Original research paper

A STATISTICAL APPROACH TO ESTIMATE WIND SPEED DISTRIBUTION IN IBADAN, NIGERIA.

ABSTRACT

In this paper, the wind energy potential in Ibadan (Lat. 7.43^0N; Long. 3.9^0E; Alt. 227.2 m) and (7.38 ^{o}N, 3.98 ^{o}E) is statistically analyzed using daily wind speed data for 10 years (1995-2004) obtained from the International Institute of Tropical Agriculture (IITA) and 1 year (2006) obtained from Nigeria Micro-scale Experimental (NIMEX) Ibadan, Nigeria. The statistical wind data set was analyzed using Weibull distributions in order to investigate the Weibull shape and scale parameters. The daily, monthly, seasonal, and yearly wind speed probability density distributions are modeled using Weibull Distribution Function. The measured annual mean wind speed is 0.76 m/s and the total extractable wind power has been estimated as 0.33 kW at IITA while the annual mean wind speed ranges between 0.74 m/s, 1.02 m/s, 1.16 m/s and 1.34 m/s at (3m, 6m, 12m and 15m) respectively at NIMEX. The maximum extractable annual wind power density value of $0.90W/m^2$ for the whole year at IITA and $5.61W/m^2$ at the highest height of 15m at NIMEX indicates that, Ibadan can be classified as a low wind energy region and it belongs to the wind power class 1, since the density is less than $100W/m^2$ (Akpinar and Akpinar, 2004). It is concluded that at both sites, the highest wind speed that prevailed in Ibadan is in the month of March which corresponds to the work of Mayoub, (2006) and the location can be explored for wind power.

Keywords: Wind Energy, Renewable Energy, Wind Speed, Weibull Distribution, Wind Power, Fossil

1.0 INTRODUCTION

Wind speed is a random variable which is affected by lots of factors such as geometric shapes, roughness and elevation of ground surface. Therefore, the easiest and most direct method of obtaining wind speed distribution in different locations is to set up a measurement station at each location. Generally, the wind speed is characterized by a high variability both in space and time. It is therefore very important to describe the variation in wind speed for optimizing the design of the systems in order to reduce energy generating costs (Akpinar and Akpinar, 2005). In recent times, numerous studies have been carried out to access the wind speed characteristics and associated wind energy potentials in different part of the world (Mayhoub and Azzam, 1997).

Renewable energy sources have attracted increasing attention from all over the world due to their almost inexhaustible and non-polluting characteristics (Al-Buhairi, 2006). In Nigeria today, a great percentage of the general population reside in rural areas where they do not have access to the nation's electric power source. In view of this, people have resorted to migrating back to the urban areas, where they receive the benefits of such amenities.

The major source of electricity in Nigeria is hydropower, which is usually restricted to the generation of shaft power from falling water (Medugu and Malgwi, 2005). The Power Holding Company of Nigeria (PHCN) is charged with the responsibility of managing the nation's Hydroelectric Power (HEP) station across the River Niger in Kainji. However the company has been noted for unreliable power supply characterized by low voltage and incessant power cuts, often without warning or even apologies to consumers (Uchendu, 1993). The unreliability of this situation has led to search for a more viable energy source for Nigeria. The adoption of power generating sets has rather worsened the situation because it constitutes environmental noise and pollution.

Wind energy has been noted as an alternate source of energy that can be exploited to meet of the needs of Nigeria and other developing nations (Syed, 2004).

Wind energy as one of these important sources is perhaps the most suitable, most effective and inexpensive sources for electricity production. As a result it is vigorously pursued in many countries. In recent times, there has been a continual decline in supply of conventional energy due to the depletion of the national reserve while the demand increases every day. In statistical modeling of the wind speed variation, much consideration has been given to the Weibull two parameter (shape parameter k and scale parameter c) function because it has been found to fit a wide collection of wind data (Mayhoub and Azzam, 1997).

2.0 MATERIALS AND METHODS

The daily wind speed data used in this study were obtained from NIgeria Mesoscale Experimental (NIMEX) site, University of Ibadan (7.38^{0}N, 3.98^{0}E) for the period of one year (2006) and from International Institute of Tropical Agriculture, IITA (7.43^{0}N and 3.9^0 E), Ibadan, for the period of ten years (1995-2004). The wind speed data was measured continuously with a cup generator anemometer at a hub height of 3, 6, 12, 15 meters respectively at NIMEX site and 2 meters at IITA above the ground level. The daily mean speeds were computed as the average of the speeds for each day.

2.1 COMPUTATION OF WEIBULL PARAMETERS OF THE WIND SPEEED

In statistical analysis of wind speed variation, the Weibull two parameters (shape parameter k and scale parameter c) functions have been widely applied by many researchers. The probability density function of the Weibull distribution is given as (Akpinar and Akpinar, 2004):

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

where $f(v)$ is the probability of observing wind speed v, k is the dimensionless Weibull shape parameter and c is the Weibull scale parameter with units of speed ms^{-1}, which could be related to the average wind speed through the shape factor k, which describes the distribution of the wind speeds. The relationship between the Weibull scale factor c, and Weibull shape factor k and average wind speed v_m is given as (Akpinar and Akpinar, 2004):

$$v_m = c\Gamma\left(1+\frac{1}{k}\right) \tag{2}$$

where Γ is usual gamma function.

