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Horizontal Axis Wind Turbine Blade (HAWT) Analysis Based on Blade Element Momentum Theory (BEM) for Some Cities in Nigeria

P.J Manga[1], R.O Amusat[2], S.D Buteh[3], F.W Burari[4], Adisa A. Bello[5], A.M Tijjani[6]

[1&2]Department of Physics,
University of Maiduguri,
Borno,
Borno State – Nigeria

[3]Department of Chemistry,
Adamu Tafawa Balewa College of Education,
Kagere Bauchi,
Bauchi State – Nigeria

[4&6]Department of Physics,
Abubakar Tafawa Balewa University,
Bauchi,
Bauchi State – Nigeria

[5]Department of Mechanical Engineering,
Abubakar Tafawa Balewa University,
Bauchi,
Bauchi State – Nigeria

Abstract

In this research, the blade element momentum (BEM) theory of a horizontal axis wind turbine (HAWT) blade with 1 kW power output has been analysed for one station across the six geopolitical zones. Twenty years wind speed data (2000 – 2020) obtained from Nigeria meteorological Agency (NIMET) Head quarter, Abuja. In an effort to optimally explore and utilize wind energy, an optimal design of wind turbine blade needs to be obtained. Therefore, a computational method to analysed and optimize the performance of the wind turbine blades needs to be developed. For that purpose, a computational method based on the Blade Element Momentum (BEM) theory is developed in this study. In this method, the blade of a wind turbine is divided into several elements and it is assumed that there is no aerodynamic interaction amongst the elements. Furthermore, this (BEM) method incorporated with equations from momentum and blade element theories to obtain equations which are useful in wind turbine blades design process. In this research a computed result for aerodynamic characteristics based on BEM theory shows that, Maiduguri Metropolis is suitable for surface wind electrification among the selected stations with an estimated maximum wind power of $1.774kW$ *at total lift to drag ratio* (F_L/F_D) *of* 27.2674 *and a mean relative velocity of 14.99m/s. There is an agreement with my findings and that of other researchers.*

Keywords: Airfoil, Blade Element Momentum Theory, Lift forces, Drag Force, Angle of Attack

**Author for Correspondence*

Nomenclature

dF_{Ti}	Incremental Thrust Force	Ω	Angular Velocity
dF_{Mi}	Incremental Moment Force	N	Rotor Speed
dF_{Li}	Incremental Lift Force	F_L	Total Lift Force
dF_{Di}	Incremental Drag Force	F_D	Total Drag Force
dP_i	Incremental power	C_D	Drag Coefficient
dM_i	Incremental moment on each element	C_L	Lift Coefficient
V_i	Relative Velocity	C_P	Power Coefficient
ω_i	Linear Velocity	r_{ei}	Radius at the centre of element

INTRODUCTION

For the prediction of both aerodynamics rotor blade and airplane propellers characteristics in describing how a wind turbine blade operate can be well understood using the blade element momentum theory (BEMT). The blade element momentum theory (BEMT) is a power and fast technique, used for better performance of wind turbines and the simplest approach among the other propeller theories (Povl. *et, al.,* 2013). Clarity, precision and the possibility to apply it using low computer resources or even on paper is the advantage of blade element momentum theory (BEMT). The BEM theory allow you to divide wind turbine blade into sectional airfoil to assess it aerodynamic effect and thrust force acting on the blade element. Basically we can say, the inflow disc can be analysed separately from the rest of the flow when a stream tube is passing. Hence, the difference in the fluid dynamic amount occur both in the axial and radial directions in each strip, without adding the radial equilibrium between the strips. BEMT is reliable and practically proved when there is distribution of air circulation over the blade (Bharath *et, al*., 2011). Another assumption of the BEMT is that the radial components of the flow velocity must be neglected everywhere within the fluid volume, i.e. the flow is in two dimensional (Willem, 1982). Consequently, the results of two-dimensional tests obtained both experimentally and numerically, are used to predict the hydrodynamic forces applied by the fluid on each blade element. Furthermore, the non-zero rake angle of the screw blade has a velocity component that along the radius that is neglected. Moreover, BEMT does not include secondary effects such as three dimensional flow velocities generated on the rotor blade by the shed tip vortex or the angular acceleration induced by radial components of the due to the rotation of rotor blade. This theory is known globally for estimation of forces acting on a wind turbine blade like the propeller of an airplane (Muyiwa, 2014). The theoretical efficiency of the over predicted thrust force and under predicted torque resulting into an increase with the value ranging from 5-10%. This caused, a correction model is often confining that is able to improve performance prediction. Despite the previous restrictions, the BEMT has been found very functional in analysing the blade of a wind turbine and the propellers of airplane. BEMT can be one of the best ways to obtain comprehensible estimation and predictions of thrust, torque and efficiency for rotor blade of a wind turbine since using other methods such as CFD (computational fluid dynamic) or full RANS simulation will require a high computer resources, high cost, and extra time consumption (Nolan, 2014). In this study, we make used of an empirical model based on blade element momentum theory to estimate the forces acting on blade element section and the available wind power the study area for an efficient performance of the wind turbine.

There are two types of wind machines (turbines) used today based on the direction of the rotating shaft (axis): horizontal–axis wind machines and vertical-axis wind machines. The size of wind machines varies widely. Small turbines used to power a single home or business. Larger turbines are often grouped together into wind farms that provide power to the electrical grid (David, 2011).

Most wind machines being used today are the horizontal-axis type. Horizontal-axis wind machines have blades like airplane propellers. A typical horizontal wind machine stands as tall as a 20-story building and has three blades that span 200 feet across. The largest wind machines in the world have blades longer than a football field! Wind machines stand tall and wide to capture more wind (David, 2011).

