Global Scientific JOURNALS

GSJ: Volume 7, Issue 3, March 2019, Online: ISSN 2320-9186
www.globalscientificjournal.com

OFFSHORE WIND ENERGY ASSESSMENT AND ITS UTILIZATION IN COMPARISON TO GAS TURBINE OPERATIONS

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ABSTRACT

This research is geared towards assessing the wind characteristics of three target locations within the Nigerian exclusive economic zone and the utilization of offshore wind energy in offshore operations in Nigeria. The three target areas are offshore locations within the boundaries of Lagos, Onne and Warri. Wind speed data was obtained from Nigerian Meteorological Agency (NIMET) for this work. Weibull distribution function was used to analyze the wind data and standard deviation method was used to determine the scale and shape factor values. Comparative economic analysis was carried out where the net present value of setting up a 35.52 MW offshore wind turbine system was compared with a gas turbine system of same capacity. The results of the analysis show that Lagos has the highest annual mean wind speed followed by Onne and Warri. The annual mean wind speed in Lagos at measured height (2 m) and hub height (80 m) are 3.82 m/s and 8.63 m/s respectively; those at Onne and Warri are 2.60 m/s / 6.60 m/s and 1.85m/s /5.14m/s respectively. Lagos also has the highest annual mean wind power density and annual mean wind energy density of 1158.54 W/m^2 and 834.15 kWh/m^2 respectively, Onne has 640.45 W/m^2 and 461.12 kWh/m^2 respectively while Warri has 337.82 W/m^2 and 243.228 kWh/m^2 respectively. Using 3MW wind turbine selected for Lagos as a case study in the economic analysis, 28 wind turbine units are required to produce 35.52 WW of electricity with average capacity factor of 0.423. The net annual cash flow and the net present value of the wind turbine operation for a period of 20 years for 11 % interest rate are USD 14.78 million and USD -42.14 million respectively compared to USD 3.16 million and USD 2.78 million respectively for a gas turbine system.

Keywords: Gas turbine, Net present value, net annual cash flow, Offshore, Weibull distribution, Wind characteristics, Wind energy density, Wind power density.

1. INTRODUCTION

Electrical power can be generated from different sources which include hydroelectric plants, nuclear plants, thermal plants and renewable sources [1]. Currently, due to promotion of decarburization and greener energy, renewable energy is most preferred and most countries and industries have invested significant amount of resources into research and development of renewable energy. Consequently, this has led to discovery of different forms of renewably energy of which some has gained reasonable recognition and attained significant commercial height [2]. The notion of the blue economy refers to those economic activities that directly or indirectly take place in the ocean and in coastal areas that use outputs from the ocean; this includes goods and services that support ocean activities, as well as the contribution that those activities make to equitable economic growth, social, cultural and environmental well-being [3]. Electric power used in oil and gas offshore platforms is generated mostly by gas turbines installed on the platforms. Cost of operation is quite high and gives out notable amounts of greenhouse gas. Options of supplying power from the shore has been considered and deemed expensive for platforms located in deeper offshore. Another suitable option is offshore wind farms which are currently being developed also for deep offshore locations. If utilized optimally, they are capable of saving cost of fuel and curbing greenhouse gas emissions [4].

Nigeria having its coastal line in the south lying in the gulf of guinea presents opportunities to harness the resources in the ocean, reduce pressure for space on land and optimize the value of other marine activities within the blue economy. The power generation for offshore platforms in Nigeria are majorly diesel generators or gas turbines and on land it has hugely dependent on thermal energy (gas) and hydroelectricity and its technology has experienced a slow growth; from thermal (coal) to hydro to thermal (gas) [5]. Offshore wind energy has experienced tremendous increase in growth across the globe, especially within Europe followed by Asia and America; hence, drawing the interest of other countries who are non-users [6]. Evaluation of the wind resources potential is a vital step into any wind energy project. This is done to give a future estimation on the farm's energy performances [7].

The most important factors in setting up (development, sitting and operation) an offshore wind farm include the accurate wind resource estimation and forecast of the wind resources and secondly, the quantifying of the inherent variability in wind power generation [8]. The various methodologies for wind resource estimation were discussed in [8]. Wind resource assessment is broken down into wind power density and energy production [9]. Wind speed characteristics and its energy potential for three target areas within the south eastern states of Nigeria has been investigated [10]. This work borrows a lot of the methodologies presented in [10]. Wind resource assessment and integration has been severally studied [11-16]. Majority of the reviewed published works involve wind assessment and power analysis of some existing oil and gas offshore platforms within a specified target territory located mostly in Europe, Asia, Africa and America. In Nigeria, there are works involving onshore wind power potential across some regions and also integration of onshore wind farms into the national grid. Hence in this study, focus will be on offshore wind assessment and its utilization on oil and gas offshore platform for three target areas within the exclusive economic zones of Nigeria: Lagos, Warri and Port Harcourt.

