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Analysis of Wind Energy Potential in Kano Nigeria Using WindPRO: A Case Study of Kwankwasiyya City

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Abstract- **Proper assessment of wind energy potential is one of the critical factors in siting wind turbines as it helps in estimating the minimum power production expected from the site. This research evaluates the potentials of developing wind power for Kwankwasiyya city in Kano Nigeria (latitude 11.901° and longitude 8.5113°, elevation 478 m), by identifying the prevalent wind direction and the expected yearly energy to be captured. WindPRO was deployed for this analysis using Enercon wind turbine generator of 800kW capacity at hub height of 73m. The research uses monthly mean wind speed of Kano at 10m height from 2008 to 2014 found from METAR meteorological satellite data and then extrapolated it to 73m height. Results show the plot of wind rose, wind speed frequency distribution, the Weibull distribution and the energy rose. The energy rose shows that more than 750kWh/m^2/yr of power will be realised from west-south-west (WSW) direction when the wind speed is 10-15m/s. Annual Energy Production Probability of exceedance graph was plotted and the probability of producing power by the turbine at P50, P84, and P90 were estimated. The Uncertainty associated with the power production at P50 estimated results in a net annual energy production of 2,273 MWh/yr. the overall analysis indicates that Kwankwasiyya city may be viable for power generation using wind energy system.**

Key words: Wind Energy, wind turbine generator, prevalent wind direction, annual energy production

I. INTRODUCTION

Wind is a free natural resource that originates due to the movement of atmospheric air masses, as a result of atmospheric pressure variations. This in turn results in the uneven solar heating of different parts of the earth's surface [1]. The technological advancement in windmill design and production have made the generation of electricity through wind power more efficient in different part of the world. Several studies linked to the assessment of wind potentials in Nigeria show that the country has the potentials to generate electricity from wind energy. Quite a number of these studies conducted choose Kano as one of their research areas due to its strategic importance as well as its enormous wind potentials that put the state ahead of its peers. However, wind speed is specific even within the windiest areas and so assessment of the wind energy before siting is necessary in order to identify the most favourable location for the wind energy development. Therefore, this research finds it worthy to analyse the wind energy potential of Kwankwasiyya city, so that wind farm can be developed in form of decentralised system to cater for the energy requirement of the location. Kwankwasiyya city is a modern Housing estate situated in Kano state, Nigeria, having about 400 housing units. The estate is located along Zaria road, latitude 11.901° and longitude 8.5113° with an elevation 478 meters [2] few miles away from the central city of Kano. Figure 1 shows the geographical map of the location.

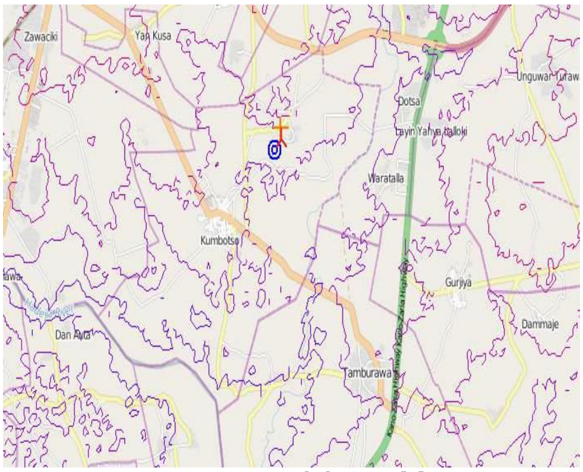

Figure 1: study location [2]

Some of the studies conducted on the wind speed related to Kano include the work of [3], which indicates that the coastal area of the country, the middle belt mountain terrains, the north inland hilly region, and the northern part of the country of which Kano is part, enjoy huge amount of wind annually. Another research by [4] shows that Kano with 20, 0389 m^2 area has approximately 90 % windy area (18350 m^2). [5] also conducted a fascinating study on wind resources in Nigeria in which the study compares wind speeds of different places in the country. The investigator reviews the wind potentials of 10 locations in the country with Kano being one of the study areas. A work by [6] reveals the wind data record of Kano measured at Oshodi meteorological department Lagos Nigeria. While wind speed is the major parameter in wind energy development, assessment of the location is vital before siting. Identification of prevalent wind direction over the year, expected annual energy production, problem associated with shadow flicker, noise (decibal), grid network, environmental effect and other factor must all be investigated.

