MODELLING AND PREDICTION OF WIND SPEED AND WIND TURBINE HUB HEIGHT FOR MAXIMUM POWER DEVELOPMENT IN NIGERIA

BY

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ABSTRACT

The study, modeling and prediction of wind speed and wind turbine hub height for maximum power development in Nigeria, was successfully carried out. Researchers achieved the study using variable study locations chosen to cover all the major cities in Nigeria to ensure that the values of the results could be applicable to nearby communities. Furthermore, wind speed and elevation data gotten from NASA website were prepared in excel and imported into matlab for modeling and prediction. Modeling computed both the linear and non linear models between wind speed and wind turbine hub height to ensure accuracy of results. Standard error for the non linear model was observed to be 45.027, with P-value of 0.891 and degrees of freedom 13 while root mean squared error was 192. General power graph, suggested that the relationship between wind turbine hub height and wind speed is nonlinear and wind turbine hub height is within the range of 200m to 300m. Also, standard error for the linear model was observed to be 55.792, with P-value 0.961 and degrees of freedom 13 while root mean squared error was 192. The P-value and degrees of freedom of the generated linear model are consistent with the P-value and degrees of freedom of anova model, and non linear model, that proves correctness/accuracy of the model. In addition, prediction shows that at site wind speed of 4 m/s, the expected wind turbine hub height for maximum power development was 239.74 m. Researchers made the following recommendations: To avoid failure of wind turbine and poor operational performance, wind turbine hub height must be computed to make appropriate choice of tower material, etc.

Keywords ---- *wind turbine hub height, wind speed, modeling, prediction, matlab, anova, NASA.*

INTRODUCTION

1. Background to the Study

The maximum wind energy output in Nigeria could be traced to Katsina wind farm project owned by the federal ministry of power; this is also the pioneer project aiming to generate 10MW of power through wind turbine with the federal Government desire to improve electricity supply in Nigeria for the actualization of constant power supply. This renewable source (wind) energy project will go a long way in actualizing this target in view of its low cost of maintenance and thereby complementing the already deteriorating non-renewable plants in the country (Aliyu and Mohammed, 2014).

According to Abdelaziz et al (2011) and Fangbele et al (2011) as cited in Aliyu and Mohammed (2014) explained that “harnessing of kinetic energy through the wind has existed for centuries. However it was not until 1979 that the modern wind power industry began in earnest with the production of wind turbines. The use of wind energy as a form of renewable energy gained momentum in the 80s and 90s and there are now thousands of wind turbines operating all over the world. The modern and most commonly used wind turbine has a horizontal axis with two or more aero-dynamic blades mounted on the shaft. These blades can travel at over several times the wind speed, generating electricity which is captured by a medium voltage power collection system and fed through to the power transmission network”.

Malhotra (2001) as cited in Nkwor et al (2023) explained that wind turbine towers and foundations must be designed to withstand wind loads and moments due to extreme wind conditions to prevent failures, as well as other forces that are introduced with alternative site designs. The tower structure must also resist earthquake loads, which can be designed based on checking resistance in the steel’s plastic range. In addition, the soil has to have adequate bearing

capacity to resist the loads on the tower and weight of the foundation. The forces that the tower and foundation must resist are wind loads, ice loads, and the self-weight of the tower.
AWS Scientific (1997) as cited in Njoku et al. (2022) opined that wind speed data of a site is the first parameter to be considered in the harvest of wind energy source in any location. It is necessary to determine the adjusted average wind speeds at a raise wind turbine hub height. This is essential as wind speed significantly increases with height above the earth surface with respect to terrain roughness.

Nkwor et al (2023) explained that the Best value of wind speed represents “a numerical value of wind speed and turbine hub height at which installed wind turbine would develop maximum power with zero tower displacement”.

Modeling here, involves the establishment of mathematical relationship between wind speed and wind turbine hub height; using the relevant site data. Whereas prediction covers long term forecasting of wind turbine hub height at any giving site wind speed. The dependent variable is wind turbine hub height whereas the independent variable is wind speed. Hence, the paper aimed to study modeling and prediction of wind speed and wind turbine hub height for maximum power development in Nigeria.

2. Statement of the Problem

Ngala et al (2007), Justus (1978) & Kumau et al (2011) as cited in Aliyu and Mohammed, (2014) stated that wind power forecasting methods are used, but predictability of any particular wind farm is low for short-term operation. For any particular generator there is an 80% chance that wind output will change less than 10% in an hour and a 40% chance that it will change 10% or more in 5 hours. As the distance between sites increases, the correlation between wind speeds measured at those sites, decreases. Thus, while the output from a single turbine can vary greatly and rapidly as local wind speeds vary, as more turbines are connected over larger and larger areas the average power output becomes less variable and more predictable. Wind speeds can be accurately forecast over large areas, and hence wind is a predictable source of power for feeding into an electrical grid.