2. MATERIALS AND METHODS

The essence of this study is to ascertain the amount of wind energy extractable from the available resources located within the Nigerian economic exclusive zones with specific target locations at Lagos, Onne and Warri. The general approach to this study is presented in Figure 1:

Figure 1: Offshore wind assessment approach

2.1 Data Collection

The first step in wind resource assessment with regards to this project is obtaining offshore wind data. The data includes wind speed and wind direction for the three locations highlighted above for five years each - 2013 to 2017. Consequently, the offshore wind data used in this work were obtained from the Nigerian Meteorological Agency (NIMET) through their branch office at Port Harcourt International Airport Omagwa. Details of the locations are as follows:

Lagos Station
Coordinates: Latitude 06.26°N, Longitude 03.25°E
Height: 2.0m above sea level
Distance: 100m away from shoreline

Onne Station
Coordinates: Latitude 04.65°N, Longitude 07.15°E
Height: 2.0m above sea level
Distance: 100m away from shoreline

Warri port station
Coordinates: Latitude 05.13°N, Longitude 05.44°E
Height: 6.0m above sea level
Distance: 150m away from shoreline

Wind vane and cup anemometer were used to measure wind direction and wind speed respectively for the three target areas.

2.2 Wind Data Analysis

Wind data analysis is the major task in this research having obtained the data. There are several mathematical functions available for wind data analysis such as the normal, lognormal, Rayleigh and Weibull distribution functions. Weibull distribution function is commonly and frequently used in most wind data analysis because it is suitable for wind energy assessment and gives a better fit for measured probability density distributions when compared to other mathematical functions [10]. Hence, in this present work Weibull distribution function was used. In Weibull distribution, the probability density function (pdf) and its corresponding cumulative distribution function (cdf) are used to characterize the variation in the wind velocity. The probability density function, denoted as $f(V)$ indicates the probability of the wind at a given velocity V while the cumulative distribution function, denoted as$F(V)$, gives the probability that the wind velocity is equal to or lower than the velocity V or within a specified wind speed range [10]. These functions are given by Equations (1) and (2) respectively,

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

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

Where k is shape factor (-) and c is scale factor (m/s).

The two parameter Weibull distribution function is widely used and also it is a recommended distribution function for any wind data analysis [8], [10]. They are the shape factor, k (-) and the scale factor, c (m/s). There are several methods of estimating k and c but standard deviation method was used as presented in Equations (3) and (4), [10]

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

$$c = \frac{V_m}{\Gamma\left(1+\frac{1}{k}\right)} \quad (4)$$

where $\Gamma(x)$ is gamma function, V_m is mean speed/velocity (m/s) and σ is standard deviation which are defined as,

$$\Gamma(x) = \int_0^{\infty} t^{x-1} e^{-t} dt \quad (5)$$

$$V_m = \frac{\sum_{i=1}^{N} V_i}{N} \quad (6)$$

$$\sigma = \left(\frac{\sum_{i=1}^{N}(V_i - V_m)^2}{N-1}\right)^{\frac{1}{2}} \quad (7)$$

Where N is the count of data points. In addition to mean wind speed, V_m, the most probable wind speed, V_F and the wind speed carrying maximum energy, i.e. the optimum wind speed, V_E are two other relevant wind speeds for the estimation of wind energy. The most probable wind speed is given as [17],

$$V_F = c\left(\frac{k-1}{k}\right)^{\frac{1}{k}} \quad (8)$$

The optimum wind speed on the other hand is expressed as, [18]

$$V_E = c\left(\frac{k+2}{k}\right)^{\frac{1}{k}} \quad (9)$$

For extrapolation purposes, i.e. when the wind data is obtained at a height distinct from the wind turbine hub height (wind speed at hub height is mandatory for wind power usage), the following power law equations is used [17],

$$\frac{V_h}{V_{h_o}} = \left(\frac{h}{h_o}\right)^{\alpha} \quad (10)$$

In most cases α is assumed to be equal to 0.1429 and this value was adopted in this work.

Furthermore, the mean wind power $P_m(V)$, mean wind power density P_{D_m}, and mean energy density E_{D_m} are calculated as thus as,

$$P_m(V) = \frac{\rho A V_m^3}{2} \quad (11)$$

$$P_{D_m} = \frac{P_m(V)}{A} = \frac{\rho V_m^3}{2} \quad (12)$$

$$E_{D_m} = P_{D_m} t = \frac{\rho V_m^3}{2} t \quad (13)$$

Where ρ, A and t represent density of air (kg/m3), swept area of the rotor blades (m^2) and time (seconds) respectively. The density of air is a function of the atmospheric pressure p, temperature T and gas constant given y Equation (14),

$$\rho = \frac{P}{RT} \tag{14}$$

The mean power output $P_{e,ave}$ and the conversion efficiency or capacity factor of a turbine C_f is used to examine the performance of a wind turbine installed in a given site over a time period. The mean power output is the product of the rated power P_{eR} and the capacity factor given as,

$$P_{e,ave} = P_{eR}C_f \tag{15}$$

The capacity factor is expressed as [17],

$$C_f = \left(\frac{e^{-\left(\frac{V_c}{c}\right)^k} - e^{-\left(\frac{V_r}{c}\right)^k}}{\left(\frac{V_r}{c}\right)^k - \left(\frac{V_c}{c}\right)^k} - e^{-\left(\frac{V_f}{c}\right)^k} \right) \tag{16}$$

Where V_c is the cut-in wind speed of the wind turbine, V_f is cut-off wind speed of the wind turbine and V_r is rated wind speed of the wind turbine.