Overall, it can be said that Kano is among the windiest area in the country, however, locations intended for wind power development requires further assessment as mentioned earlier so as to minimise risk associated with intermittency of the fuel source.

This research work is structured in five sections: Section 2 presents discussion on wind assessment and theoretical energy output. Section 3 talks about WindPRO simulation package. Section 4 reports the results of the simulation. Finally, section 5 provides conclusive remarks.

II. WIND ASSESSMENT

Wind assessment is among the most critical factors that affect wind power system design; any site without adequate wind regime will not be suitable for wind energy system. Site average wind speed determines the energy and power extractable by the wind turbines. As one of the meteorological variables, described by the motion of air masses in synoptic scale with potential and kinetic energies [7], wind has to be analysed in order to properly establish the viability of a site. With the advent of computer simulation software, wind assessment can be carried out to predict the power outputs, as well as the average mean speed of sites. The statistical analysis of wind speed gives an insight of how the wind varies with time and area. Probability estimations from available time series help to predict for extreme speeds and recurrence intervals [7]. Studies have shown that wind energy analysis mostly rely upon the arithmetic mean of the wind speed [7]. Weibull distribution is the most widely used function for modelling wind speed around the globe [8]. It is used to represent the wind speed relative frequencies. Weibull cumulative distribution function is represented statistically as [9]:

$$f(t) = \exp[-(v/c)^k] \qquad (1)$$

Where c = the scale parameter, a factor related to the annual mean wind speed, and 'k' is the dimensionless shape parameter, a factor that describes the variation about the mean.

The expression of the corresponding Weibull cumulative density function takes the form of y = mx + C [6] after applying basic rules of natural logarithm. The linear form is written as:

$$\ln\{-\ln[F(t)]\} = k\ln v - k\ln c \qquad (2)$$

Where: $\ln\{-\ln[F(t)]\} = y$; $k\ln v = mx$; $k\ln c = C$

The mean value of the wind speed v_m is established by applying differential and integral laws to the Weibull distribution (1) and the result is given as:

$$v_m = c\Gamma(1+1/k) \qquad (3)$$

Where: Γ represent gamma function expressed as:

$$\Gamma(x) = \int_0^\infty e^{-t} t^{x-1} dt = (n-1)! \qquad (4)$$

or

$$\Gamma(x) = (\sqrt{2\pi x})(x^{x-1})(e^{-x})[1 + (\frac{1}{12x}) + (\frac{1}{288x^2}) \qquad (5)$$

$$+ (\frac{1}{51840x^3}) + \ldots]$$

Weibull distribution served as a reference point for wind measurement as it gives an excellent overview of the wind speed variations in the hourly basis over a year for different wind directions and helps in predicting the recurrence interval. Ascertaining wind speeds probability of exceedance help in correctly forecasting and estimating the uncertainties of wind speed and the expected power output from wind development site. It provides a broader understanding of how energy yield varies with respect to time at a particular location. The method is very common and gives more physical result as it gives a holistic picture of how the wind varies with time. In the present days, simulation packages developed that uses Weibull principle helps in simulating wind of a site. WindPRO is simulation software that analyses wind regime and the expected annual energy production (AEP) of a site based on probability of exceedance.

A. Theoretical Turbine Power Output

One important aspect of wind power systems design is the estimation of energy from the moving wind by the turbines. The Wind turbines extract energy by slowing down the wind moving into the area swept by the blades of the turbine. The theoretical formula for estimating power output indicates that the wind power is proportional to the third power of the wind speed [9] as presented in (6) and the result was compared with that obtained from simulation.

$$P = \tfrac{1}{2}\rho A V^3 \qquad (6)$$

Where: ρ = density of air, A = swept area of the turbine, V = wind mean velocity, and P = available power.

The maximum theoretical value of the wind turbine performance coefficient is 0.593 known as the Betz limit. The theoretical available power in the moving wind given in (7) is unachievable by rotor due to wind velocity drop during energy extraction and some other losses. As a result, the actual extractable power by the rotor blades becomes the difference between upstream and the downstream wind powers. This relation is expressed as a function of the turbine power coefficient (C_p) as shown in (7).

$$P_o = \tfrac{1}{2}\rho A V^3 C_p \qquad (7)$$

Where: $C_P = [1 + v_1/v_2][1 - (v_1/v_2)^2] / 2 \qquad (8)$

P_o is the rotor expected power, and v_1 and v_2 representing upstream wind velocity at the rotor blades entrance and downstream wind velocity at exit of rotor blades respectively.