Undoubtedly, the establishment of accurate mathematical relationship between wind speed and wind turbine hub height; using the relevant site data for long term forecasting of wind turbine hub height at any giving site wind speed would be a step-wise shift in optimizing Nigerian wind power output. It is on this note that the researchers aimed to study modeling and prediction of wind speed and wind turbine hub height for maximum power development in Nigeria.

3. Purpose of the Study

The general purposes of the study are to formulate accurate mathematical model connecting wind speed and wind turbine hub height. The study would also predict wind turbine hub height for any given site wind speed.

4. Significance of the Study

The result of this study will be beneficial to the Nigerian federal ministry of power and renewable energy companies through the elimination of intense site experiments and site simulation cost prior to installation.

5. Methodology

Nigeria situated in the West Coast of Africa, with human population around 216.7 million as at 2022 and lies between latitude $3^o15'$ to $13^o30'$N and Longitude $2^o59'$ to $15^o00'$(Federal Ministry of Environment, 2019). In this study, the average monthly wind speed data from 1981 -2021 (40 years) for fourth-seven (47) study locations are sourced from National Aeronautics and Space Administration (NASA) website as cited in Nkwor et al (2023). These study locations have been chosen to cover all the major cities in Nigeria as the values of the wind data can be applicable to nearby communities. The wind speed and elevation data were prepared in excel and imported into matlab for modeling and prediction. The wind speed and elevation data were prepared in excel and imported into MATLAB for modeling and prediction. The dependent variable is wind turbine hub height and it was assigned variable Y whereas the independent variable is average wind speed and was assigned variable X. The elevation and average wind speed data from table 1.0 below were assigned to Y and X respective in matlab window. The following matlab programs were used to model the two variables to achieve both linear and non linear models. Prediction was made at 4 m/s of site wind speed.

5.1 Table and Figure

Table 1:0 Average Monthly Wind Speed for Study Locations at 10m/s from 1981-2022 (NASA, 2023)

Locations	Lat. (°N)	Long. (°E)	Elev. (m)	Jan	Feb	Mar m/s	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave
Abakaliki	6.33	8.12	88.44	2.77	2.54	2.7	2.84	2.67	2.88	3.16	3.21	2.76	2.26	1.84	2.4	2.67
Abeokuta	7.15	3.37	80.92	2	2.23	2.44	2.44	2.26	2.42	2.84	2.94	2.45	1.99	1.65	1.73	2.28
Abuja	9.08	7.4	406.97	2.9	2.75	2.56	2.48	2.2	2.19	2.42	2.45	1.99	1.77	2.12	2.67	2.37
Ado-Ekiti	7.62	5.24	379.21	2.14	2.2	2.39	2.46	2.23	2.28	2.62	2.68	2.11	1.75	1.64	1.88	2.2
Akure	7.26	5.21	379.21	2.14	2.2	2.39	2.46	2.23	2.28	2.62	2.68	2.11	1.75	1.64	1.88	2.2
Asaba	6.21	6.7	103.94	2.53	2.43	2.56	2.64	2.5	2.79	3.19	3.28	2.81	2.3	1.86	2.14	2.59
Awka	6.23	7.09	103.94	2.53	2.43	2.56	2.64	2.5	2.79	3.19	3.28	2.81	2.3	1.86	2.14	2.59
Bauchi	10.31	9.83	518.79	4.11	4.18	3.83	3.47	3.28	3.01	2.59	2.3	2.3	2.63	3.28	3.82	3.23
Benin-City	6.34	5.61	93.92	1.76	1.71	1.74	1.74	1.64	1.8	2.06	2.13	1.83	1.5	1.29	1.5	1.73
Bida	9.08	6.01	126.59	2.26	2.21	2.23	2.35	2.17	2.14	2.34	2.36	1.89	1.66	1.71	2.05	2.11
BirininKebbi	12.44	4.2	241.96	3.64	3.64	3.24	3.08	3.27	2.99	2.43	1.96	1.75	1.89	2.54	3.29	2.81
Calabar	4.98	8.35	39.48	2.08	2.25	2.38	2.43	2.41	2.72	2.99	3.07	2.76	2.39	1.97	1.88	2.45
Damaturu	11.75	11.97	402.61	4.81	4.94	4.62	4.06	3.96	3.94	3.38	2.74	2.39	2.58	3.86	4.54	3.81
Duste	11.75	9.34	465.94	3.02	3.11	3.07	2.98	2.79	2.61	2.17	1.8	1.77	1.99	2.39	2.78	2.53
Enugu	6.46	7.55	151.33	2.78	2.61	2.74	2.85	2.67	2.91	3.28	3.32	2.81	2.3	1.88	2.37	2.71
Gombe	10.28	11.18	381.62	4.47	4.62	4.12	4	4.06	3.76	3.27	2.76	2.36	2.32	3.08	4.01	3.56
Gusau	12.17	6.68	529.87	4.92	4.82	4.28	3.84	3.61	3.51	3.08	2.61	2.31	2.68	3.74	4.53	3.66
Ibadan	7.38	3.95	188.89	2.17	2.31	2.6	2.71	2.52	2.65	3.08	3.16	2.53	2.03	1.71	1.89	2.45
Ijebu-Ode	6.83	3.92	90.82	1.77	1.94	2.12	2.14	2	2.17	2.54	2.63	2.2	1.78	1.46	1.54	2.02
Ikeja	6.61	3.36	25.49	2.48	2.9	3.24	3.21	2.98	3.36	3.92	4	3.54	2.88	2.29	2.15	3.08
Ikom	5.97	8.73	116.85	2.16	2.31	2.51	2.58	2.48	2.74	3.01	3.12	2.73	2.29	1.82	1.9	2.47
Ilorin	8.48	4.55	344.93	2.72	2.96	3.51	3.84	3.4	3.21	3.47	3.51	2.62	2.25	2.14	2.4	3
Jalingo	8.9	11.38	251.79	3.51	3.5	3.61	4.1	3.67	3.49	3.45	3.16	2.4	2.08	2.32	3.13	3.2
Jos	9.9	8.86	980.85	4.3	4.2	3.82	3.43	2.89	2.68	2.54	2.49	2.41	2.71	3.45	4.06	3.24
Kaduna	10.52	7.42	623.54	4.77	4.49	3.67	3.18	2.85	2.73	2.61	2.47	2.09	2.23	3.46	4.43	3.24
Kano	12.01	8.6	442.08	2.84	2.89	2.78	2.64	2.51	2.39	1.94	1.52	1.44	1.69	2.16	2.58	2.28