The parameter k and c may be estimated by the linear regression of the cumulative Weibull distribution given as (Akpinar and Akpinar, 2004):

$$F(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^k\right] \tag{3}$$

where $F(v)$ is cumulative Weibull distribution function.

2.2 ESTIMATION OF WIND POWER DENSITY

The available power in the wind flowing at mean speed v_m through a wind rotor blade with sweep area at any given site can be estimated as (Akpinar and Akpinar, 2004):

$$p(v) = \frac{1}{2}\rho A v^3{}_m \tag{4}$$

where $p(v)$ is the wind power (Watt) and ρ is the air density at site $=1.21 kgm^{-3}$, A is the swept area of the rotor blades m^{-2} , v_m is the wind speed at that location ms^{-1}

and the wind density (wind power per unit area) based on the weibull probability density function can be calculated as (Jaramillo and Borja, 2004):

$$p_w(v) = \frac{p(v)}{A} = \frac{1}{2}\rho v_m^3 \tag{5}$$

$$p_w(v) = \frac{1}{2}\rho c^3\left(1+\frac{3}{k}\right) \tag{6}$$

$$k = \left(\frac{\sigma}{v_m}\right)^{-1.068} \tag{7}$$

$p_w(v)$ is the wind power density Wm^{-2} and σ is the standard deviation.

According to (Justus, 1997) and

$$c = \frac{v_m}{\Gamma\left(1+\frac{1}{k}\right)} \quad (8)$$

3.0 RESULTS AND DISCUSSIONS

Results and Analysis

Figure 1 shows the daily mean wind speed variation in Ibadan over the period of 10 years from 1995-2004, while the yearly mean wind speed, standard deviation and power available are presented in Table 1. It can be seen in Table 1 that the highest yearly wind speeds occur in the year 1996 while the minimum occur in the 2002 as shown from Figure 1

The monthly variation of the wind speed is presented in Table 2. It is seen that the highest monthly wind speeds occur in the months of February (0.90 m/s), March (1.07 m/s), April (0.96 m/s) and May (0.88 m/s) for the whole year, while the minimum monthly wind speeds occur in the months of October (0.54 m/s) and November (0.56 m/s).

The monthly standard deviation, mean wind speed, Weibull distribution parameters, predicted wind power density, cumulative frequency and available power for the whole year are shown in Table 3. It can be seen that the shape parameter (k) varies between 1.94 and 3.69, while the scale parameter (c) ranges from 0.61 to 1.20 m/s. A high variation in shape parameter was observed compared with that of scale parameter.

Table 1: Yearly Mean Wind Speed, Standard Deviation and wind power in Ibadan between 1995 and 2004 (IITA).

Year	v_m	σ	P (kW)
1995	0.95	0.24	0.65
1996	1.21	0.23	1.35
1997	1.10	0.26	1.01
1998	0.92	0.42	0.59
1999	0.83	0.42	0.43
2000	0.81	0.36	0.40
2001	0.46	0.26	0.07
2002	0.40	0.26	0.05
2003	0.41	0.27	0.05
2004	0.53	0.23	0.11
Yearly	0.76	0.30	0.33

where V_m is mean wind speed and σ is the standard deviation.

Table2: Monthly and Yearly Wind Speed and Standard Deviation from 1995-2004 (IITA).

month	par	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	whole Yr
Jan	V_m	0.65	0.83	1.24	0.97	0.96	0.85	0.29	0.18	0.40	0.23	**0.66**
	σ	0.21	0.23	0.27	0.45	0.33	0.38	0.55	0.20	0.17	0.14	**0.29**
Feb	V_m	1.01	1.20	1.15	1.22	1.03	0.89	0.73	0.28	0.98	0.54	**0.90**
	σ	0.21	0.23	0.32	0.31	0.30	0.45	0.36	0.15	0.75	0.65	**0.37**
Mar	V_m	1.20	1.50	1.44	1.34	0.99	1.34	1.00	0.80	0.67	0.39	**1.07**
	σ	0.28	0.24	0.32	0.31	0.29	0.39	0.27	0.52	0.36	0.16	**0.31**
Apr	V_m	1.14	1.12	1.18	1.50	1.04	1.48	0.79	0.35	0.43	0.53	**0.96**
	σ	0.32	0.31	0.29	0.34	0.37	0.40	0.50	0.29	0.31	0.30	**0.34**
May	V_m	0.97	1.27	1.08	1.14	0.90	1.02	1.17	0.42	0.54	0.33	**0.88**
	σ	0.27	0.24	0.23	0.28	0.37	0.63	0.50	0.25	0.29	0.17	**0.32**
Jun	V_m	0.98	1.43	1.11	0.90	0.89	0.87	0.36	0.46	0.34	0.25	**0.76**
	σ	0.26	0.22	0.23	0.29	0.39	0.51	0.19	0.26	0.23	0.16	**0.27**
Jul	V_m	1.12	1.40	1.26	0.94	0.85	0.86	0.29	0.41	0.23	0.32	**0.77**
	σ	0.26	0.22	0.26	0.36	0.50	0.53	0.10	0.32	0.17	0.17	**0.29**
Aug	V_m	1.08	1.36	0.86	1.06	1.00	0.50	0.28	0.52	0.46	0.36	**0.75**
	σ	0.25	0.23	0.26	0.49	0.48	0.21	0.13	0.35	0.33	0.27	**0.30**
Sep	V_m	1.04	1.21	1.19	0.64	0.46	0.52	0.18	0.38	0.27	0.87	**0.68**
	σ	0.24	0.19	0.26	0.49	0.39	0.25	0.12	0.25	0.26	0.24	**0.27**
Oct	V_m	0.82	1.08	0.99	0.25	0.35	0.50	0.13	0.24	0.23	0.82	**0.54**
	σ	0.22	0.25	0.21	0.82	0.68	0.23	0.08	0.15	0.12	0.15	**0.29**
Nov	V_m	0.59	1.06	0.86	0.59	0.68	0.42	0.14	0.32	0.14	0.82	**0.56**
	σ	0.15	0.22	0.21	0.31	0.53	0.14	0.08	0.18	0.11	0.18	**0.21**
Dec	V_m	0.72	1.09	0.89	0.30	0.85	0.44	0.14	0.40	0.28	0.87	**0.60**
	σ	0.20	0.17	0.31	0.58	0.41	0.16	0.19	0.25	0.14	0.19	**0.26**
Year		**0.95**	**1.21**	**1.1**	**0.92**	**0.83**	**0.81**	**0.46**	**0.4**	**0.41**	**0.53**	**0.76**
		0.24	**0.23**	**0.26**	**0.42**	**0.42**	**0.36**	**0.26**	**0.26**	**0.27**	**0.23**	**0.3**