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III. SIMULATION

WindPRO is software used for modelling wind farms. It is a module-based software package suitable for wind project design (specifically designed for wind energy development), planning of large wind farms as well as single wind turbine generators (WTGs). Each module in the package carries out a particular task. The software package is flexible for users to combine modules depending on the system design demand. Fig. 2 shows the block diagram of the modules that made up the software package.

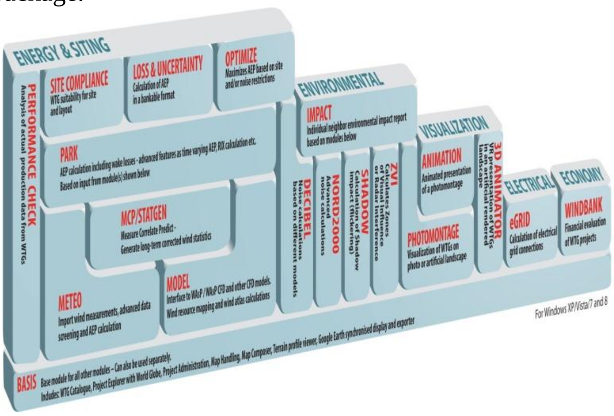

Fig. 2: Block Diagram of WindPRO Modules [2]

The modules are fully integrated to one another in a process that whenever there is a change in one of the modules input data, the effect will be recorded automatically on all other modules. Then the entire project calculations will be revised accordingly [2]. The inputs to the software depend upon the chosen modules, but, meteorological data (wind data) and wind turbine generator are required for energy output calculation. The wind meteorological data may be imported from a file or can be added online from meteorological stations. This research uses meteorological data from online meteorological station (METAR) and WindPRO analysed these data up the software package. Also, park module, and loss and uncertainty module are the two used in this study.

A. Study Location Wind speed

The mean wind speed of Kano from 2008 to 2014 was found from METAR meteorological satellite data. Fig. 3 shows the Mean wind speed at 10 m height.

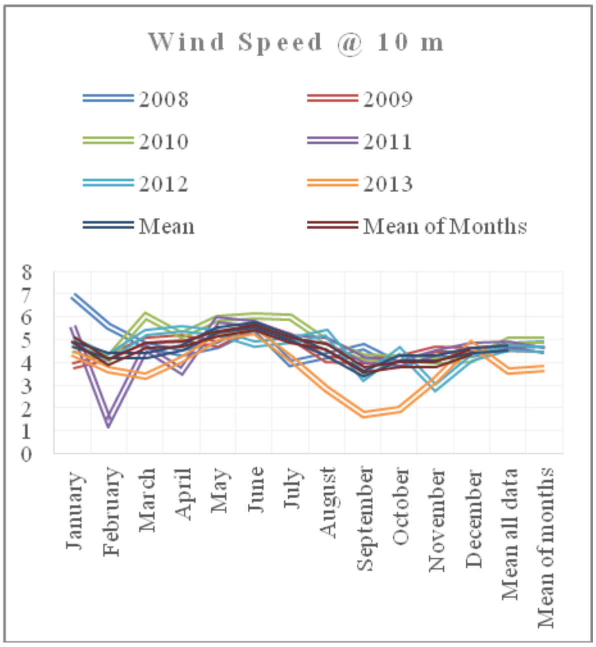

Fig. 3: Mean Wind Speed @10 m Height

The Wind speed of any location changes with the change in the hub height of measurement. When wind speed of a particular height is measured, then estimation of wind speed at another height can be done by extrapolation to obtain the desired wind speed at the hub height of interest. The expression commonly used in predicting the wind speed at another height is the power law, expressed mathematically as follow:

$$v_2/v_1 = (h_2/h_1)^{\alpha} \qquad (9)$$

Where: v_1 = mean wind speed at height h_1, v_2 = mean wind speed at height h_2 and α = exponential factor.

The value of the exponential factor (α) depends upon the characteristics of the location such as surface [10]; as such, 0.22 was used in this research.