2.3 Wind Turbine Selection

Wind turbine is selected for a given area based on the wind characteristics. The mean power output and the conversion efficiency are two performance parameters of the turbine. These parameters depend on the rated power, cut-in wind speed and speed cut-off wind. The number of turbines to be installed depends on the power requirement of the offshore platform

2.4 Economics of Offshore Wind Turbine Operation in Comparison to Gas Turbines

Offshore wind energy conversion is the most costly means of generating electricity today [19]. Most offshore oil and gas platforms make use of gas turbines as means of producing power for their operations. The cost of operating gas turbines is very high because of the fuel cost in addition to the maintenance cost. The cost of maintaining wind turbines is much lower. Also, gas turbines come with environmental pollution issues. There is thus need to compare the economics of wind turbine operation compared to the usage of gas turbines. The net present value (NPV) of the operation of both systems considering 20 years period will be considered here. A frame 6 gas turbine engine (Model: PG 6581 B) which analyzed in [20] will be used in this work. The pressure ratio of the turbine is 12.7, the power output is 35.52 MW while the fuel flow rate is 2.13 kg/s. The number of wind turbine units n_t to be installed to meet the power output will be,

$$n_t = \frac{P_{req}}{P_{e,ave}} \tag{17}$$

where P_{req} is the require power output (35.52 MW in this case).

The NPV of the wind turbine operation can be expressed as,

$$NPV = \sum_{i=1}^{n} \frac{NACF_i}{(1+r)^i} - IC \tag{18}$$

where $NACF_i$ is the net annual cash flow , IC is the installation cost and r is the interest rate. The net annual cash flow is expressed as,

$$NACF_i = AR_i - AC_i \tag{19}$$

where AR_i is the annual revenue (which comes from the sale of electricity if the electricity produced is assumed to be sold) and AC_i is the annual operating cost. The annual operating cost comes in the form of operation and maintenance (O&M) cost. The cost of installation of off-shore wind turbine varies and in the range USD 3300 to USD 5000/kW [19], but values as high as USD 6000/kW has been quoted [20]. The generation or fixed operation and maintenance cost is varies between 15 to 45 €/MWh (USD 17/MWh to USD 51/MWh) [21]. USD 4500/kW was used as the installation cost while USD 40/MWh was used as the O&M cost for the NPV analysis considering a period of 20 years and the results were compared to those obtained for the gas turbine plant analyzed in [22]. The wind turbine selected for Lagos with rated power output of 3 MW was used for the economic analysis. It was assumed that the turbine produced the rated power continuously for the period under study. This is to create level platform for comparing the results from the two power sources.

3. RESULTS AND DISCUSSIONS

The annual pdf and cdf for the three locations considered in this work using the Weibull distribution function for fives period are shown in Figures 2, 3 and 4.

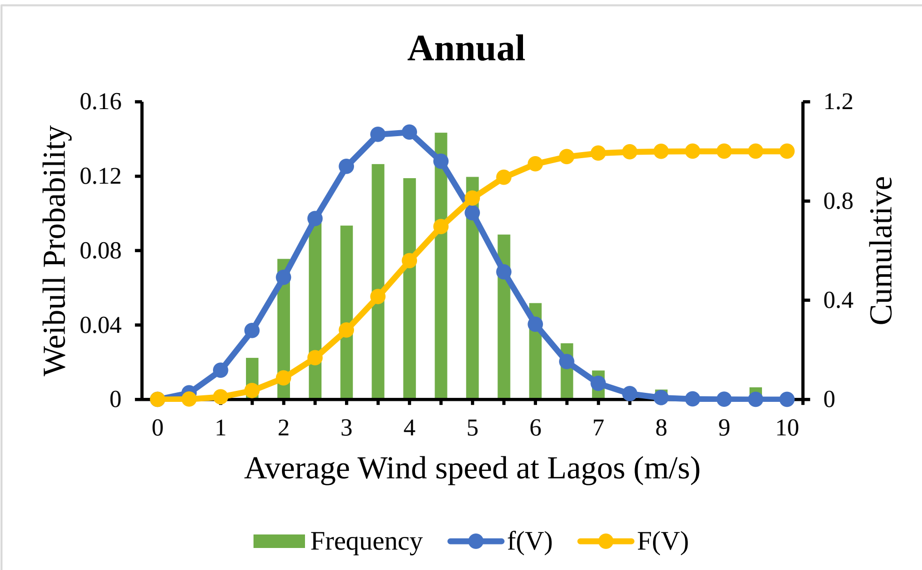

Figure 2: Weibull probability density function curve, cumulative distribution function curve and wind speed frequency in Lagos at height of 2m

