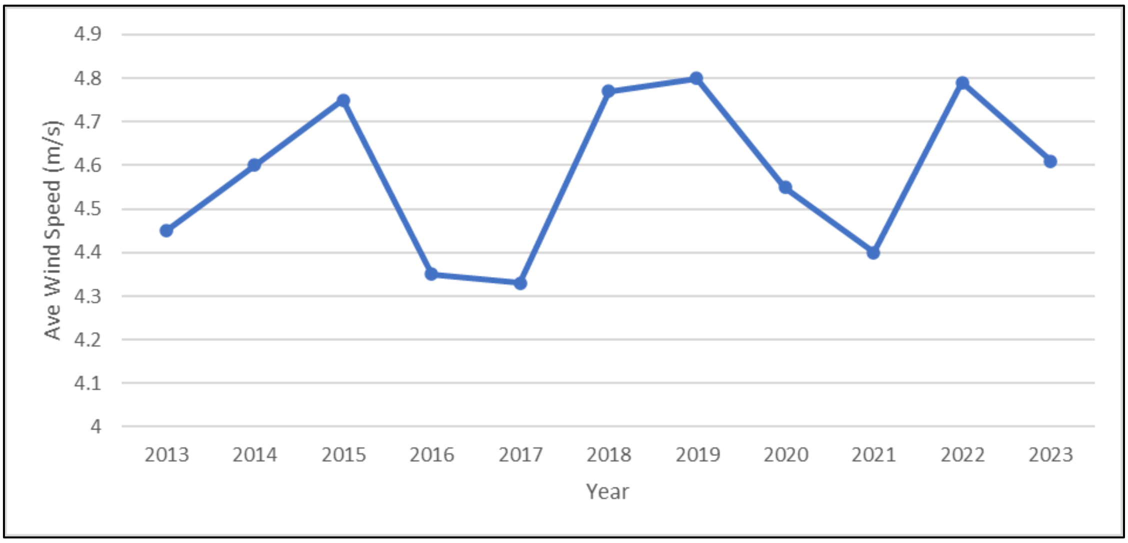

Figure 1 Yearly mean wind speed variations in Jalingo (2013 – 2023).

The graph of monthly and yearly wind energy estimates for Jalingo (2013 – 2023) is presented in Figure 2. The computed monthly mean wind energy (MWh/month) is within the range 2.41 – 3.66 while mean yearly wind energy (MWh/year) is in the range 29.37 – 44.47. A wind turbine of medium size 10 – 25 m with rating of 10 -150 kW may be preferred for economic reason.

Table 2 Monthly and Yearly Wind Energy Estimates for Jalingo (2013 – 2023)

Year	**η**	**C_p**	**Rotor Dia. (m)**	**k**	**C (m/s)**	**Monthly Mean Wind Energy (MWh/month)**	**Annual Energy Production (AEP) (MWh/year)**
2013	0.3	0.405	20	4.60	5.24	2.50	30.40
2014	"	"	"	4.87	5.30	2.57	31.24
2015	"	"	"	4.90	5.90	3.54	43.04
2016	"	"	"	4.20	5.20	2.41	29.37
2017	"	"	"	4.60	5.49	2.86	37.77
2018	"	"	"	4.75	5.99	3.66	44.47
2019	"	"	"	4.04	5.49	2.86	34.81
2020	"	"	"	4.55	5.33	2.63	31.95
2021	"	"	"	4.49	5.28	2.54	30.87
2022	"	"	"	4.98	5.49	2.76	33.62
2023	"	"	"	4.90	5.56	2.86	34.85

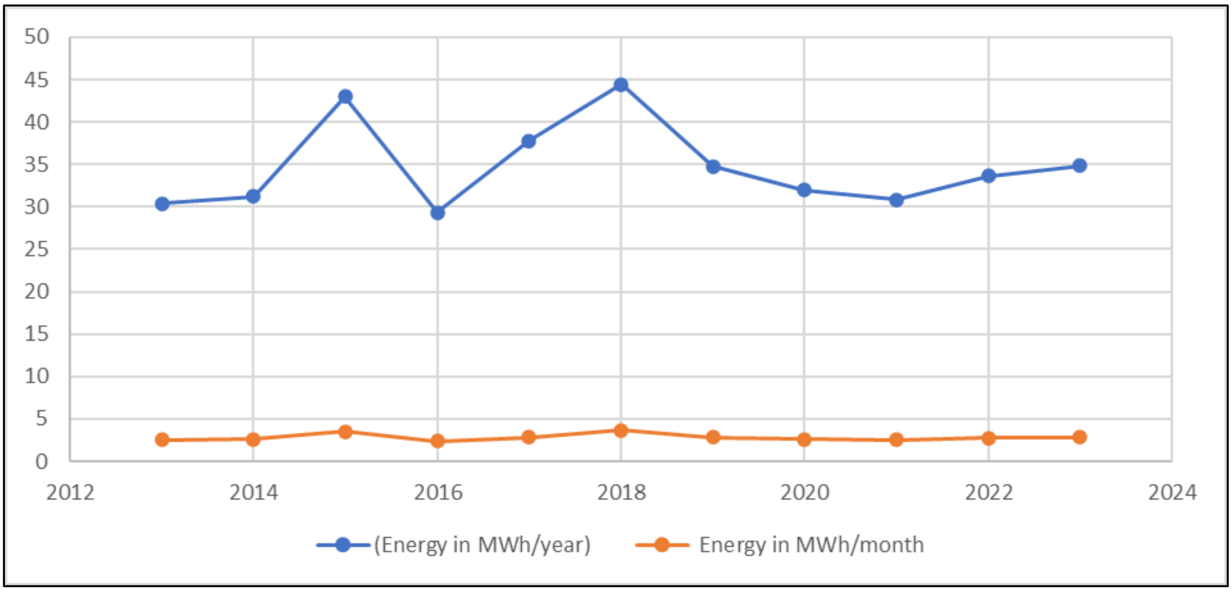

Figure 2 Wind Energy estimates for Jalingo (2013 – 2023)

In the estimation of wind turbine design or rated wind speed, wind speed carrying maximum energy is very essential. Wind turbine system has been reported to operate efficiently at its rated wind speed. Therefore, it is required that the rated wind speed and the wind speed carrying maximum energy should be as close as possible [33]. Therefore, for Jalingo station, a wind turbine of size 10 – 25 m with rating of 10 – 150 kW is recommended.

4. Conclusion

In this study, wind speed data to determine its wind energy potential for Jalingo have been analyzed using Weibull distribution functions. The following findings and are derived from this study

- The yearly mean wind speed (2013 – 2023) is in the range 4,33 m/s – 4.80 m/s i.e., within the classification of marginal potential.
- The annual mean Weibull shape parameter, k was within 4.20 – 4.99, while the annual mean of the Weibull scale parameter, c is within 5.24 – 5.99 m/s.
- The yearly mean power and energy densities were within 32.50 - 153.32 W/m^2 and 23.90 – 111.05 kWh/m^2 respectively.
- The estimated wind energy for Jalingo is within the range 2.50 – 3.66 MWh/month and 29.37 – 44.47 MWh/year.
- A wind turbine of medium size 10 – 25 m with rating of 10 -150 kW is recommended for economic reasons.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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