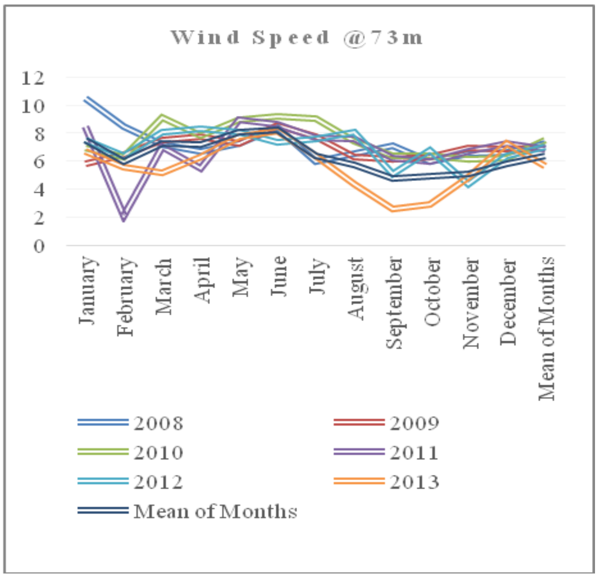

Fig. 4: Mean Wind Speed @70 m Height

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B. Turbine selection

The class of wind speed in a given site varies with the height of the wind speed measurement, because, as the height increases, the wind speed also increases. For this research, the site wind speed at 73 m height indicates that the location has an average mean wind speed of 7.05 m/s. This wind speed falls under low wind speed category of class III, and this classification is used in selecting the WTG (depicted in Table 1) for the site with Fig. 5 showing power curve.

Table 1: WTG Selection

Turbine name	Size (kW)	Number
ENERCON E-53	800	1

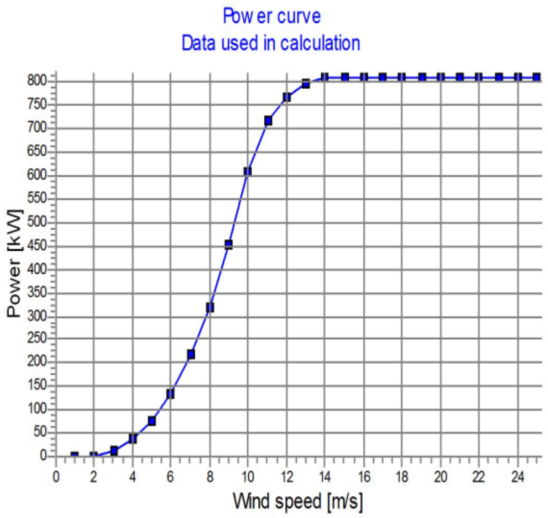

Fig. 5: power curve

IV. RESULTS AND DISCUSSION

WindPRO calculate annual energy output of the site by considering the available wind potential of that location. A broad analysis of the wind regime of the research area was conducted by giving details of the prevalent wind direction (wind rose), the Weibull distribution and the time series of the wind speed. The selected modules modelled the wind turbine selected and calculate annual energy production (AEP) as well as the loss and uncertainties in the AEP.

A. Wind speed assessment result

1) Weibull distribution

As discussed earlier, Weibull distribution gives an excellent overview of the wind speed variations for a given location. Here, the Weibull distribution of the site is as depicted in figure 6.

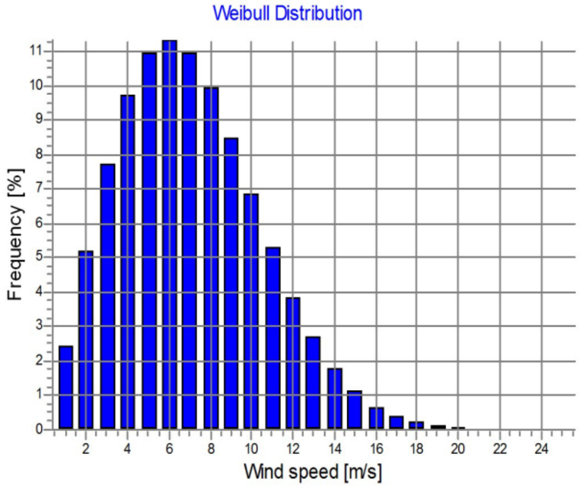

Fig. 6: Weibull Distribution

1) Wind speed frequency distribution

Fig. 7 shows the wind frequency distribution rose of the study site at height 73 m. The frequency distribution can be explained by considering the spoke and the colours that appeared in the rose.