Katsina	12.97	7.63	474.54	5.05	4.93	4.54	4.03	3.77	3.85	3.46	2.72	2.45	2.94	4.02	4.7	3.86
Lafia	7.81	6.74	167.21	2.38	2.54	3.01	3.23	2.82	2.71	2.88	2.84	2.32	2.03	1.89	2.12	2.57
Lokoja	7.81	6.74	167.21	2.38	2.54	3.01	3.23	2.82	2.71	2.88	2.84	2.32	2.03	1.89	2.12	2.57
Maidugri	11.84	13.16	318.25	4.57	4.78	4.65	4	3.77	3.98	3.64	2.88	2.57	2.79	3.91	4.34	3.82
Makurdi	7.74	5.54	373.17	2.53	2.65	3.01	3.16	2.83	2.82	3.14	3.19	2.52	2.12	1.97	2.23	2.68
Mbaise	5.54	7.29	92.75	2.34	2.28	2.35	2.41	2.33	2.6	2.92	3.02	2.65	2.21	1.79	1.98	2.41
Minna	7.61	8.09	149.83	3.02	3	3.3	3.42	2.98	2.97	3.18	3.14	2.57	2.17	1.98	2.59	2.86
Nguru	12.88	10.46	345.61	4.94	4.95	4.75	4.07	3.57	3.62	3.39	2.7	2.52	3.1	4.33	4.75	3.89
Onitsha	6.14	6.8	103.94	2.53	2.43	2.56	2.64	2.5	2.79	3.19	3.28	2.81	2.3	1.86	2.14	2.59
Oshogbo	7.79	4.55	337.39	2.43	2.6	3.03	3.23	2.91	2.9	3.31	3.38	2.55	2.06	1.89	2.13	2.7
Owerri	5.47	7.02	62.54	2.26	2.18	2.22	2.25	2.16	2.44	2.77	2.87	2.52	2.1	1.72	1.9	2.28
Port-Harcourt	4.34	7.05	6.8	1.65	1.77	1.76	1.66	1.62	1.86	2.17	2.29	2.03	1.71	1.5	1.45	1.79
Potiskum	11.7	11.09	411.77	4.36	4.47	4.13	3.56	3.43	3.33	2.8	2.27	2.06	2.25	3.38	4.06	3.34
Sokoto	13.01	5.25	276.18	4.51	4.42	3.94	3.59	3.8	3.71	3.12	2.44	2.19	2.38	3.3	4.14	3.46
Umuahia	5.53	7.5	92.75	2.34	2.28	2.35	2.41	2.33	2.6	2.92	3.02	2.65	2.21	1.79	1.98	2.41
Uyo	5.04	7.92	39.48	2.08	2.25	2.38	2.43	2.41	2.72	2.99	3.07	2.76	2.39	1.97	1.88	2.45
Warri	5.55	5.57	9.6	1.36	1.41	1.4	1.3	1.2	1.36	1.64	1.79	1.58	1.28	1.07	1.15	1.38
Yelwa	10.84	4.75	257.74	3.94	3.89	3.36	3.35	3.15	2.9	2.65	2.48	2.07	2.05	2.81	3.54	3.01
Yenegoa	4.93	6.28	17.26	2.08	2.15	2.23	2.19	2.09	2.37	2.72	2.87	2.56	2.14	1.78	1.77	2.25
Yola	9.04	12.5	344.13	2.48	2.82	3.36	3.55	2.94	2.68	2.59	2.36	1.91	1.91	2.05	2.21	2.57
Zaria	11.13	7.73	646.9	4.86	4.67	3.97	3.5	3.23	3.11	2.82	2.53	2.2	2.39	3.51	4.45	3.43
			Ave	3.01	3.05	3.04	2.97	2.77	2.82	2.88	2.76	2.36	2.18	2.33	2.71	2.74
			Max	5.05	4.95	4.75	4.1	4.06	3.98	3.92	4	3.54	3.1	4.33	4.75	3.89
			Min	1.36	1.41	1.4	1.3	1.2	1.36	1.64	1.52	1.44	1.28	1.07	1.15	1.38