Vertical–axis wind machines have blades that go from top to bottom and the most common type (Darrieus wind turbine) looks like a giant two-bladed egg beaters. The type of vertical wind machine typically stands 100 feet tall and 50 feet wide. Vertical-axis wind machines make up only a very small percent of the wind machines used today. Module channel surfaces. The concave surfaces channel wind toward the turbines, amplifying wind speeds by 50 percent or more. Eneco, the company that designed WARP, plans to market the technology to power offshore oil platforms and wireless telecommunications systems (David, 2011).

Most wind turbines have the following main parts, a rotor, a generator, gearbox and an electric converter. Each of these components has lesser efficiency. The total efficiency of such a turbine is defined by (David, 2006) as:

$$\eta_{total} = \frac{P_{grid}}{P_{max}} = \eta_{rotor}\eta_{gear\ box}\eta_{gen}\eta_{conv} \qquad \dots (1)$$

where:

$$\eta_{rotor} = \frac{P_{rotor}}{P_{max}} \qquad \dots (2)$$

$$\eta_{gear\ box} = \frac{P_{L.S}}{P_{rotor}} \qquad \dots (3)$$

$$\eta_{gen} = \frac{P_{gen}}{P_{L.S}} \qquad \dots (4)$$

$$\eta_{conv} = \frac{P_{grid}}{P_{gen}} \qquad \dots (5)$$

where the indices stand for LS = Low speed (shaft)
"Gen" = generator, "conv" = frequency converter and "grid" = grid net.

METHODOLOGY

Description of the Study Area

Nigeria is a country situated in West Africa and borders on Benin in the west, Niger in the North, Chad in the North East and Cameroon in the East and South East in the South. Nigeria is washed by the waters of Atlantic Ocean and with a total land mass area of 923,800 ($sq\ km$) falls within the latitude 10^0 north and longitude 8^0 east. Nigeria is located within the equator latitude 40^0 and 140^0 North of the equator and longitude 30^0 and 140^0 East of Greenwich meridian. The tropic of cancer latitude 23.5^0N and falls within the tropic zone. By virtue of Nigeria's location, it enjoys warm tropical climate with relatively high temperature throughout the year, with two major season's (rainy and dry seasons) Martin. S (1988).

Data Collection
Wind speed data was collected at NIMET Head Quarter Abuja for the period of twenty years (2000 – 2020) for some station across the six geopolitical zones in Nigeria.

Analysis of Wind Data
Aerodynamic characteristic of 1kW output, horizontal axis wind turbine blade based on blade element momentum theory as in equations (7) to (29) was analysed

Wind Speed Characteristic
The wind speed measured at 2m above the ground is not sufficient enough to set a wind turbine into motion to generate electricity therefore it is needed to calculate the design wind speeds of site location (Manga *et, al.,* 2022). The relation of annual average wind speed and design wind speeds are shown in table 2.

$$V_{average} = V_z = V_{zr}(\frac{z}{z_{ref}})^m \quad \dots (7)$$

Table 1; Relations and results of wind speed

Wind speed characteristics	wind speed relation	Estimated Results (m/s)
$V_{average}$		V_{AV}
V_{cut-in}	$0.7V_{average}$	μ
V_{rated}	$2V_{average}$	σ
$V_{cut-out}$	$3V_{average}$	δ

Table 1 defined the wind speed characteristic of the study area. The $V_{average}$ *is the* analysed yearly average wind speed while the V_{cut-in} is the required wind speed by a wind turbine to start mechanical motion likewise the V_{rated} is the required velocity for a wind turbine to produce a steady electricity, this is also called the peak velocity and $V_{cut-out}$ is called the breaking point were the wind turbine stop operation to prevent it from being damage.
For the purposed of this research, the rated velocity was chosen due to the fact that at V_{rated} the wind speed is sufficient enough for optimal electricity generation.

Rotor Sizing by (Sathyajith, 2006)
In this step, the rotor size need to be calculated, the solidity, chord length and blade length were also considered, because it is not all the available wind captured by the rotor blade will be used by a wind turbine for electricity production. According to Sathyajith (2006) defined the power coefficient C_p as $^{16}/_{27}$.

$$\eta_{overall} = C_P \eta_{mechanical} \eta_{generator} \quad \dots (8)$$

$$C_P = 0.8 \quad \dots (9)$$

$$Betz's\ limit\ for\ 3\ bladed\ wind\ turbine = 0.47 \quad \dots (10)$$

Efficiency of generator in general $\eta_{generator} = 70\%$ … (11)

Mechanical efficiency in general $\eta_{mechanical} = 96\%$ … (12)

Therefore the system overall efficiency $\eta_{overall} = \tau$ … (13)

Power = $0.5\rho_{air} A_T (V_{rated})^3 \eta_{overall}$ … (14)

Blade Length (R)= R … (15)

Chord length =C … (16)

Solidity $(\sigma) = \frac{Bc}{2\pi R}$ … (17)

For three blade rotor (B=3)

Velocity Components of the Blade is defined by Grant (2011)
The velocity component is defined in equations (18 - 22). This is the second step. In this step, the aerodynamic forces acting on each sections of blade element were calculated, such as lift force, drag force, thrust force and moment force on each section of the blade element.