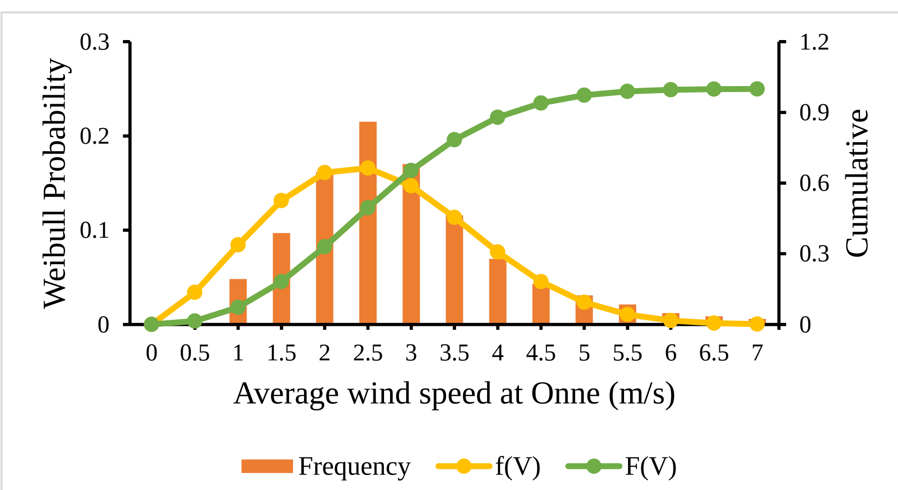

Figure 3: Weibull probability density function curve, cumulative distribution function curve and wind speed frequency in Onne at height of 2m

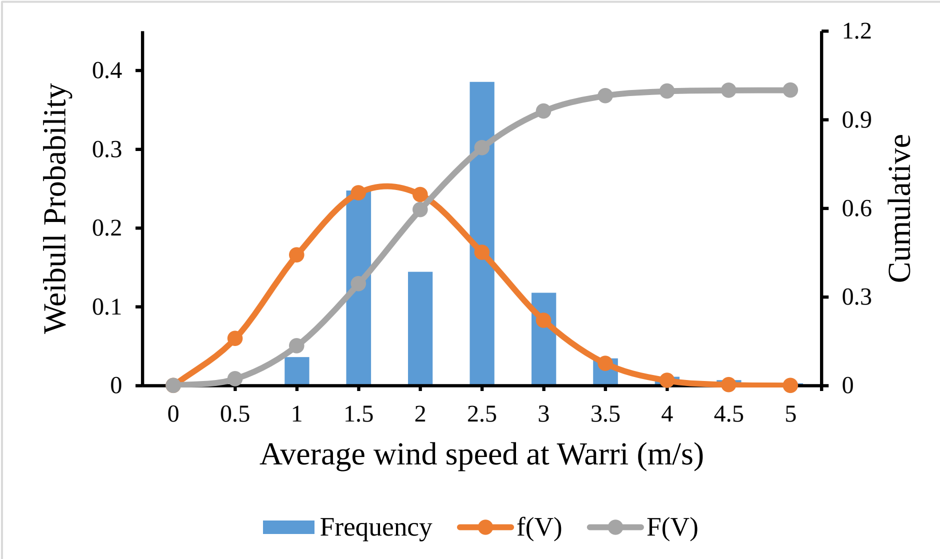

Figure 4: Weibull probability density function curve, cumulative distribution function curve and wind speed frequency in Warri at height of 6m

The Weibull probability density function is used to determine the wind speed that occurs more often within a specified location. At Lagos, the V_m bin of 4 m/s has the highest probability value of 0.14 as shown in Figure 2. Hence, the annual V_m, 3.82 m/s and the V_F, 3.77 m/s at Lagos falls within that wind speed bin of 4m/s. However, the V_E, 4.99 m/s falls outside the bin that has the highest probability.. Moreover, the annual V_m bin with the highest frequency is 4.5m/s. From Figure 3, it could be observed that, for Onne, the annual V_m, 2.6m/s falls within the wind speed bin of 2.5m/s and 3m/s with probability of 0.17 and 0.15 respectively while the annual V_F, 2.31m/s falls within the wind speed bin of 2 m/s and 2.5 m/s with probability of 0.16 and 0.17 respectively. The annual V_E for Onne, 3.82 m/s falls close to the wind speed bin of 4 m/s with the probability of 0.08. Also, it can be noticed that the wind speed bin of 2.5m/s has the highest frequency. Figure 4, both the annual V_m and V_F, 1.85 m/s and 1.65 m/s respectively at Warri fall within the wind speed boundaries of 1.5 m/s and 2 m/s with probabilities of approximately 0.25 and 0.15 respectively. The annual V_E at Warri, 2.69 m/s is in-between the wind speed bin of 2.5 m/s and 3m/s with probabilities of approximately 0.17 and 0.08 respectively. The wind speed bin with the highest frequency is 2.5 m/s.On the other hand, within a specified wind speed interval, the CDF could be used to quantify the time of a particular wind speed. From the Figures 2, 3 and 4 it can be deduced that Lagos, Onne and Warri will have wind speed frequencies of 99.9%, 98.6% and 97.7% respectively for wind speeds greater than or equal to 2 m/s. In turn, for wind speeds greater than or equal to 3m/s, the wind speed frequencies for Lagos, Onne and Warri will be 99.0%, 92.7% and 86.5% respectively.

The monthly mean wind speed Vm with its respective c, k, VF, VE, PD and ED for the three target areas at both their respective measured and hub heights were obtained as shown from Tables 1 to 6.