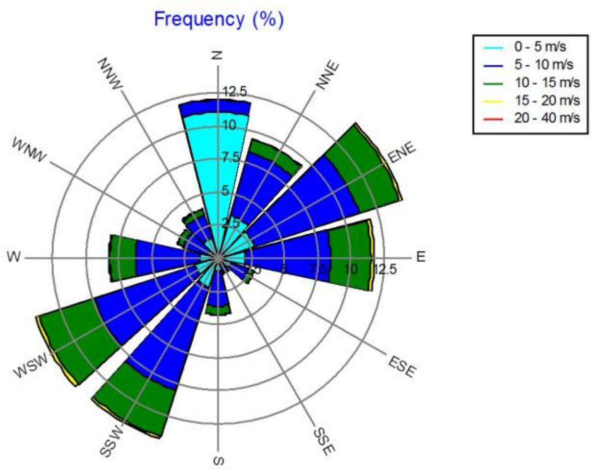

Fig. 7: Wind Speed Frequency Distribution Rose

The colours denote speeds of the wind whereas the spokes lengths display the frequency of occurrence per unit time. It can be seen that the wind blows for about 17.5 % from direction West-South-West (WSW) over the period of one year as depicted in fig. 7. Moreover, the wind blows from south-south-east (SSE) is 0m/s over the year; implying that no energy will be captured if wind turbine can be sited at the direction. Fig. 8 shows the mean wind speed of the site at different direction with the peak mean speed coming from west-south-west (WSW) direction.

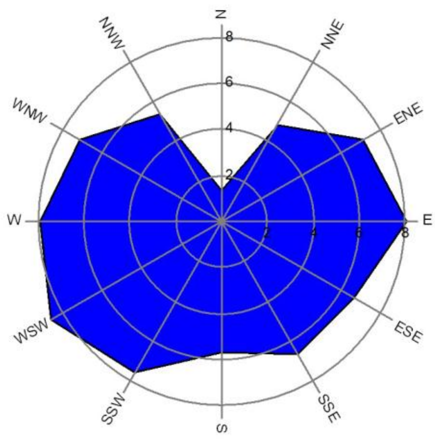

Fig. 8: Mean Wind Speed Rose

B. Energy Output Result

1. Annual energy production (AEP)

The annual energy production expected from the site is as depicted in Table 2. It can be seen that about a gross of 2,637.3 MWh/yr. may be produced at a capacity factor of 33.8 %. Although, it is far less than the theoretical Betz limit, however, the yield is of reasonable amount and far better than what is obtainable in many wind farms.

Table 2: *Annual energy production*

WTG combination	Wind farm
Result PARK [MWh/y]	2,637.3
Result-10.0% Free WTGs [MWh]	2,373.6
GROSS (no loss) [MWh/y]	2,637.3
Park efficiency [%]	100.0
Capacity factor [%]	33.8
Mean WTG result [MWh/y]	2,373.6
Full load hours [Hours/year]	2,967
Mean wind speed @hub height [m/s]	7.1

The number of operational hours per year for each direction was estimated with their full load equivalent. East-North-East (ENE) sector has the highest operational hours per year of 1,256 and WSW sector represent the highest value for Full Load Equivalent, having 654 hours/year.

2. nergy rose

The energy rose displays the amount of energy that may be captured at different wind speed and direction from the location over a year. Figure 9 depicts the wind rose of the simulated WTG at the hub height of 73 m and average wind speed of 7.1 m/s.

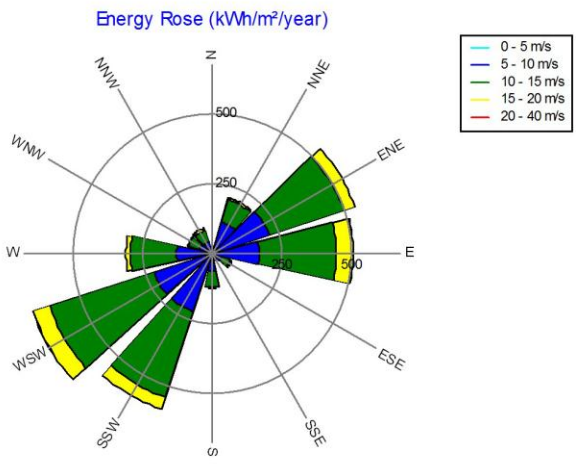

Figure 9: Energy Rose

A careful study of the energy rose shows that up to 750 $kWh/m^2/year$ of power will be realised from WSW direction when wind speed is 10-15 m/s at 73 m height; and from east (E) direction, about 500$kWh/m^2/yr$. is expected to be the yield.