Linear velocity at each element $\omega_i = r_{ei}\Omega$ … (18)

Angular velocity $\Omega = 2\pi N/60$ … (19)

Rotor Speed $N = \frac{60\lambda V_{rated}}{(2\pi R)}$ … (20)

Radius at centre of element
$r_{ei} = 0.1728 + dr/2$ and $r_{ei} = r_{ei-1} + dr/2$ … (21)

Relative wind velocity at each element
$V_i = (Vrated^2 + \omega_i{}^2)^{0.5}$ … (22)

Lift and drag forces of each section of the blade element is given by Thiri (2007)
$dF_{Li} = 0.5\rho_{air} dA_b V_i^2 C_L$ … (23)

$dF_{Di} = 0.5\rho_{air} dA_b V_i^2 C_D$ … (24)

Element area,
$dA_{bi} = 0.5(C_s cos\beta_s + C_{s+1} cos\beta_{s+1})dr$ … (25)

Thrust and Moment Forces on each section of the blade element is defined by Perkins *et, al.*, (1978)

The thrust force on each blade element is defined in equation (26 – 27). This gives the aerodynamic characteristic of wind turbine blade for its effective performances.
$dF_{Ti} = dF_{Li} Cos\phi_i + dF_{Di} Sin\phi_i$ … (26)

Moment force of each element,
$dF_{Mi} = dF_{Li} Sin\phi_i + dF_{Di} Cos\phi_i$ … (27)

Available Wind Power from the Designed calculations, given by Peter *et, al.*, (2011).
The calculated wind power as defined in equation (28-29) by Peter. J. *et, al.,* (2011). is the calculated wind power on the basis of blade element momentum (BEM) theory.
Moment of each element**,**
$dM_i = dF_{Mi} r_{ei}$ … (28)
Power of each element,

$$dP_i = \Omega dM_i \quad \ldots (29)$$

RESULTS AND DISCUSSIONS

A micro horizontal axis wind turbine blade (HAWT) was optimised based on blade element momentum theory (BEM) for efficient extraction of wind energy to improve its performance. The blade element momentum theory allow you to divide a wind turbine blade into section of airfoil as in table (2-19), the aforementioned empirical model was subjected to each section of the turbine blade to assessed its aerodynamics effect such as lift force, drag force, thrust force, moment force, moment on each blade element and the extractible wind power as shown in table (2-19).

Table 2: Velocity Components of the Blade for Maiduguri

Section element number	Rotor Speed (rpm)	Angular Velocity (rad/s)	Linear Velocity (m/s)	Radius at Centre of Element (m)
1	353.3345	37.0059	6.3946	0.1728
2	353.3345	37.0059	7.2827	0.1968
3	353.3345	37.0059	8.1709	0.2208
4	353.3345	37.0059	9.0590	0.2448
5	353.3345	37.0059	9.9471	0.2688
6	353.3345	37.0059	10.8353	0.2928
7	353.3345	37.0059	11.7234	0.3168
8	353.3345	37.0059	12.6116	0.3408
9	353.3345	37.0059	13.4997	0.3648
10	353.3345	37.0059	14.3878	0.3888

Table 2 is the results of velocity component based on blade element momentum theory for Maiduguri Metropolis from equation (7-29). Similar work was done by manga *et, al.,* (2022), were they optimised a Horizontal Wind Axis Turbine Blade Using Computational Fluid Dynamic Software.

The first step of this study is to calculate the Mean Rotor Speed, Mean Angular Velocity and Mean Linear Velocity as in equation (18-22). The results show that, the Mean Rotor Speed ($\partial\overline{w_i}$) is 353.33 (rpm), the Mean Angular Velocity($\partial\overline{\Omega}$) is 37.01(rad/s), the Mean Linear Velocity ($\partial\bar{v}$) is 10.39 (m/s) and the Mean Radius at the Centre of the Element ($\partial\overline{r_{ei}}$) is 0.281m.

Table 3: Lift and Drag forces on each blade section for Maiduguri

Section element number	Section area (m^2)	Relative Velocity (m/s)	Rated Wind Speed (m/s)	Section Lift Force (N)	Section Drag Force (N)
1	0.0213	12.4257	10.654	3.0163	0.1106
2	0.0401	12.9052	10.654	1.7369	0.0636
3	0.0299	13.4265	10.654	2.5167	0.0922
4	0.0289	13.9847	10.654	2.8255	0.1036
5	0.0215	14.5758	10.654	4.1250	0.1512
6	0.0202	15.1957	10.654	4.7734	0.1750
7	0.0171	15.8413	10.654	6.1298	0.2248
8	0.0156	16.5094	10.654	7.2975	0.2676
9	0.0137	17.1974	10.654	9.0208	0.3308
10	0.0115	17.9030	10.654	11.5935	0.4251

Table 3 is the results of aerodynamic analysis for Maiduguri Metropolis. Grant *et, al.,* (2011) conducted a research on wind turbine blade analysis using blade element momentum theory, in his research he was able to deduced a model to calculate the aerodynamic effect in a rotating angular stream tube.

This study is focused on estimating the effect of aerodynamic forces acting on each blade element based on (BEM) theory of horizontal axis wind turbine blade. The results shows that, the mean sectional area is $0.022m^2$, mean relative velocity is$14.99m/s$ and the rated velocity is$10.65m/s$.

Secondly, the total lift forces exerted on each blade element can be obtained by summation of all lift forces dF_{L1} to dF_{L10} given as, F_L is $53.035N$ and for three blade wind turbine is$159.11N$. Thirdly, the total drag forces exerted on each blade can be obtained by summation of all drag forces dF_{D1} to dF_{D10} given as F_D is 1.945N and for three blade wind turbine is 5.835N, at a condition we the total lift force per total drag force is 27.2674 which is said to be equal to the coefficient of lift to drag ratio obtained from airfoil design workshop during selection of airfoil.