Table 3: Monthly Weibull Shape Parameter k, and Scale Parameter c, Mean Wind Speed, Power available and Power Density, 1995-2004 (IITA).

Month	σ	v_m	Scale Factor C	Shape Factor k	Power Density W/m^2, P	Available power (kW)
Jan	0.29	0.66	0.74	2.38	0.57	0.22
Feb	0.37	0.90	1.02	2.57	1.40	0.56
Mar	0.31	1.07	1.20	3.69	1.94	0.93
Apr	0.34	0.96	1.08	2.99	1.54	0.67
May	0.32	0.88	1.00	2.92	1.22	0.52
Jun	0.27	0.76	0.86	2.98	0.77	0.33
Jul	0.29	0.77	0.86	2.83	0.82	0.35
Aug	0.30	0.75	0.84	2.64	0.78	0.32
Sep	0.27	0.68	0.76	2.68	0.58	0.24
Oct	0.29	0.54	0.61	1.94	0.35	0.12
Nov	0.21	0.56	0.64	2.84	0.33	0.13
Dec	0.26	0.62	0.70	2.52	0.45	0.18
Total	0.30	0.76	0.86	2.75	0.90	0.33

Table 4: Seasonal Weibull Distribution Parameters, Mean Wind Speed, Wind Power Density and Power Available in Ibadan between 1995 and 2004 (IITA).

Season	*k*	c (m/s)	v_m	P (**W/m$^{2)}$**	P(kW)
Rainy	2.83	0.87	0.77	0.93	0.40
Dry	2.49	0.82	0.73	0.82	0.32
Whole Year	2.75	0.86	0.76	0.90	0.33

In order to determine the Weibull parameters for the seasonal mean wind speed, the months are divided into two seasons identified as follows:

(a) Rain season: March to November.

(b) Dry season: December to February

The mean wind speed predicted by the Weibull probability density function for rainy and dry seasons are 0.77 and 0.73 m/s, the power available are 0.40 and 0.32 kW, while the power density predicted are 0.93 and 0.82 Wm^{-2} respectively. The mean wind speed and power availability was slightly higher during the rainy season than the dry season.

Table 5: Monthly Probability density distribution of the measured wind speed from Weibull distribution function IITA

Month	v_m	f(v)
Jan	0.66	0.03
Feb	0.90	0.02
Mar	1.07	0.00
Apr	0.96	0.01
May	0.88	0.01
Jun	0.76	0.02
Jul	0.77	0.02
Aug	0.75	0.02
Sep	0.68	0.02
Oct	0.54	0.05
Nov	0.56	0.03
Dec	0.62	0.03
Total	0.76	0.02

Table 6: Yearly Probability Density Distribution of the Measured Wind Speed from Weibull Distribution Function IITA

Year	v_m	σ	Shape Factor k	Scale Factor c	f(v)
1995	0.945	0.239	4.340	0.768	0.085
1996	1.213	0.229	5.943	1.038	0.080
1997	1.103	0.265	4.588	0.905	0.084
1998	0.918	0.419	2.310	0.641	0.101
1999	0.834	0.420	2.079	0.563	0.104
2000	0.808	0.357	2.394	0.570	0.100
2001	0.458	0.256	1.863	0.298	0.108
2002	0.396	0.264	1.541	0.240	0.115
2003	0.413	0.270	1.578	0.253	0.114
2004	0.526	0.233	2.393	0.371	0.100
Total	0.762	0.295	2.752	0.559	0.096

Table 7: Monthly Wind Speed IITA.