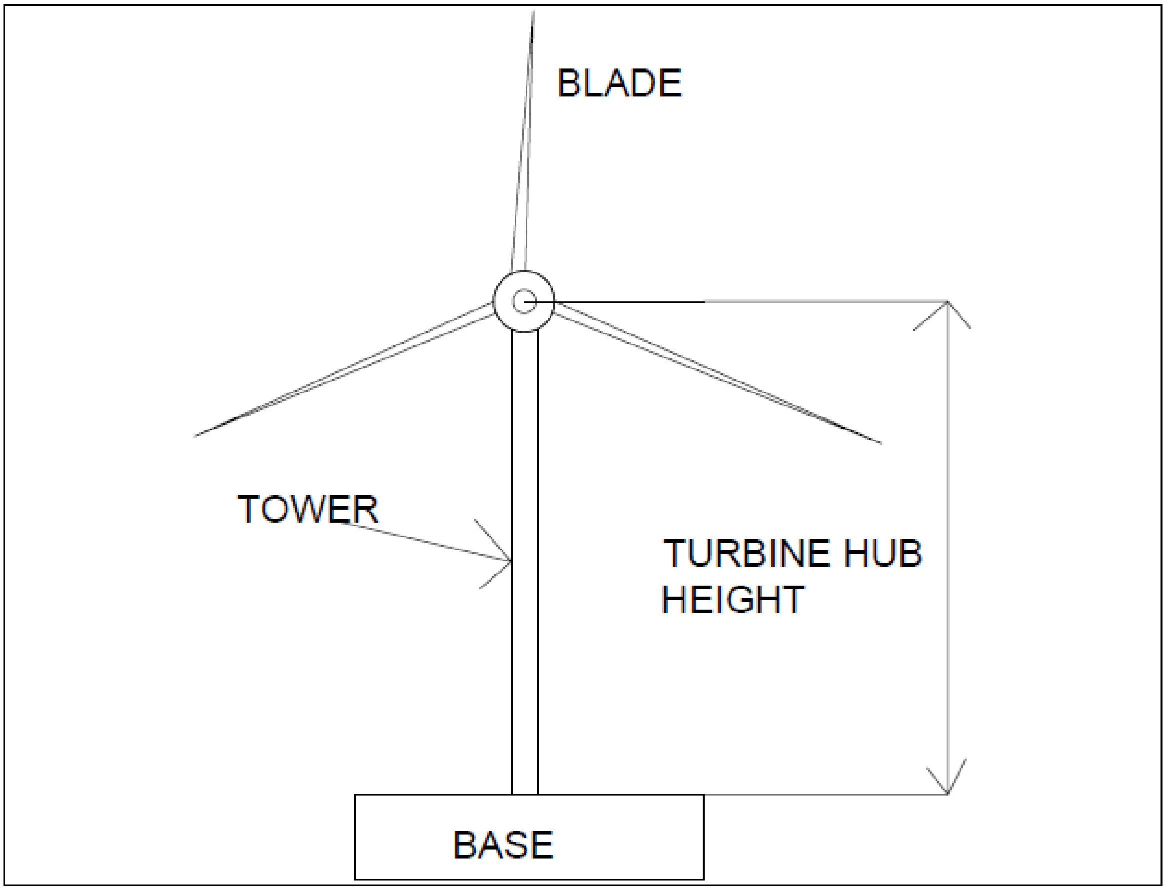

Fig 1.0: Wind Turbine Hub Height, Blade and Tower (Source: Nkwor et al, 2023)