3. Directional production analysis

The Directional production shown in Table 3 gives detail values of energy yield for different sector. It gives a more elaborate result than the wind rose, which only indicates the sector yield.

Table 3: Directional production analysis

Sector	**Resulting energy [MWh]**	**Specific energy [kWh/m²]**	**Specific energy [kWh/kW]**	**Utilization [%]**	**Operational [Hours/yr]**	**Full Load Equivalent [Hours/yr]**
N	**23.2**			45.8	1,033	29
NNE	**185.8**			42.3	810	232
ENE	**436.5**			38.6	1,256	546
E	**386.2**			36.3	1,017	483
ESE	**62.4**			40.0	250	78
SSE	**24.3**			42.4	104	30
S	**108.7**			42.2	370	136
SSW	**469.5**			38.2	1,236	587
WSW	**523.2**			37.0	1,251	654
W	**258.8**			39.8	711	323
WNW	**80.6**			42.3	284	101
NNW	**78.1**			38.6	340	98
Total	**2,637.3**	1,195	3,297	38.5	8,661	3,297

Furthermore, Fig. 10 depicts the annual energy yield per year per sector and the array losses expected.

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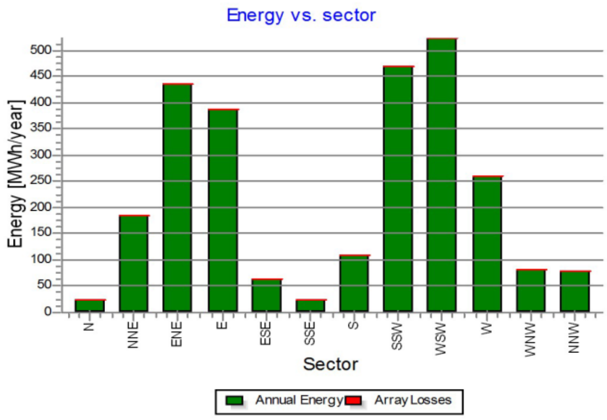

Fig. 10: Energy vs. sector

C. Loss and uncertainty

The most striking characteristic of the wind resource is its variability from the point of view of wind energy [9] and this poses a big risk and uncertainty for developers. Despite the fact that forecasting of wind regime improves all the time, but still no guarantee from wind farm developer that a location with a history of strong energy estimate can't underperform from time to time. So to minimise the risk, calculation of probabilities for energy production typically P50, P75, P84 and P90 probabilities are employed. Here in this study, P50, P84 and P90 probabilities were estimated as can be seen in the subsequent subsections.

1) Probability of exceedance

Fig. 11 shows the annual energy production probability of exceedance curve of the site.

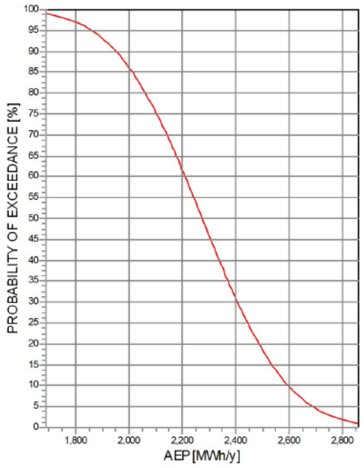

Fig. 11: AEP Probability of exceedance graph

Table 4 shows the AEP versus exceedance level over the assumed time horizon the WTG is expected to operate. WindPRO provides the simulation result at an interval for 1yr., 5yrs, 10yrs., and 20yrs.

Table 4: AEP versus exceedance level / time horizon

PXX [%]	1 yr. [MWh/yr]	5 yrs. [MWh/yr]	10 yrs [MWh/yr]	20 yrs. [MWh/yr]
50	2,273	2,273	2,273	2,273
75	2,053	2,094	2,100	2,103
84	1,949	2,009	2,018	2,022
90	1,855	1,933	1,944	1,950
95	1,737	1,837	1,851	1,859

It can be seen that P50 result represents level of energy production estimated to exceed 50% of the year; meaning half of the year production will exceed 50 % and the other half falls below this level (50:50). As the Pxx value increases towards P100 the estimate becomes more conservative because it comes with lower level of risk which an investor normally prefers. For instance, a P90 value indicates that 90 % of the time in a year the energy output will be exceeded thereby gives a more reliable estimate to meet the performance target of the site. The interpretation of P75, P84, and P95 likewise follows the same manner as P90.