Table1: Mean wind speed, most probable wind speed, optimum wind speed, wind power density, energy density, scale and shape parameter values in Lagos at height of 2m

Month	V_m (m/s)	k (-)	c (m/s)	V_F (m/s)	V_E (m/s)	P_D (W/m^2)	E_D (kWh/m^2)
Jan	3.70	2.83	4.15	3.56	5.02	45.05	32.438
Feb	3.74	2.71	4.21	3.55	5.15	47.80	34.416
Mar	3.96	3.16	4.42	3.92	5.16	51.81	37.305
Apr	3.83	2.78	4.30	3.67	5.23	50.58	36.419
May	3.66	3.13	4.09	3.61	4.79	41.14	29.619
Jun	3.60	3.17	4.03	3.57	4.70	39.09	28.146
Jul	4.36	3.65	4.84	4.43	5.46	65.07	46.847
Aug	4.67	3.64	5.18	4.75	5.85	80.06	57.640
Sep	4.02	4.09	4.43	4.14	4.88	48.69	35.060
Oct	3.62	2.96	4.06	3.53	4.83	41.15	29.626
Nov	3.29	3.37	3.66	3.30	4.21	28.87	20.786
Dec	3.34	2.67	3.75	3.15	4.63	34.26	24.666
Annual	3.82	3.18	4.26	3.77	4.99	47.80	34.414

Table 2: Mean wind speed, most probable wind speed, optimum wind speed, wind power density, energy density, scale and shape parameter values in Lagos at hub height of 80m

Month	V_m (m/s)	k (-)	c (m/s)	V_F (m/s)	V_E (m/s)	P_D (W/m^2)	E_D (kWh/m^2)
Jan	8.43	3.96	12.54	8.20	10.48	1111.69	800.416
Feb	8.50	3.79	12.63	8.19	10.69	1147.11	825.923
Mar	8.85	4.42	13.02	8.79	10.70	1222.56	880.244
Apr	8.64	3.89	12.81	8.38	10.80	1189.97	856.779
May	8.36	4.37	12.42	8.29	10.14	1062.72	765.157
Jun	8.27	4.43	12.30	8.22	10.00	1031.90	742.967
Jul	9.49	5.10	13.75	9.59	11.13	1419.81	1022.263
Aug	9.97	5.09	14.33	10.08	11.70	1608.61	1158.199
Sep	8.95	5.72	13.03	9.13	10.28	1202.87	866.069
Oct	8.30	4.13	12.36	8.15	10.20	1057.25	761.219
Nov	7.75	4.71	11.62	7.77	9.24	864.22	622.236
Dec	7.83	3.73	11.79	7.51	9.89	936.92	674.583
Annual	8.63	4.49	12.73	8.55	10.43	1158.54	834.149

Table 3: Mean wind speed, most probable wind speed, optimum wind speed, wind power density, energy density, scale and shape parameter values in Onne at height of 2m

Month	V_m (m/s)	k (-)	c (m/s)	V_F (m/s)	V_E (m/s)	P_D (W/m^2)	E_D (kWh/m^2)
Jan	2.25	1.97	2.54	1.78	3.62	13.56	9.761
Feb	2.55	1.87	2.87	1.91	4.23	20.70	14.902
Mar	2.46	2.52	2.78	2.27	3.50	14.38	10.350
Apr	2.32	3.01	2.60	2.27	3.08	10.75	7.737
May	2.38	2.80	2.68	2.29	3.24	12.10	8.714
Jun	2.67	2.26	3.01	2.33	3.99	19.92	14.342
Jul	2.94	2.16	3.32	2.49	4.49	27.56	19.845
Aug	3.36	2.40	3.79	3.03	4.89	37.90	27.291
Sep	2.96	2.67	3.33	2.79	4.10	23.88	17.192
Oct	2.39	2.46	2.70	2.18	3.44	13.42	9.661
Nov	2.58	2.46	2.91	2.35	3.70	16.79	12.086
Dec	2.33	2.22	2.64	2.01	3.52	13.49	9.715
Annual	2.60	2.40	2.93	2.31	3.82	18.70	13.466

Table 4: Mean wind speed, most probable wind speed, optimum wind speed, wind power density, energy density, scale and shape parameter values in Onne at hub height of 80m

Month	V_m (m/s)	k (-)	c (m/s)	V_F (m/s)	V_E (m/s)	P_D (W/m^2)	E_D (kWh/m^2)
Jan	5.91	2.76	9.32	4.98	8.31	516.70	372.026
Feb	6.45	2.62	10.03	5.25	9.28	662.06	476.684
Mar	6.30	3.51	9.83	5.94	8.11	551.47	397.061
Apr	6.04	4.20	9.45	5.95	7.39	471.48	339.464
May	6.15	3.92	9.62	5.97	7.67	502.93	362.111
Jun	6.68	3.15	10.34	6.05	8.90	662.87	477.265
Jul	7.15	3.02	10.95	6.35	9.69	801.86	577.340
Aug	7.87	3.35	11.87	7.31	10.29	983.82	708.352
Sep	7.18	3.73	10.97	6.89	9.08	753.63	542.614
Oct	6.17	3.43	9.67	5.77	8.00	527.59	379.866
Nov	6.51	3.44	10.12	6.10	8.44	604.04	434.906
Dec	6.06	3.11	9.53	5.46	8.13	523.18	376.689
Annual	6.60	3.41	10.22	6.09	8.63	640.45	461.123