Table 4: Thrust, Moment and Power on each blade section for Maiduguri

Section Element Number	Thrust Force (N)	Moment Force (N)	Moment (Nm)	Power (W)
1	2.1309	2.2880	0.3953	14.6309
2	1.0743	1.4412	0.2836	10.4964
3	1.3746	2.2052	0.4869	18.0190
4	1.3772	2.5635	0.6275	23.2236
5	1.8127	3.8313	1.0298	38.1108
6	1.9093	4.5066	1.3195	48.8305
7	2.2501	5.8558	1.8551	68.6512
8	2.4760	7.0327	2.3967	88.6941
9	2.8464	8.7519	2.3967	118.1488
10	3.4229	11.3058	3.1927	162.6674

Table 4 is the results of thrust, moment and available wind power for Maiduguri Metropolis. Muyiwa (2014) conduct an evaluation on Rotor Blade Performance Analysis with Blade Element Momentum Theory. He used computational model to predict wind power which depends on optimised chord length, twisted angle and pitch angle. He also deduces a relationship between axial induction and tangential induction against extractible wind power. Firstly in this study we calculate the total thrust force exerted on each blade element, which can be obtained by summation of $dF_{T1} to\ dF_{T10}$. the total thrust force of each blade element F_T is $20.6744N$ and for three blade wind turbine is$62.0232N$.

Secondly, the total moment force exerted on each blade element can be obtained by summation of$dF_{M1} to\ dF_{M10}$. Total moment force of each blade element, F_M is 49.782 N and for three blade wind turbine is149.346 N.

Thirdly, the total moment exerted on each section of the blade element can be obtained by the summation of dM_1 todM_{10}. The total moment of each blade element, dM is 13.9838Nm and for three blade wind turbine is $41.9514Nm$

Fourthly, the total power extracted by each blade can be obtained by the summation of dP_1 todP_{10}. Total power of each blade element, P is $591.4727W$ and for three blade wind turbine is $1774.4181W$ or $1.774kW$.

Table 5: Velocity Components of the Blade for Sokoto

Section element number	Rotor Speed (rpm)	Angular Velocity (rad/s)	Linear Velocity (m/s)	Radius at Centre of Element (m)
1	326.37	34.18	5.9066	0.1728
2	326.37	34.18	6.8660	0.2008
3	326.37	34.18	7.8253	0.2289
4	326.37	34.18	8.7847	0.2569
5	326.37	34.18	9.7440	0.2850
6	326.37	34.18	10.7033	0.3131
7	326.37	34.18	11.6627	0.3411
8	326.37	34.18	12.6220	0.3692
9	326.37	34.18	13.5814	0.3973
10	326.37	34.18	14.5407	0.4253

Table 5 is the results of velocity component based on blade element momentum theory for Sokoto Metropolis from equation (7-29). Similar work was done by manga *et, al.,* (2022), were they optimised a Horizontal Wind Axis Turbine Blade Using Computational Fluid Dynamic Software.

The first step of this study is to calculate the Mean Rotor Speed, Mean Angular Velocity and Mean Linear Velocity as in equation (18-22). The results show that, the Mean Rotor Speed ($\partial\overline{w_i}$) is 326.37 (rpm), the Mean Angular Velocity($\partial\overline{\Omega}$) is 34.18(rad/s), the Mean Linear Velocity ($\partial\bar{v}$) is 10.224 (m/s) and the Mean Radius at the Centre of the Element ($\partial\overline{r_{ei}}$) is 0.29904m.

Table 6: Lift and Drag Forces on each Blade Section for Sokoto

Section element number	Section area (m^2)	Relative Velocity (m/s)	Rated Wind Speed (m/s)	Section Lift Force (N)	Section Drag Force (N)
1	0.0308	11.4775	9.841	2.5735	0.0943
2	0.0164	11.9994	9.841	1.5016	0.0550
3	0.0220	12.5730	9.841	2.2069	0.0809
4	0.0022	13.1915	9.841	0.2514	0.0092
5	0.0306	13.8488	9.841	3.7238	0.1365
6	0.0326	14.5398	9.841	4.3702	0.1602
7	0.0385	15.2599	9.841	5.6881	0.2086
8	0.0422	16.0050	9.841	6.8584	0.2515
9	0.0481	16.7720	9.841	8.5801	0.3146
10	0.0571	17.5579	9.841	11.1504	0.4089

Table 6 is the results of aerodynamic analysis for Sokoto Metropolis. Grant *et, al.,* (2011) conducted a research on wind turbine blade analysis using blade element momentum theory, in his research he was able to deduced a model to calculate the aerodynamic effect in a rotating angular stream tube.

This study is focused on estimating the effect of aerodynamic forces acting on each blade element based on (BEM) theory of horizontal axis wind turbine blade. The result shows that, the mean sectional area is $0.03205m^2$, mean relative velocity is$14.323m/s$ and the rated velocity is$9.841m/s$.

Secondly, the total lift forces exerted on each blade element can be obtained by summation of all lift forces dF_{L1} to dF_{L10} given as, F_L is $46.9044N$ and for three blade wind turbine is$140.7132N$.

Thirdly, the total drag forces exerted on each blade element can be obtained by summation of all drag forces dF_{D1} to dF_{D10} given as F_D is 1.719N and for three blade wind turbine is 5.159N, at a condition where the total lift force per total drag force is 27.2748 which is said to be equal to the coefficient of lift to drag ratio obtained from airfoil design workshop during selection of airfoil.