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Jan	0.65	0.83	1.24	0.97	0.96	0.85	0.29	0.18	0.40	0.23
Feb	1.01	1.20	1.15	1.22	1.03	0.89	0.73	0.28	0.98	0.54
Mar	1.20	1.50	1.44	1.34	0.99	1.34	1.00	0.80	0.67	0.39
Apr	1.14	1.12	1.18	1.50	1.04	1.48	0.79	0.35	0.43	0.53
May	0.97	1.27	1.08	1.14	0.90	1.02	1.17	0.42	0.54	0.33
Jun	0.98	1.43	1.11	0.90	0.89	0.87	0.36	0.46	0.34	0.25
Jul	1.12	1.40	1.26	0.94	0.85	0.86	0.29	0.41	0.23	0.32
Aug	1.08	1.36	0.86	1.06	1.00	0.50	0.28	0.52	0.46	0.36
Sep	1.04	1.21	1.19	0.64	0.46	0.52	0.18	0.38	0.27	0.87
Oct	0.82	1.08	0.99	0.25	0.35	0.50	0.13	0.24	0.23	0.82
Nov	0.59	1.06	0.86	0.59	0.68	0.42	0.14	0.32	0.14	0.82
Dec	0.72	1.09	0.89	0.47	0.85	0.44	0.14	0.40	0.28	0.87
Yearly	**0.95**	**1.21**	**1.10**	**0.92**	**0.83**	**0.81**	**0.46**	**0.40**	**0.41**	**0.53**

The monthly and yearly wind speed probability density distributions are shown in Table 5 and Table 6 respectively using equation 1. It is observed that the scale factor is directly related to the mean wind speed. The higher the mean wind speed, the higher the scale factor parameter.

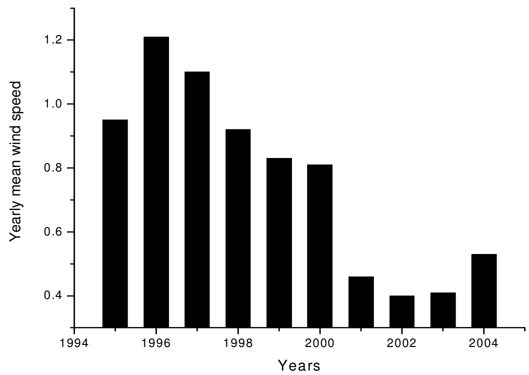


Figure1: Yearly mean wind speed distribution in Ibadan between 1995 and 2004.

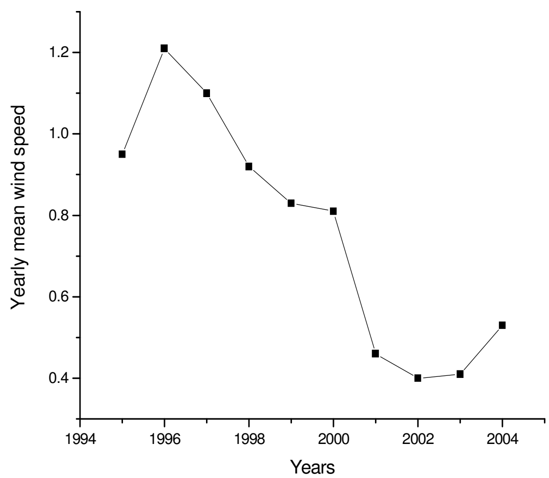
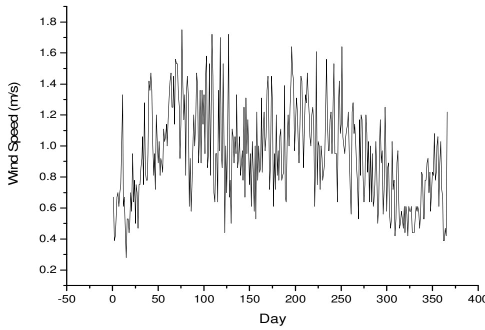
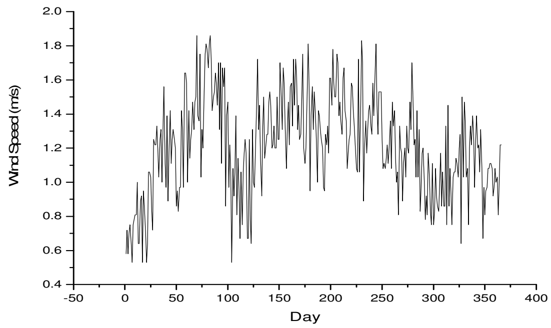


Figure 2: Annual Mean Wind Speed Distribution in Ibadan between 1995 and 2004.