Table 5: Mean wind speed, most probable wind speed, optimum wind speed, wind power density, energy density, scale and shape parameter values in Warri at height of 6m

Month	V_m (m/s)	k (-)	c (m/s)	V_F (m/s)	V_E (m/s)	P_D (W/m^2)	E_D (kWh/m^2)
Jan	1.96	2.06	2.21	1.60	3.08	8.59	6.187
Feb	1.93	3.23	2.15	1.92	2.50	5.93	4.266
Mar	2.08	3.56	2.31	2.10	2.61	7.08	5.098
Apr	2.04	3.20	2.27	2.02	2.65	7.02	5.057
May	1.79	3.31	2.00	1.79	2.31	4.72	3.395
Jun	1.74	3.45	1.93	1.75	2.20	4.19	3.016
Jul	1.87	1.50	2.08	0.99	3.66	11.01	7.927
Aug	1.72	2.77	1.93	1.64	2.34	4.55	3.276
Sep	1.68	2.13	1.90	1.41	2.60	5.26	3.785
Oct	1.83	2.06	2.06	1.49	2.87	6.95	5.000
Nov	1.80	2.28	2.03	1.58	2.67	6.01	4.331
Dec	1.82	2.20	2.05	1.56	2.75	6.41	4.614
Annual	1.85	2.65	2.08	1.65	2.69	6.48	4.663

Table 6: Mean wind speed, most probable wind speed, optimum wind speed, wind power density, energy density, scale and shape parameter values in Warri at hub height of 80m

Month	V_m (m/s)	k (-)	c (m/s)	V_F (m/s)	V_E (m/s)	P_D (W/m^2)	E_D (kWh/m^2)
Jan	5.37	2.88	8.64	4.65	7.42	402.09	289.508
Feb	5.30	4.52	8.49	5.29	6.01	337.96	243.330
Mar	5.59	4.99	8.85	5.64	6.59	379.36	273.142
Apr	5.52	4.48	8.78	5.49	6.65	374.03	269.303
May	5.04	4.64	8.12	5.04	6.03	295.30	212.615
Jun	4.92	4.83	7.95	4.95	5.84	276.02	198.731
Jul	5.20	2.09	8.31	3.30	8.39	445.97	321.096
Aug	4.88	3.88	7.95	4.73	6.10	284.14	204.583
Sep	4.81	2.97	7.88	4.24	6.56	300.56	216.401
Oct	5.11	2.88	8.28	4.42	7.05	353.86	254.780
Nov	5.05	3.20	8.19	4.60	6.70	328.81	236.741
Dec	5.08	3.08	8.25	4.55	6.84	339.98	244.788
Annual	5.14	3.78	8.28	4.75	6.61	337.82	243.228

The monthly and annual values of the Vm, V_E, V_F, P_D and E_D with their respective k and c values for the three target locations: Lagos, Onne and Warri, at the measured heights of 2 m, 2 m and 6 m respectively, and at the hub heights of 80 m (for the three locations) are shown in Tables 1to 6. From Tables 1 and 2, the monthly Vm at both the measured height, 2 m and hub height, 80 m in Lagos have its highest value, 4.67 m/s (at 2 m) and 9.97 m/s (at 80 m), in the month of August and its lowest value, 3.29 m/s (at 2 m) and 7.75 m/s (at 80 m), in the month of November. The highest value of the monthly Vm in Onne at the measured height and hub height are 3.36 m/s and 7.87 m/s respectively experienced at the month of August while the lowest value, 2.25 m/s (at 2 m) and 5.91 m/s (at 80 m) is experienced in the month of January as shown in Tables 3 and 4. In Warri, at the measured height of 6 m, the highest monthly Vm is 2.08 m/s while the lowest monthly Vm is 1.68 m/s. At the hub height of 80 m, the highest monthly Vm is

5.59 m/s while the lowest monthly is 4.81 m/s. The months of March and September experiences the highest and lowest Vm, respectively at both the measured and hub height. At both the measured and hub height, Lagos has the highest annual Vm of 3.82 m/s and 8.63 m/s respectively. In addition, for the annual P_D and annual E_D, Lagos tops the chart with annual wind power density of 47.8 W/m^2 and 1158.54 W/m^2 at both the measured height and hub height respectively.

Based on the wind characteristics (V_m, P_D and E_D) of the target locations, wind turbines were carefully selected to give a C_P within the boundaries of 0.59. Table 7 shows the specification of the wind turbines selected while Tables 8, 9 and 10 shows the values of the C_P and C_f at each of the target locations at their respective hub heights.