6. Results and Presentations

6.1 Matlab Programme for Linear Modelling

>> % MATLAB PROGRAMME FOR MODELLING WIND SPEED AND WIND TURBINE HUB HEIGHT

>> % X IS THE INDEPENDENT VARIABLE, WIND SPEED

>> % Y IS THE DEPENDENT VARIABLE, WIND TURBINE HUB HEIGHT

>> X= [2.28 2.37 2.2 2.2 2.59 3.23 1.73 2.11 2.81 2. 45 2.71 3.56 3.66 3.86, …];

>> Y = [88.44 80.92 406.97 379.21 379.21 103.94 103.94 518.79 93.92 126.59 241.96 39.48 465. 21 515.33, …];

>> mdl = fitlm(X,Y)

mdl =

Linear regression model:

```
  y ~ 1 + x1

Estimated Coefficients:

              Estimate     SE      tStat       pValue
              ________   ______   ________   __________

  (Intercept)   236.38    55.792    4.2367   0.00097083
  x1           0.23137    4.6817  0.049421      0.96134

Number of observations: 15, Error degrees of freedom: 13
Root Mean Squared Error: 192
R-squared: 0.000188,  Adjusted R-Squared -0.0767
F-statistic vs. constant model: 0.00244, p-value = 0.961
>> tbl = anova(mdl)
tbl =

            SumSq     DF   MeanSq       F        pValue
          _________   __   ______   _________   _______

  x1         89.861    1   89.861   0.0024424   0.96134
  Error   4.783e+05   13    36792
>>end
```

The computed linear model between wind speed and wind turbine hub height is shown below;

$$\boldsymbol{Y = 0.23137X + 236.38}$$

Where Y = wind turbine hub height in meters and X = wind speed in m/s.

6.2 Matlab Programme for Nonlinear Modelling

```
>> modelfun = @(b,x)b(1) + b(2)*x(:,1).^b(3);
>> beta0 = [2.28  2.37  2.2  2.2  2.59  3.23  1.73  2.11  2.81  2. 45  2.71  3.56  3.66  3.86, …];
>> mdl = fitnlm(X,Y,beta0)
>> beta0 = [2.28 2.37 3.88];
>>  mdl = fitnlm(X,Y,modelfun,beta0)
mdl =
Nonlinear regression model:
```

y ~ b1 + b2*x1^b3

Estimated Coefficients:

	Estimate	SE	tStat	pValue
b1	-6360.9	45.027	-141.27	4.2173e-22
b2	6588	45.028	146.31	2.6735e-22
b3	0.0013822	0.010899	0.12682	0.90102

Number of observations: 15, Error degrees of freedom: 13

Root Mean Squared Error: 192

R-Squared: 0.00149, Adjusted R-Squared -0.0753

F-statistic vs. constant model: 0.0194, p-value = 0.891

>>end

The computed non linear model between wind speed and wind turbine hub height is shown below;

$$\boldsymbol{Y = -6360.9 + 6588X^{0.0013822}}$$

Where Y = wind turbine hub height in meters and X = wind speed in m/s.

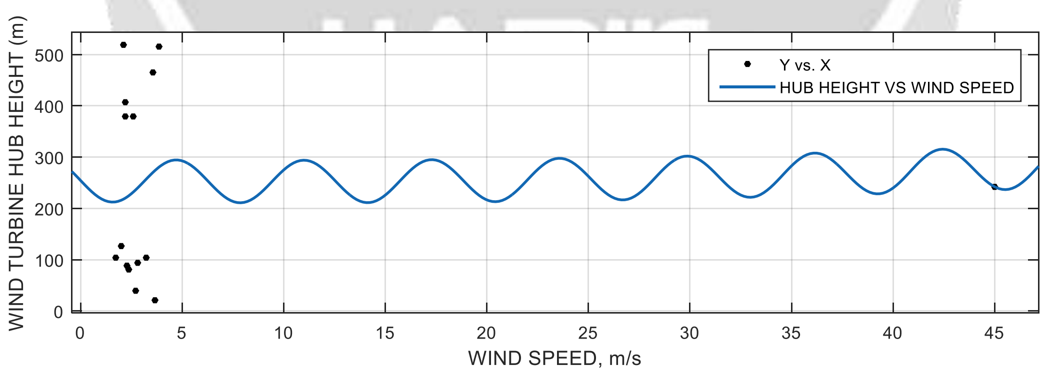

Fig 1.1: Graph of Linear Model

6.3 Linear Model:

f(x) = a*(sin(x-pi)) + b*((x-10)^2) + c

Coefficients (with 95% confidence bounds):

a = 41.53 (-170.8, 253.8)

b = 0.02044 (-0.3728, 0.4137)

c = 252.4 (108, 396.7)