1995 1996





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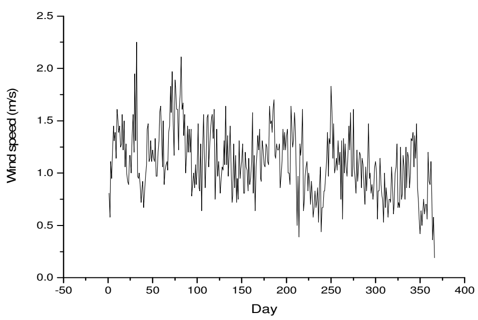

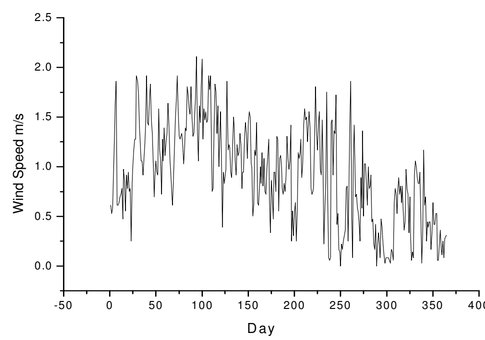

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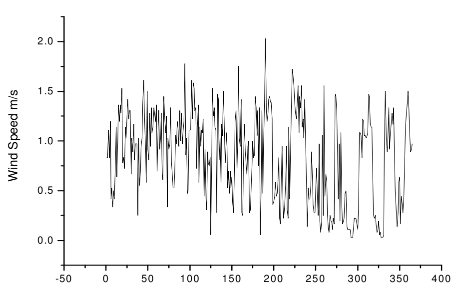
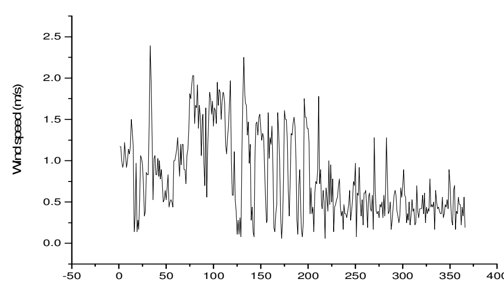
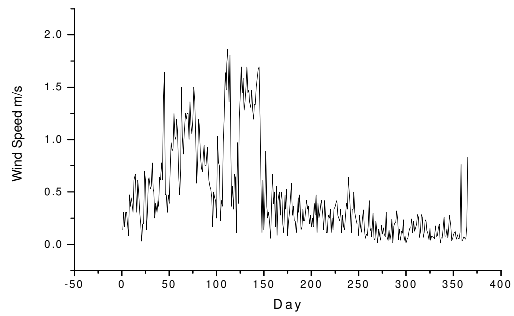




2001 2002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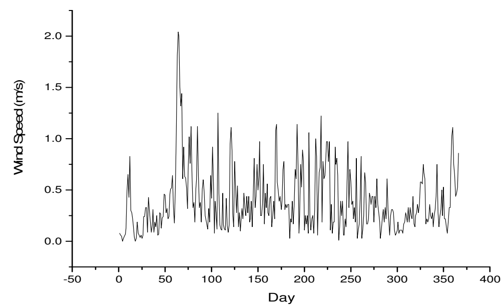
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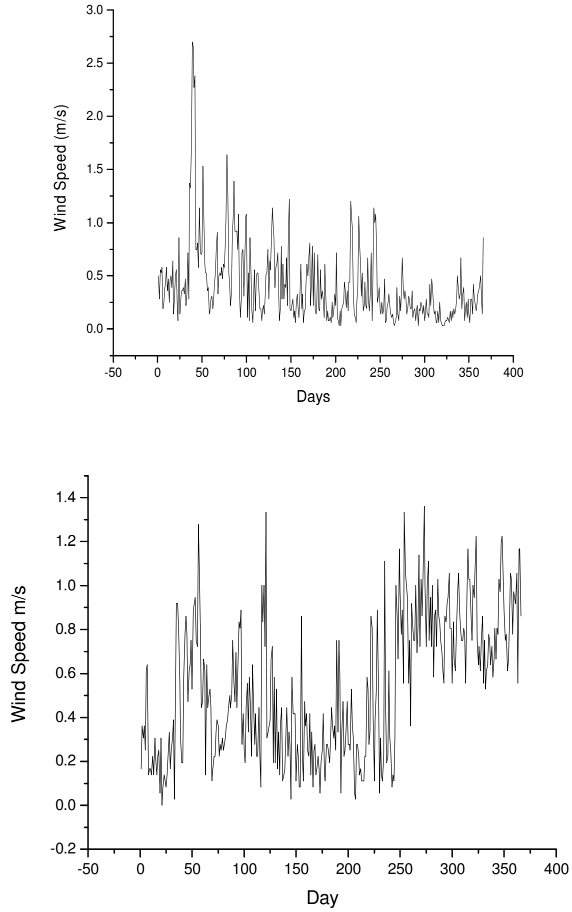
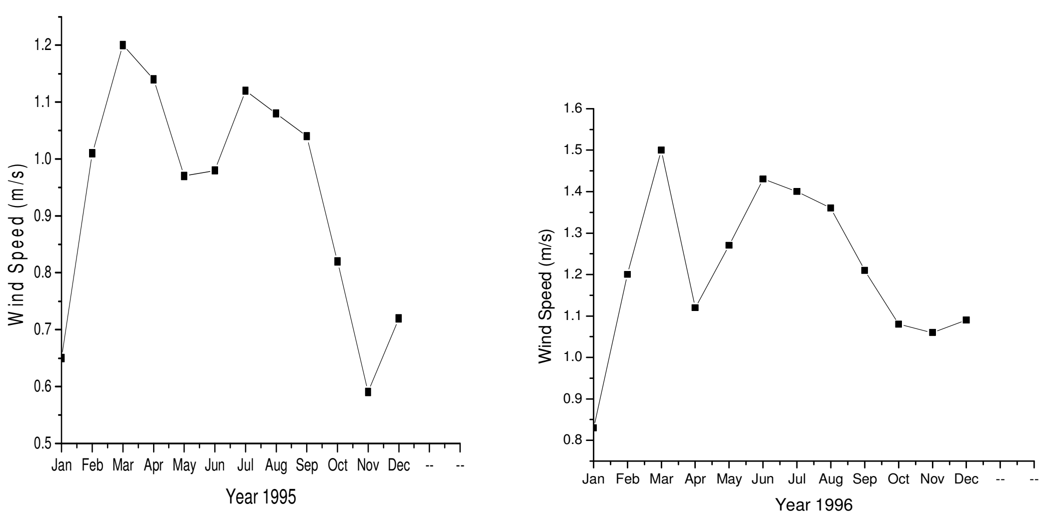
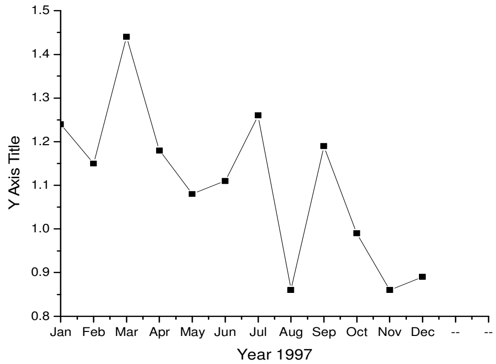