Table 7: Thrust, Moment and Power on each Blade Section for Sokoto

Section Element Number	Thrust Force (N)	Moment Force (N)	Moment (Nm)	Power (W)
1	2.4244	1.0437	0.1803	6.1652
2	1.3848	0.6831	0.1372	4.6903
3	1.9878	1.1052	0.2530	8.6489
4	0.2207	0.1364	0.0350	1.1988
5	3.1830	2.1655	0.6173	21.1010
6	3.6319	2.6954	0.8440	28.8505
7	4.5926	3.6898	1.2589	43.0341
8	5.3763	4.6481	1.7163	58.6691
9	6.5268	6.0414	2.4004	82.0515
10	8.2307	8.1167	3.4528	118.0244

Table 7 is the results of thrust, moment and available wind power for Sokoto Metropolis. Muyiwa (2014) conduct an evaluation on Rotor Blade Performance Analysis with Blade Element Momentum Theory. He used computational model to predict wind power which depends on optimised chord length, twisted angle and pitch angle. He also deduces a relationship between axial induction and tangential induction against extractible wind power. Firstly in this study we calculate the total thrust force exerted on each blade element, which can be obtained by summation of $dF_{T1} to\ dF_{T10}$. the total thrust force of each blade element F_T is $37.559N$ and for three blade wind turbine is$112.677N$.

Secondly, the total moment force exerted on each blade element can be obtained by summation of$dF_{M1} to\ dF_{M10}$. Total moment force of each blade element, F_M is $30.3253\ N$ and for three blade wind turbine is$90.9759\ N$.

Thirdly, the total moment exerted on each section of the blade element can be obtained by the summation of dM_1 todM_{10}. The total moment of each blade element, dM is $10.8952Nm$ and for three blade wind turbine is $32.6856Nm$

Fourthly, the total power extracted by each blade can be obtained by the summation of dP_1 todP_{10}. Total power of each blade element, P is $372.4338W$ and for three blade wind turbine is $1117.301W$ or $1.117kW$.

Table 8: Velocity Components of the Blade for Plateau

Section element number	Rotor Speed (rpm)	Angular Velocity (rad/s)	Linear Velocity (m/s)	Radius at Centre of Element (m)
1	301.33	31.56	5.4534	0.1728
2	301.33	31.56	6.4878	0.2055
3	301.33	31.56	7.5221	0.2383
4	301.33	31.56	8.5564	0.2711
5	301.33	31.56	9.5908	0.3038
6	301.33	31.56	10.6251	0.3366
7	301.33	31.56	11.6594	0.3694
8	301.33	31.56	12.6938	0.4022
9	301.33	31.56	13.7281	0.4349
10	301.33	31.56	14.7624	0.4677

Table 8 is the results of velocity component based on blade element momentum theory for Plateau Metropolis from equation (7-29). Similar work was done by manga *et, al.,* (2022), were they optimised a Horizontal Wind Axis Turbine Blade Using Computational Fluid Dynamic Software.
The first step of this study is to calculate the Mean Rotor Speed, Mean Angular Velocity and Mean Linear Velocity as in equation (18-22). The results show that, the Mean Rotor Speed ($\partial \overline{w_i}$) is 301.33 (rpm), the Mean Angular Velocity($\partial \overline{\Omega}$) is 31.56(rad/s), the Mean Linear Velocity ($\partial \bar{v}$) is 10.1079 (m/s) and the Mean Radius at the Centre of the Element ($\partial \overline{r_{ei}}$) is 0.32023m.

Table 9: Lift and Drag Forces on each Blade Section for Plateau

Section element number	Section area (m^2)	Relative Velocity (m/s)	Rated Wind Speed (m/s)	Section Lift Force (N)	Section Drag Force (N)
1	0.0308	10.5969	9.086	2.1938	0.0804
2	0.0164	11.1645	9.086	1.2999	0.0476
3	0.0220	11.7956	9.086	1.9425	0.0712
4	0.0022	12.4807	9.086	0.2250	0.0082
5	0.0306	13.2113	9.086	3.3889	0.1242
6	0.0326	13.9803	9.086	4.0403	0.1481
7	0.0385	14.7817	9.086	5.3372	0.1957
8	0.0422	15.6105	9.086	6.5245	0.2392
9	0.0481	16.4626	9.086	8.2664	0.3031
10	0.0571	17.3345	9.086	10.8689	0.3985

Table 9 is the results of aerodynamic analysis for Plateau Metropolis. Grant *et, al.,* (2011) conducted a research on wind turbine blade analysis using blade element momentum theory, in his research he was able to deduced a model to calculate the aerodynamic effect in a rotating angular stream tube.

This study is focused on estimating the effect of aerodynamic forces acting on each blade element based on (BEM) theory of horizontal axis wind turbine blade. The result shows that, the mean sectional area is $0.03265m^2$, mean relative velocity is$13.7419m/s$ and the rated velocity is$9.086m/s$.

Secondly, the total lift forces exerted on each blade element can be obtained by summation of all lift forces dF_{L1} to dF_{L10} given as, F_L is $44.0874N$ and for three blade wind turbine is$132.2622N$.

Thirdly, the total drag forces exerted on each blade element can be obtained by summation of all drag forces dF_{D1} to dF_{D10} given as F_D is 1.6162N and for three blade wind turbine is 4.8486N, at a condition where the total lift force per total drag force is 27.2784 which is said to be equal to the coefficient of lift to drag ratio obtained from airfoil design workshop during selection of airfoil.