Table 5 depicts the results of net AEP, capacity factor, and full load hours for P50, P84, and P90.

Table 5: AEP Probability of exceedance

Results		P50	P84	P90
NET AEP	[MWh/yr.]	2,273	2,022	1,950
Capacity factor	[%]	32.4	28.9	27.8
Full load hours	h/yr.	2841	2528	2438

Although higher values of Pxx forecast a lower level of risk associated to wind project, however P50 represent the average AEP most likely to be achieved in a year. The gross and net AEP from the simulation is based on P50. Table 6 depicts the uncertainty connected P50, which produces a net AEP of 2,273 MWh/yr.

Table 6: P50 Uncertainty Result

	P50	Uncertainty	
GROSS AEP	2,637 MWh/yr	-1.6%	11.1%
Bias correction	-42 MWh/yr.	-12.4%	0.0%
Loss correction	-322 MWh/yr.	0.0%	0.0%
Wake loss		-12.4%	
Other losses			11.1%
NET AEP	2,273 MWh/yr		

2) Loss

WindPRO analyses the loss associated with wind energy development. Fig. 12 shows the simulation result associated to this research, having an overall loss of 12.4%. The loss is due to turbine performance, availability, curtailment, among others.

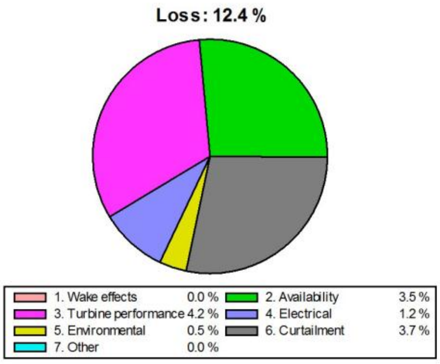

Fig. 12: Source of loss

D. *Theoretical and Simulated Power Output*

The theoretical power output of the site at 73 m height has been calculated based on the Betz limit using the following variables: A (swept area of the chosen turbine), ρ=1.223 kg/m^3 having a total power output of 2,753,266.48 kWh/yr. Fig. 13 shows the chart of the monthly expected output energy.

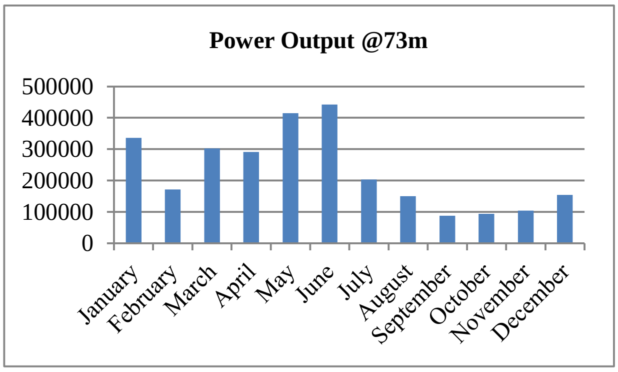

Fig. 13: power output based on Betz limit

Comparing the theoretical output power to the gross output of the simulated result, there is a difference of 2.91 % when P50 is considered. Similarly, the total output from the theory shows a difference of about 17.4% higher when compared to the net AEP simulation result value for P50. This drop is because, in practice, the extractable power by the rotor is less than the Betz limit due to electrical losses, mechanical losses, and aerodynamic losses (0.2 <C_P< 0.5) [11]. However, the capacity factor from the simulation result indicates a good wind regime even though, it is less than the Betz limit.

V. CONCLUSION

A methodical analysis of the wind speed and the expected annual energy production has been carefully conducted. The directions with the prevailing wind speed have been identified. The expected power out from the site was estimated and compared with the theoretical calculations. The Pxx values were presented and analysed. From the results of presented, the research deduce that the site may be suitable for power generation; and recommends that it is important to consider the direction of prevailing wind speed when siting a turbine in this location in order to maximize the energy output from the turbine generator.

VI. ACKNOWLEDGEMENT

I will like to appreciate and acknowledge the effort of Kingston University London for providing the WindPRO software and an enabling environment to carry out this research.

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