Figure 3: Daily Mean Actual Wind Speed Variation in Ibadan between 1995 and 2004 IITA.

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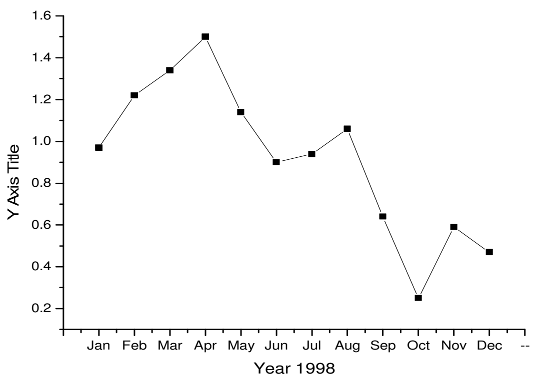
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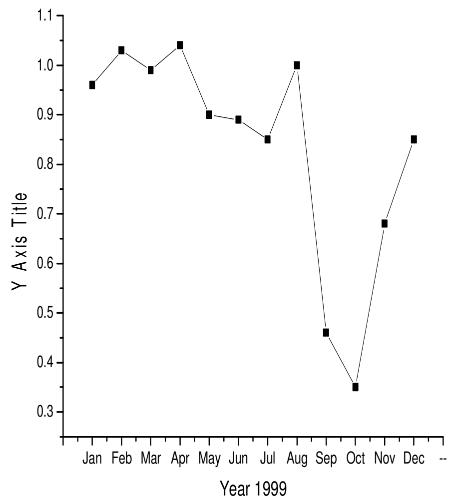
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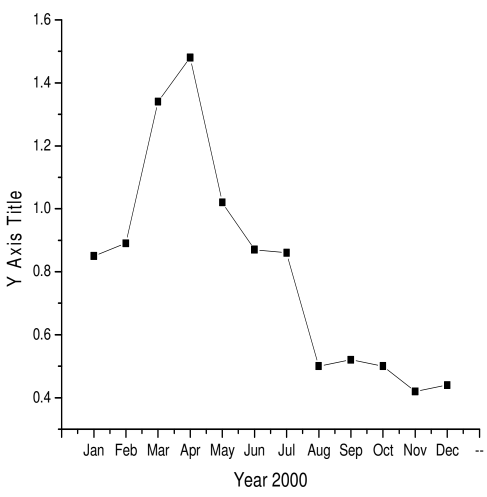
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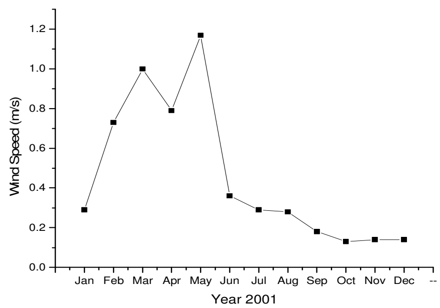