Table 10: Thrust, Moment and Power on each Blade Section For Plateau

Section Element Number	Thrust Force (N)	Moment Force (N)	Moment (Nm)	Power (W)
1	2.0666	0.8897	0.1537	4.8523
2	1.1611	0.6697	0.1376	4.3454
3	1.6296	1.1760	0.2803	8.8464
4	0.1763	0.1525	0.0413	1.3055
5	2.4757	2.4926	0.7575	23.9065
6	2.7517	3.1558	1.0624	33.5311
7	3.3929	4.3621	1.6115	50.8601
8	3.8798	5.5210	2.2206	70.0835
9	4.6101	7.1875	3.1265	98.6715
10	5.7022	9.6544	4.5160	142.5231

Table 10 is the results of thrust, moment and available wind power for Plateau Metropolis. Muyiwa (2014) conduct an evaluation on Rotor Blade Performance Analysis with Blade Element Momentum Theory. He used computational model to predict wind power which depends on optimised chord length, twisted angle and pitch angle. He also deduces a relationship between axial induction and tangential induction against extractible wind power. Firstly in this study we calculate the total thrust force exerted on each blade element, which can be obtained by summation of $dF_{T1} to\ dF_{T10}$. the total thrust force of each blade element F_T is $27.846N$ and for three blade wind turbine is$83.538N$.

Secondly, the total moment force exerted on each blade element can be obtained by summation of$dF_{M1} to\ dF_{M10}$. Total moment force of each blade element, F_M is $35.2613\ N$ and for three blade wind turbine is$105.784\ N$.

Thirdly, the total moment exerted on each section of the blade element can be obtained by the summation of dM_1 todM_{10}. The total moment of each blade element, dM is $13.9074Nm$ and for three blade wind turbine is $41.7222Nm$

Fourthly, the total power extracted by each blade can be obtained by the summation of dP_1 todP_{10}. Total power of each blade element, P is $438.925W$ and for three blade wind turbine is $1316.776W$ or $1.3167kW$.

Table 11: Velocity Components of the Blade for Lagos

Section element number	Rotor Speed (rpm)	Angular Velocity (rad/s)	Linear Velocity (m/s)	Radius at Centre of Element (m)
1	288.69	30.24	5.2248	0.1728
2	288.69	30.24	6.2985	0.2083
3	288.69	30.24	7.3723	0.2438
4	288.69	30.24	8.4461	0.2793
5	288.69	30.24	9.5199	0.3148
6	288.69	30.24	10.5937	0.3503
7	288.69	30.24	11.6675	0.3858
8	288.69	30.24	12.7413	0.4213
9	288.69	30.24	13.8150	0.4569
10	288.69	30.24	14.8888	0.4924

Table 11 is the results of velocity component based on blade element momentum theory for Lagos Metropolis from equation (7-29). Similar work was done by manga *et, al.,* (2022), were they optimised a Horizontal Wind Axis Turbine Blade Using Computational Fluid Dynamic Software.
The first step of this study is to calculate the Mean Rotor Speed, Mean Angular Velocity and Mean Linear Velocity as in equation (18-22). The results show that, the Mean Rotor Speed ($\partial\overline{w_i}$) is 288.69 (rpm), the Mean Angular Velocity($\partial\overline{\Omega}$) is 30.24(rad/s), the Mean Linear Velocity ($\partial\bar{v}$) is 10.0568 (m/s) and the Mean Radius at the Centre of the Element ($\partial\overline{r_{el}}$) is 0.3326m.

Table 12: Lift and Drag forces on each Blade Section for Lagos

Section element number	Section area (m^2)	Relative Velocity (m/s)	Rated Wind Speed (m/s)	Section Lift Force (N)	Section Drag Force (N)
1	0.026	5.2248	8.705	2.0136	0.0738
2	0.0312	6.2985	8.705	1.2040	0.0441
3	0.03029	7.3723	8.705	1.8167	0.0666
4	0.0285	8.4461	8.705	0.2125	0.0077
5	0.0266	9.5199	8.705	3.2310	0.1184
6	0.0245	10.5937	8.705	3.8864	0.1425
7	0.0223	11.6675	8.705	5.1762	0.1898
8	0.0201	12.7413	8.705	6.3753	0.2338
9	0.0181	13.8150	8.705	8.1327	0.2982
10	0.0159	14.8888	8.705	10.7593	0.3945

Table 12 is the results of aerodynamic analysis for Lagos Metropolis. Grant *et, al.,* (2011) conducted a research on wind turbine blade analysis using blade element momentum theory, in his research he was able to deduced a model to calculate the aerodynamic effect in a rotating angular stream tube.

This study is focused on estimating the effect of aerodynamic forces acting on each blade element based on (BEM) theory of horizontal axis wind turbine blade. The result shows that, the mean sectional area is $0.02435m^2$, mean relative velocity is$10.0568m/s$ and the rated velocity is$8.705m/s$.

Secondly, the total lift forces exerted on each blade element can be obtained by summation of all lift forces dF_{L1} to dF_{L10} given as, F_L is $42.877N$ and for three blade wind turbine is$128.63N$.
Thirdly, the total drag forces exerted on each blade element can be obtained by summation of all drag forces dF_{D1} to dF_{D10} given as F_D is 1.5694N and for three blade wind turbine is

4.7082N, at a condition where the total lift force per total drag force is 27.3206 which is said to be equal to the coefficient of lift to drag ratio obtained from airfoil design workshop during selection of airfoil.