Table 7: Specifications of selected wind turbines (The wind power, 2018)

Parameter	Vestas V90	Acciona AW1500	Enercon E-138 EP3
Rated Power (MW)	3	1.5	3
Hub Height (m)	80	80	80
Rotor diameter (m)	90	82	138.6
Cut-in wind speed (m/s)	3.5	3	2
Rated wind speed (m/s)	15	10.5	13
Cut-out wind speed (m/s)	25	20	25
Location	Lagos	Onne	Warri

Table 8: Capacity factor, power coefficient and wind power in Lagos at hub height of 80m

Month	P_D (W/m^2)	P (MW)	P_e (MW)	E_D (KWh/m^2)	$P_{e,ave}$ (MW)	C_f	C_P
Jan	1111.69	7.07	4.17	800.42	1.28	0.43	0.42
Feb	1147.11	7.30	4.31	825.92	1.33	0.44	0.41
Mar	1222.56	7.78	4.59	880.24	1.35	0.45	0.39
Apr	1189.97	7.57	4.47	856.78	1.36	0.45	0.40
May	1062.72	6.76	3.99	765.16	1.18	0.39	0.44
Jun	1031.90	6.56	3.87	742.97	1.13	0.38	0.46
Jul	1419.81	9.03	5.33	1022.26	1.52	0.51	0.33
Aug	1608.61	10.23	6.04	1158.20	1.70	0.57	0.29
Sep	1202.87	7.65	4.51	866.07	1.20	0.40	0.39
Oct	1057.25	6.73	3.97	761.22	1.20	0.40	0.45
Nov	864.22	5.50	3.24	622.24	0.87	0.29	0.55
Dec	936.92	5.96	3.52	674.58	1.11	0.37	0.50
Annual	1158.54	7.37	4.35	834.15	1.27	0.42	0.42

Table 9: Capacity factor, power coefficient and wind power in Onne at hub height of 80m

Month	P_D (W/m^2)	P (MW)	P_e (MW)	E_D (KWh/m^2)	$P_{e,ave}$ (MW)	C_f	C_P
Jan	516.70	2.73	1.62	372.03	0.79	0.53	0.55
Feb	662.06	3.50	2.07	476.68	0.87	0.58	0.43
Mar	551.47	2.91	1.73	397.06	0.85	0.56	0.52
Apr	471.48	2.49	1.48	339.46	0.76	0.50	0.60
May	502.93	2.66	1.57	362.11	0.80	0.53	0.56
Jun	662.87	3.50	2.07	477.27	0.92	0.61	0.43
Jul	801.86	4.23	2.51	577.34	0.98	0.66	0.35
Aug	983.82	5.20	3.08	708.35	1.09	0.72	0.29
Sep	753.63	3.98	2.36	542.61	1.01	0.67	0.38
Oct	527.59	2.79	1.65	379.87	0.82	0.55	0.54
Nov	604.04	3.19	1.89	434.91	0.89	0.59	0.47
Dec	523.18	2.76	1.64	376.69	0.81	0.54	0.54
Annual	640.45	3.38	2.00	461.12	0.89	0.59	0.47

Table 10: Capacity factor, power coefficient and wind power in Warri at hub height of 80m

Month	P_D (W/m^2)	P (MW)	P_e (MW)	E_D (KWh/m^2)	$P_{e,ave}$ (MW)	C_f	C_P
Jan	402.09	6.07	3.58	289.51	0.88	0.29	0.49
Feb	337.96	5.10	3.01	243.33	0.44	0.15	0.59
Mar	379.36	5.72	3.38	273.14	0.44	0.15	0.52
Apr	374.03	5.64	3.33	269.30	0.51	0.17	0.53
May	295.30	4.46	2.63	212.61	0.34	0.11	0.67
Jun	276.02	4.16	2.46	198.73	0.28	0.09	0.72
Jul	445.97	6.73	3.97	321.10	1.05	0.35	0.45
Aug	284.14	4.29	2.53	204.58	0.44	0.15	0.70
Sep	300.56	4.53	2.68	216.40	0.66	0.22	0.66
Oct	353.86	5.34	3.15	254.78	0.79	0.26	0.56
Nov	328.81	4.96	2.93	236.74	0.67	0.22	0.60
Dec	339.98	5.13	3.03	244.79	0.72	0.24	0.58
Annual	337.82	5.10	3.01	243.23	0.58	0.19	0.59

From Tables 8, 9 and 10, it can be observed that the values of the C_P and C_f for the target locations followed the same trend. At a particular location, the month that has the highest C_f corresponds to the lowest value of the C_P and vice versa. Lagos has an annual C_f of 0.42 with the month of August having the highest value of 0.57 and the month of November having the lowest value of 0.29. As for the C_P, Lagos has its highest value of 0.55 in the month of November while its lowest value of 0.29 occurred in the month of August with an annual mean value of 0.42. Generally, all the results obtained from this analysis imply that there are ample energy wind resources at these target locations to drive a wind turbine. Appropriate wind turbines are thus selected for each of the three locations as in table 7.

Table 11: Economic parameters of wind turbine operation

S/N	Parameter	Symbol	Unit	Value
1	Number of Turbines	n_t	-	12 / 28
2	Net Annual Cash Flow	NACF	Million $	14.78
3	Payback period	n_b	Yrs	10.81

Table 11 shows some of the economic parameters of the operation of offshore wind turbine. To produce 35.52 MW, 12 wind turbine units of 3MW rated capacity will be installed if the capacity factor is unity. An average capacity factor of 0.423 was estimated from Table 8 and used for this work. At this capacity factor, the power output from the 3MW rated turbine will be 1.27MW and the number of turbine units required to produce the required power all through the year 28. The net annual cash flow is USD 14.78 million. This value is much higher than that of the gas turbine operation which is USD 3.16 million [22]. The huge difference is because there is no fuel cost in wind turbine operation. The cash flow and the NPV of the operation of the offshore wind turbines are presented in Table 12. The cash flow and the NPV of the operation of the simple gas turbine cycle are shown in Table 13 for the purpose of comparison.