Goodness of fit:

SSE: 4.712e+05

R-square: 0.01492

Adjusted R-square: -0.1493

RMSE: 198.2

Matlab Codes/Scripts of the Graph above

```
Function createfigure1(XData1, YData1, XData2, YData2)

%CREATEFIGURE1(XDATA1, YDATA1, XDATA2, YDATA2)

%  XDATA1:  line xdata
%  YDATA1:  line ydata
%  XDATA2:  line xdata
%  YDATA2:  line ydata

%  Auto-generated by MATLAB on 30-Jul-2023 16:05:04

% Create figure
figure1 = figure('Tag','Print CFTOOL to Figure',...
    'Color',[0.941176470588235 0.941176470588235 0.941176470588235]);

% Create axes
axes1 = axes('Parent',figure1,'Tag','sftool surface axes');
%% Uncomment the following line to preserve the X-limits of the axes
% xlim(axes1,[-0.434 47.164]);
%% Uncomment the following line to preserve the Y-limits of the axes
% ylim(axes1,[-3.89 543.68]);
%% Uncomment the following line to preserve the Z-limits of the axes
% zlim(axes1,[-1 1]);
box(axes1,'on');
grid(axes1,'on');
hold(axes1,'on');

% Create line
line(XData1,YData1,'Parent',axes1,'DisplayName','Y vs. X',...
    'MarkerFaceColor',[0 0 0],...
    'MarkerEdgeColor',[0 0 0],...
    'MarkerSize',3,...
    'Marker','o',...
```

```
    'LineStyle','none');

% Create line
line(XData2,YData2,'Parent',axes1,'DisplayName','HUB HEIGHT VS WIND SPEED',...
    'LineWidth',1.5,...
    'Color',[0.0705882352941176 0.407843137254902 0.701960784313725]);

% Create xlabel
xlabel({'WIND SPEED, m/s'});

% Create ylabel
ylabel({'WIND TURBINE HUB HEIGHT (m)'});

% Create zlabel
zlabel('Z');

% Create legend
legend1 = legend(axes1,'show');
set(legend1,'Interpreter','none','EdgeColor',[0.15 0.15 0.15]);
```