Table 13: Thrust, Moment and Power on each Blade Section For Lagos

Section Element Number	Thrust Force (N)	Moment Force (N)	Moment (Nm)	Power (W)
1	1.8971	0.8164	0.1410	4.2658
2	0.5688	1.1009	0.2293	6.9346
3	0.5397	1.7709	0.4318	13.0561
4	0.0468	0.2103	0.0587	1.7766
5	0.5754	3.2151	1.0123	30.6082
6	0.5889	3.8772	1.3584	41.0744
7	0.6905	5.1703	1.9951	60.3251
8	0.7666	6.3726	2.6853	81.1953
9	0.8960	8.1327	3.7159	112.3549
10	1.0993	10.7615	5.2991	160.2273

Table 13 is the results of thrust, moment and available wind power for Lagos Metropolis. Muyiwa (2014) conduct an evaluation on Rotor Blade Performance Analysis with Blade Element Momentum Theory. He used computational model to predict wind power which depends on optimised chord length, twisted angle and pitch angle. He also deduces a relationship between axial induction and tangential induction against extractible wind power. Firstly in this study we calculate the total thrust force exerted on each blade element, which can be obtained by summation of $dF_{T1} to\ dF_{T10}$. the total thrust force of each blade element F_T is $7.6691N$ and for three blade wind turbine is$23.0073N$.

Secondly, the total moment force exerted on each blade element can be obtained by summation of$dF_{M1} to\ dF_{M10}$. Total moment force of each blade element, F_M is $41.4279\ N$ and for three blade wind turbine is$124.2837\ N$.

Thirdly, the total moment exerted on each section of the blade element can be obtained by the summation of dM_1 todM_{10}. The total moment of each blade element, dM is $16.9269Nm$ and for three blade wind turbine is $50.7807Nm$

Fourthly, the total power extracted by each blade can be obtained by the summation of dP_1 todP_{10}. Total power of each blade element, P is $511.8183W$ and for three blade wind turbine is $1535.455W$ or $1.5354kW$.

Table 14: Velocity Components of the Blade for Owerri

Section element number	Rotor Speed (rpm)	Angular Velocity (rad/s)	Linear Velocity (m/s)	Radius at Centre of Element (m)
1	215.9	22.61	3.9073	0.1728
2	215.9	22.61	5.2588	0.2325
3	215.9	22.61	6.6102	0.2923
4	215.9	22.61	7.9617	0.3521
5	215.9	22.61	9.3132	0.4118
6	215.9	22.61	10.6646	0.4716
7	215.9	22.61	12.0161	0.5314
8	215.9	22.61	13.3676	0.5911
9	215.9	22.61	14.7190	0.6509
10	215.9	22.61	16.0705	0.7107

Table 14 is the results of velocity component based on blade element momentum theory for Owerri Metropolis from equation (7-29). Similar work was done by manga *et, al.,* (2022), were they optimised a Horizontal Wind Axis Turbine Blade Using Computational Fluid Dynamic Software.

The first step of this study is to calculate the Mean Rotor Speed, Mean Angular Velocity and Mean Linear Velocity as in equation (18-22). The results show that, the Mean Rotor Speed ($\partial\overline{w_i}$) is 215.9 (rpm), the Mean Angular Velocity($\partial\overline{\Omega}$) is 22.61(rad/s), the Mean Linear Velocity ($\partial\bar{v}$) is 9.9889 (m/s) and the Mean Radius at the Centre of the Element ($\partial\overline{r_{ei}}$) is 0.4417m.

Table 15: Lift and Drag forces on each blade section for Owerri

Section element number	Section area (m^2)	Relative Velocity (m/s)	Rated Wind Speed (m/s)	Section Lift Force (N)	Section Drag Force (N)
1	0.026	7.5925	6.51	1.1262	0.0413
2	0.0312	8.3687	6.51	0.7303	0.0267
3	0.03029	9.2777	6.51	1.2017	0.0440
4	0.0285	10.2844	6.51	0.1528	0.0056
5	0.0266	11.3629	6.51	2.5069	0.0919
6	0.0245	12.4946	6.51	3.2272	0.1183
7	0.0223	13.6663	6.51	4.5621	0.1673
8	0.0201	14.8685	6.51	5.9189	0.2170
9	0.0181	16.0944	6.51	7.9008	0.2897
10	0.0159	17.3390	6.51	10.8745	0.3988

Table 15 is the results of aerodynamic analysis for Owerri Metropolis. Grant *et, al.,* (2011) conducted a research on wind turbine blade analysis using blade element momentum theory, in his research he was able to deduced a model to calculate the aerodynamic effect in a rotating angular stream tube.

This study is focused on estimating the effect of aerodynamic forces acting on each blade element based on (BEM) theory of horizontal axis wind turbine blade. The result shows that, the mean sectional area is $0.02435m^2$, mean relative velocity is$12.1349m/s$ and the rated velocity is$6.51m/s$.

Secondly, the total lift forces exerted on each blade element can be obtained by summation of all lift forces dF_{L1} to dF_{L10} given as, F_L is $35.2014N$ and for three blade wind turbine is$114.6042N$.

Thirdly, the total drag forces exerted on each blade element can be obtained by summation of all drag forces dF_{D1} to dF_{D10} given as F_D is 1.4006N and for three blade wind turbine is 4.2018N, at a condition where the total lift force per total drag force is 27.2750 which is said to be equal to the coefficient of lift to drag ratio obtained from airfoil design workshop during selection of airfoil.