Table 12: Cash flow and NPV of offshore wind turbine operation

Parameter	YEAR										Total	NPV
	1	3	5	7	9	11	13	15	17	20		
Installed Cost (M$)	-159.84	0	0	0	0	0	0	0	0	0	-159.84	
NACF (M$)	14.78	14.78	14.78	14.78	14.78	14.78	14.78	14.78	14.78	14.78	295.60	
Discount factor at 11%	0.90	0.73	0.59	0.48	0.39	0.32	0.26	0.21	0.17	0.12		
Discounted NACF (M$)	13.32	10.81	8.77	7.12	5.78	4.69	3.81	3.09	2.51	1.83	117.70	- 42.14
Cumulative NACF	13.32	36.12	54.62	69.65	81.84	91.73	99.76	106.28	111.57	117.70		

Table 13: Cash flow and net present value of the simple cycle plant [22]

Parameter	YEAR										Total	NPV
	1	3	5	7	9	11	13	15	17	20		
Installed Cost (M$)	-22.38	0	0	0	0	0	0	0	0	0	-22.38	
NACF (M$)	3.16	3.16	3.16	3.16	3.16	3.16	3.16	3.16	3.16	3.16	63.18	
Discount factor at 11%	0.90	0.73	0.59	0.48	0.39	0.32	0.26	0.21	0.17	0.12		
Discounted NACF (M$)	2.85	2.31	1.87	1.52	1.23	1.00	0.81	0.66	0.54	0.39	25.15	2.78
Cumulative NACF	2.85	7.72	11.67	14.88	17.49	19.61	21.32	22.71	23.85	25.15		

The NPV of the wind turbine operation for a period of 20 years for 11 % interest rate is USD -42.14 million (but that of the gas turbine plant is USD 2.78 million). This means, the project is not yet yielding profit after 20 years at the given interest rate. This is due to the very high installation cost which is USD 159.84 million compared to that of the gas turbine plant which is USD 22.38. The wind turbine operation gives much higher value of net annual cash flow. Thus, if the interest rate is lower, which is the case in such capital intensive projects, the wind turbine operation will yield greater NPV with time. The NPV for different interest rates for both systems is shown in Figure 5. The NPV drops with the interest rate. The

NPV of the wind turbine system is greater than that of the gas turbine system at lower interest rates, becoming the same at about 5.62%. Lower interest rates thus favour the operation offshore wind system more than the gas turbine system because of the huge NACF associated with the offshore wind system.

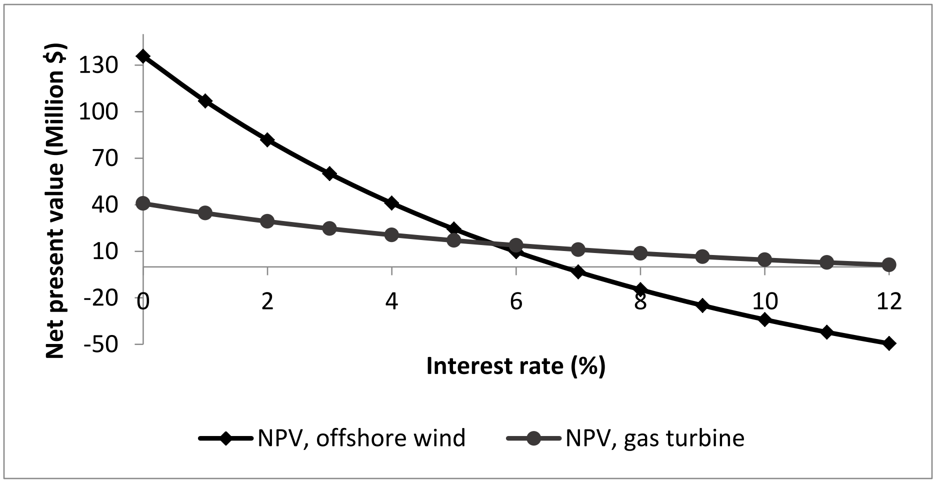

Figure 5: NPV at different interest rates of the offshore wind system and the gas turbine system.

5. Conclusion

In this research, the wind speed, wind power density and wind energy density in three target areas was investigated and significant findings were made from the analysis carried out. Annual mean wind speed in Lagos at both measured and hub heights were found to be greater than those at both Onne and Warri. The Weibull probability function suggests that there is prevalence of wind speed within the boundaries of the mean wind speed for each target location. In addition, the power density and energy density in Lagos are the highest compared to Onne and Warri. However, the wind characteristics of these three locations suggest that the wind speeds available are capable of driving a wind turbine and sufficient energy can be extracted from the available resources depending on the specifications of the wind turbine used. Using the Lagos location as a case study, 28 wind turbine units could be installed to produce 35.52 MW of electricity. The NPV of this project considering 20 years period and 11% interest rate is deficit and lower than a gas turbine plant that produces same amount of power. The NACF of the wind turbine system is much greater than the gas turbine system, hence gives higher NPV at interest rates less than 5.62%.

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