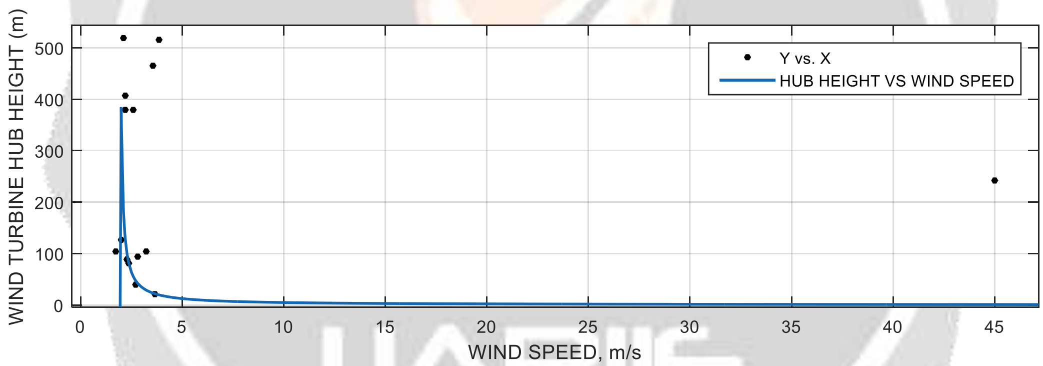

Fig 1.2: Polynomial Graph of Turbine Hub Height Against Wind Speed

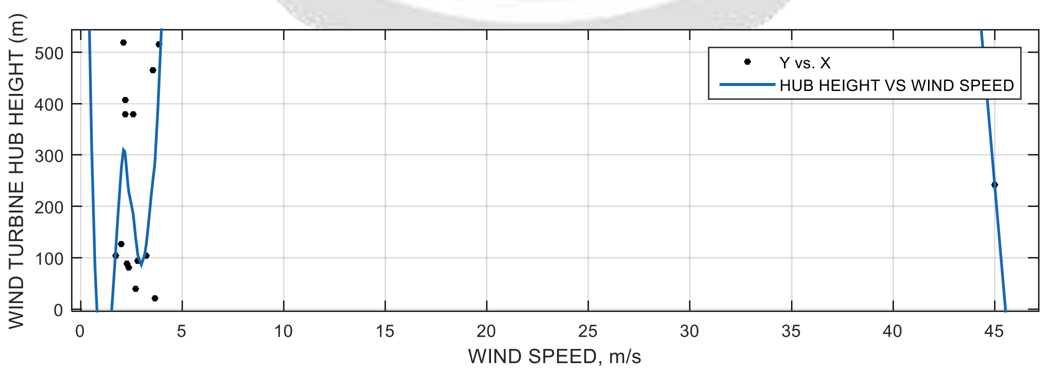

Fig 1.3: Power Graph of Turbine Hub Height Against Wind Speed

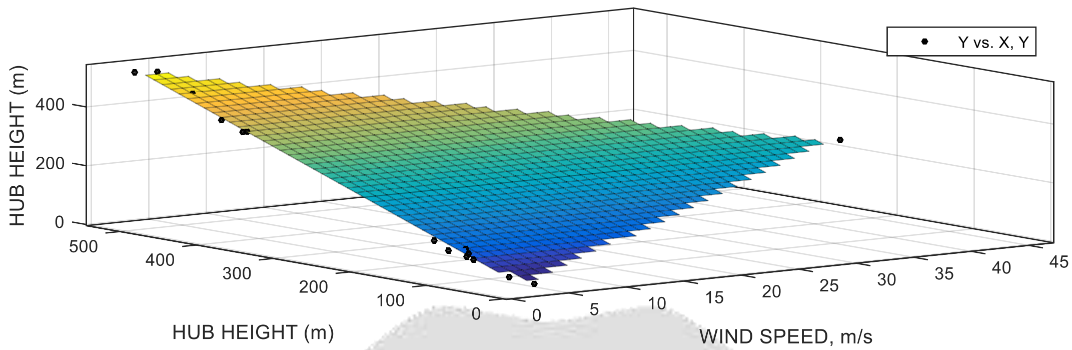

Fig 1.4: 3D Polynomial Graph of Turbine Hub Height Against Wind Speed

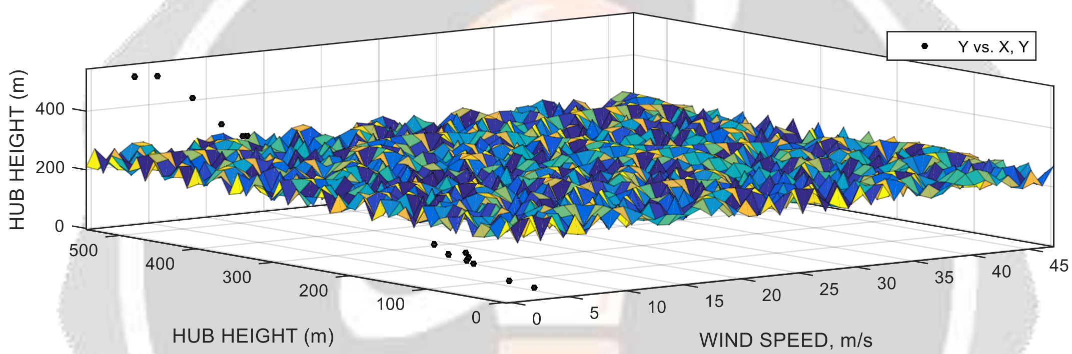

Fig 1.5: 3D Lowess Graph of Turbine Hub Height Against Wind Speed

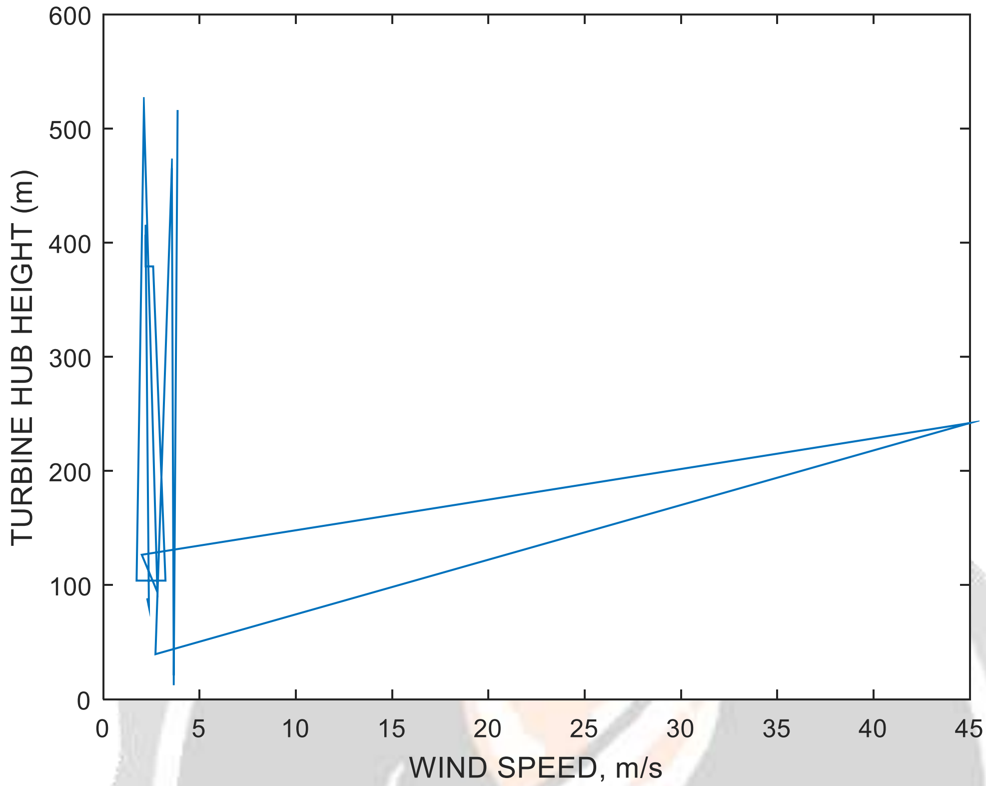

Fig 1.6: Linear Graph of Turbine Hub Height Against Wind Speed

7. Prediction

At 4 m/s site wind speed, the expected wind turbine hub height is as below:

Where Y = wind turbine hub height in meters and X = wind speed in m/s.

$$\boldsymbol{Y = -6360.9 + 6588X^{0.0013822}}$$

$$Y = -6360.9 + 6588(4)^{0.0013822}$$

$$Y = -6360.9 + 6600.64 = 239.74 \text{ m}$$

$$\boldsymbol{Y = 0.23137X + 236.38}$$

$$Y = 0.23137(4) + 236.38$$

$$Y = 0.92548 + 236.38 = 237.31\ m$$

The expected wind turbine hub height = 239.74 m

Where Y = wind turbine hub height in meters and X = wind speed in m/s.

8. Discussion

The results of the study, modeling and prediction of wind speed and wind turbine hub height for maximum power development in Nigeria, using matlab were discussed here. Researchers achieved the study using variable study locations chosen to cover all the major cities in Nigeria to ensure that the values of the wind data can be applicable to nearby communities. The wind speed and elevation data were prepared in excel and imported into matlab for modeling and prediction.

The matlab modeling also computed both the linear and non linear models between wind speed and wind turbine hub height to ensure accuracy of results. Non linear model between wind speed and wind turbine hub height is shown below.

$$\boldsymbol{Y = -6360.9 + 6588X^{0.0013822}}$$