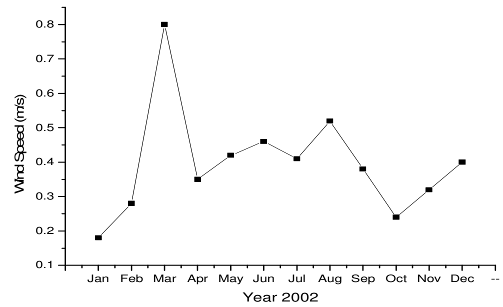

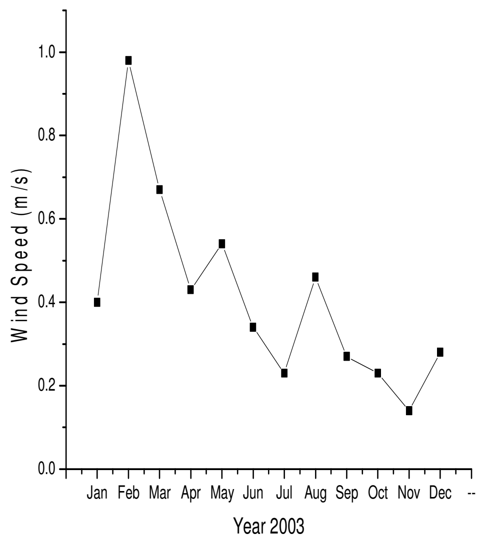

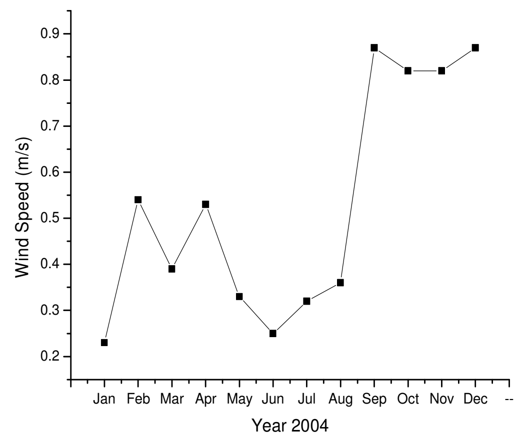

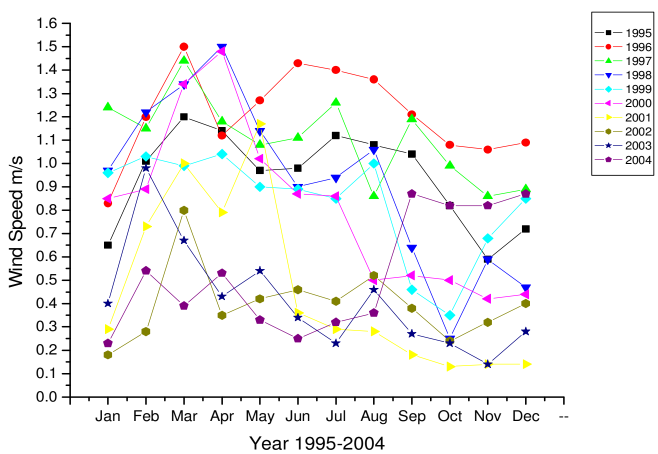

Figure 4: Monthly Wind Speed IITA for the whole Year.

Figures 1 and 3 show the yearly mean wind speed distributions plot for the year 1995-2004. It can be seen that the highest mean wind speed occurred in the year 1996 with wind speed 1.21 m/s. The wind speed fluctuates gradually from year to year for the period of observations. Figure 4 depicts the monthly wind speed IITA for the whole year. It is observed that the minimum wind speed of 0.14 ms^{-1} occurred in November in 2003 while the maximum wind speed of 1.50 ms^{-1} occurred in March, 1996 and April, 1998 respectively.

It is observed that the high wind speeds at (IITA) occurred between March and September during the rainy season, these are due to the high amount of pressure gradient in the atmosphere, the faster the difference in pressure, the faster the wind flows (from high to low pressure) to balance out the variation .
Effective utilization of wind power entails a detailed knowledge for the wind characteristics at the specified location. The power densities calculated from the measured probability density distributions as presented in Table 3 show that the minimum power densities occurred in October and November with 0.35 W/m $^{-2}$ and 0.33 W/m $^{-2}$ respectively. It was noted that the highest power density values occurred in the months of March and April, with the maximum values of 1.94 W/m $^{-2}$ and 1.54 W/m $^{-2}$ respectively at IITA.

The monthly averages of the wind speed are represented in Table 7. Maximum monthly profiles wind speeds vary between 1.50 ms^{-1} in March in the year 1996 and 1.50 ms^{-1} in April in the year 1998.

It is observed from Table 8 that the highest monthly wind speeds occurred in the month of March (1.17, 1.47, 1.72 and 1.95) ms^{-1} and April (0.98, 1.28, 1.51 and 1.84) ms^{-1} while the minimum monthly wind speeds occurred in October (0.78, 1.12, 1.23 and 1.43) ms^{-1}, November (0.04, 0.76, 0.87 and 0.28) ms^{-1} and December (0.40, 0.66, 0.26 and 1.01) ms^{-1} ranging between their respective heights (level 1-4). It is observed that the means were not the same for each month. The wind at a given site varies frequently in directions and its speed change rapidly under gusting conditions (Algifri, 1998).

It is also observed from Table 8 that the highest wind speed occurred in March and September at the highest height (level 4) with the value 1.95 m/s respectively, while the minimum wind speed of 0.04 ms^{-1} occurred in the month of November at the lowest height (level 1). The overall mean wind speed at NIMEX site, Ibadan was found to be 0.74, 1.02, 1.16 and 1.34 ms^{-1} at their respective heights (level 1-4).