The standard error was observed to be 45.027. The P-value 0.891 and degrees of freedom 13 with root mean squared error of 192. The graph of **Fig. 1.1**, suggested that wind turbine hub height is within the range of 200m to 300m.

Computed linear model between wind speed and wind turbine hub height is shown below.

$$\boldsymbol{Y = 0.23137X + 236.38}$$

Where Y = wind turbine hub height in meters and X = wind speed in m/s.

The standard error was observed to be 55.792. The P-value 0.961 and degrees of freedom 13 with root mean squared error of 192. The P-value and degrees of freedom of the generated linear model are consistent with the P-value and degrees of freedom of anova model, and non linear model that proves correctness of the model. The graphical analysis from **Fig. 1.1 to Fig. 1.6** revealed that the wind speed has a non linear relationship with the wind turbine hub height. In addition, prediction shows that at site wind speed of 4 m/s, the expected wind turbine hub height for maximum power development is 239.74 m.

9. Conclusion

The modeling and prediction of wind speed and wind turbine hub height for maximum power development in Nigeria was obviously achieved. Undoubtedly, results revealed that at any given value of site wind speed, wind turbine hub height can be easily computed. Study showed that to attain maximum wind power exceeding 10MW in Nigeria, wind turbine installation hub height was predicted to be 239.74 meters.

10. Recommendations

The following recommendations are suggested based on the study:

1) To avoid failure of wind turbine and poor operational performance, wind turbine hub height must be computed to make appropriate choice of tower material.
2) This research can also be done in future using other advanced software ANAYSIS fluent, CFD, etc, for generalization.

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