Figure 5 depicts the monthly wind speed distribution at all (NIMEX) levels. It is observed that the readings were related to the levels of the equipment installed; i.e. the higher the level of equipment installed, the higher the readings of the wind speed values. The maximum wind speeds occur during the rainy season between the month of March and September while the minimum mean wind speeds occur between the month of October and December. Wind speed data were not available for the month of January and February.

It is observed that the available power and the power density are functions of the heights of the equipment installed as shown in Table 9. The higher the height of the equipment installed, the higher the values of the available power and power density obtained. A wind speed is great at higher distance above the ground level because the effect of surface feature and turbulence diminishes as the height increases.

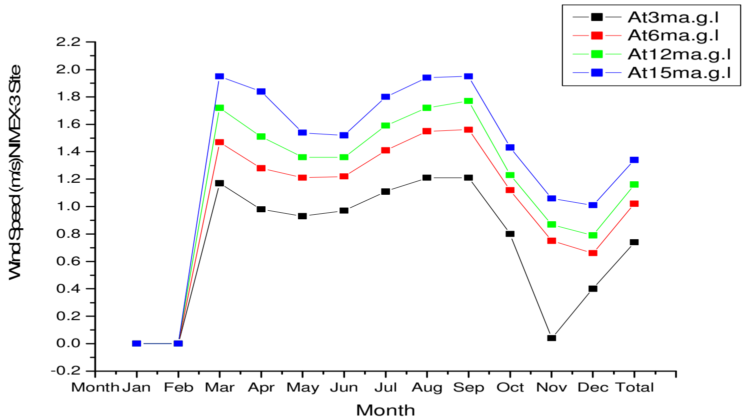

Figure 5: Monthly wind speed distribution NIMEX.

Table 8: Monthly Wind Speed and Standard Deviation NIMEX.

Months	Level 1		Level 2		Level3		Level 4	
	v_m	σ	v_m	σ	v_m	σ	v_m	σ
March	1.17	0.26	1.47	0.30	1.72	0.50	1.95	0.50
April	0.98	0.16	1.28	0.21	1.51	0.33	1.84	0.33
May	0.93	0.28	1.21	0.25	1.36	0.31	1.54	0.31
June	0.97	0.33	1.22	0.39	1.36	0.43	1.52	0.43
July	1.11	0.24	1.41	0.29	1.59	0.33	1.80	0.33
August	1.22	0.29	1.55	0.37	1.72	0.47	1.94	0.33
September	1.22	0.35	1.56	0.46	1.78	0.54	1.95	0.54
October	0.78	0.35	1.12	0.34	1.23	0.39	1.43	0.39
November	0.04	0.12	0.76	0.27	0.87	0.28	1.06	0.28
December	0.40	0.25	0.66	0.19	0.79	0.26	1.01	0.26
Total mean	0.74	0.22	1.02	0.26	1.16	0.32	1.34	0.32

Table 9: Average Wind Speed, Available Power, Mean Power and Weibull Parameters for the whole year NIMEX

	NIMEX Level 1	NIMEX Level 2	NIMEX Level 3	NIMEX Level 4
Power density, Wm^{-2}	1.24	2.59	5.52	5.61
Weibull scale parameter, c	0.83	1.15	1.80	1.51
Weibull shape parameter, k	3.03	5.43	3.43	3.39
Total wind speed	0.74	1.02	1.16	1.34
Yearly Available wind power(kW)	0.31	0.81	1.19	1.83

4.0 CONCLUSION

The wind speed data for Ibadan have been analysed statistically based on Weibull probability Distribution Function. The daily, monthly, seasonal and yearly Weibull probability Distribution parameters, mean wind speeds and available power for the location have been determined. Based on the analysis the following conclusion can be made:

1. The Annual Wind Power Density value of 0.90 W/m $^{-2}$ for the whole year and actual mean yearly wind speed of 0.76 m/s at IITA and the annual wind power density value of 5.61Wm^{-2} and available power of 1.83kW at the highest height (level 4) at NIMEX indicate that, Ibadan can be classified as a low wind energy region and it belongs to the wind power class 1, since the density value is less than 100 W/m $^{-2}$ (Akpinar and Akpinar, 2005).
2. It is concluded that the location is a good region for design of structures and building and agricultural purposes. It is also noted that, the highest wind speed prevail in Ibadan is in the month of March, this corresponds to the work of (Mayhoub and Azzam, 1997). It is observed that the higher the mast for the installation of the equipment, the higher the wind speed values.
3. The yearly power density value of 5.61Wm^{-2} at NIMEX and 0.90 W/m $^{-2}$ at IITA indicate that the level of power density is inadequate for connecting electrical and mechanical application.

NOMENCLATURE

$f(v)$	probability of observing wind speed *v*,
k	dimensionless Weibull shape factor
c	Weibull scale parameter.
$F(v)$	cumulative distribution function of observing wind speed *v*.
v	wind speed (m/s)
v_m	mean value of the wind speed
Γ	gamma function of .
$p(v)$	wind power (W)
p_w	wind power density (W/m^2)
ρ	air density at the site = 1.21(kg/m^3)
A	swept area of the rotor blades (m^2)
σ	standard deviation
N	number of observations

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