Table 16: Thrust, Moment and Power on each blade section for Owerri

Section Element Number	Thrust Force (N)	Moment Force (N)	Moment (Nm)	Power (W)
1	1.0609	0.4565	0.0788	1.7837
2	0.6199	0.4315	0.1003	2.2695
3	0.9000	0.8611	0.2517	5.6927
4	0.1007	0.1221	0.0429	0.9722
5	1.4624	2.1398	0.8813	19.9290
6	1.6810	2.8730	1.3550	30.6397
7	2.1419	4.1776	2.2200	50.1988
8	2.5275	5.5272	3.2675	73.8867
9	3.0928	7.4829	4.8709	110.1416
10	3.9318	10.4079	7.3970	167.2613

Table 16 is the results of thrust, moment and available wind power for Owerri Metropolis. Muyiwa (2014) conduct an evaluation on Rotor Blade Performance Analysis with Blade Element Momentum Theory. He used computational model to predict wind power which depends on optimised chord length, twisted angle and pitch angle. He also deduces a relationship between axial induction and tangential induction against extractible wind power. Firstly in this study we calculate the total thrust force exerted on each blade element, which can be obtained by summation of $dF_{T1} to\ dF_{T10}$. the total thrust force of each blade element F_T is $17.5189N$ and for three blade wind turbine is$52.556N$.

Secondly, the total moment force exerted on each blade element can be obtained by summation of$dF_{M1} to\ dF_{M10}$. Total moment force of each blade element, F_M is $34.4796\ N$ and for three blade wind turbine is$103.4388\ N$.

Thirdly, the total moment exerted on each section of the blade element can be obtained by the summation of dM_1 todM_{10}. The total moment of each blade element, dM is $20.4654Nm$ and for three blade wind turbine is $61.3962Nm$

Fourthly, the total power extracted by each blade can be obtained by the summation of dP_1 todP_{10}. Total power of each blade element, P is $462.7752W$ and for three blade wind turbine is $1388.376W$ or $1.388kW$.

Table 17: Velocity Components of the Blade for Enugu

Section element number	Rotor Speed (rpm)	Angular Velocity (rad/s)	Linear Velocity (m/s)	Radius at Centre of Element (m)
1	252.58	26.45	4.5711	0.1728
2	252.58	26.45	5.7715	0.2181
3	252.58	26.45	6.9719	0.2635
4	252.58	26.45	8.1723	0.3089
5	252.58	26.45	9.3727	0.3543
6	252.58	26.45	10.5731	0.3996
7	252.58	26.45	11.7735	0.4450
8	252.58	26.45	12.9739	0.4904
9	252.58	26.45	15.3747	0.5358
10	252.58	26.45	16.5751	0.5812

Table 17 is the results of velocity component based on blade element momentum theory for Enugu Metropolis from equation (7-29). Similar work was done by manga *et, al.,* (2022), were they optimised a Horizontal Wind Axis Turbine Blade Using Computational Fluid Dynamic Software.

The first step of this study is to calculate the Mean Rotor Speed, Mean Angular Velocity and Mean Linear Velocity as in equation (18-22). The results show that, the Mean Rotor Speed ($\partial\overline{w_i}$) is 252.58 (rpm), the Mean Angular Velocity($\partial\overline{\Omega}$) is 26.45(rad/s), the Mean Linear Velocity ($\partial\bar{v}$) is 10.2129 (m/s) and the Mean Radius at the Centre of the Element ($\partial\overline{r_{ei}}$) is 0.3769m.

Table 18: Lift and Drag forces on each blade section for Enugu

Section element number	Section area (m^2)	Relative Velocity (m/s)	Rated Wind Speed (m/s)	Section Lift Force (N)	Section Drag Force (N)
1	0.026	8.8825	7.616	1.5413	0.0565
2	0.0312	9.5558	7.616	0.9523	0.0349
3	0.03029	10.3253	7.616	1.4884	0.0545
4	0.0285	11.1710	7.616	0.1802	0.0066
5	0.0266	12.0769	7.616	2.8319	0.1038
6	0.0245	13.0305	7.616	3.5100	0.1287
7	0.0223	14.0221	7.616	4.8028	0.1761
8	0.0201	15.0442	7.616	6.0596	0.2222
9	0.0181	16.0908	7.616	7.8973	0.2896
10	0.0159	17.1577	7.616	10.6483	0.3905

Table 18 is the results of aerodynamic analysis for Enugu Metropolis. Grant *et, al.,* (2011) conducted a research on wind turbine blade analysis using blade element momentum theory, in his research he was able to deduced a model to calculate the aerodynamic effect in a rotating angular stream tube.

This study is focused on estimating the effect of aerodynamic forces acting on each blade element based on (BEM) theory of horizontal axis wind turbine blade. The result shows that, the mean sectional area is $0.02435m^2$, mean relative velocity is$12.7357m/s$ and the rated velocity is$7.616m/s$.
Secondly, the total lift forces exerted on each blade element can be obtained by summation of all lift forces dF_{L1} to dF_{L10} given as, F_L is $39.9121N$ and for three blade wind turbine is$119.7363N$.

Thirdly, the total drag forces exerted on each blade element can be obtained by summation of all drag forces dF_{D1} to dF_{D10} given as F_D is 1.4634N and for three blade wind turbine is 4.3902N, at a condition where the total lift force per total drag force is 27.2735 which is said to be equal to the coefficient of lift to drag ratio obtained from airfoil design workshop during selection of airfoil.

Table 19: Thrust, Moment and Power on each blade section for Enugu

Section Element Number	Thrust Force (N)	Moment Force (N)	Moment (Nm)	Power (W)
1	1.4521	0.6249	0.1079	2.8567
2	0.8310	0.5258	0.1147	3.0351
3	1.1853	0.9863	0.2599	6.8764
4	0.1303	0.1339	0.0413	1.0949
5	1.8581	2.2701	0.8043	21.2773
6	2.0982	2.9629	1.1842	31.3274
7	2.6277	4.2054	1.8716	49.5131
8	3.0531	5.4488	2.6723	70.6929
9	3.6821	7.2433	3.8811	102.6705
10	4.6175	9.9154	5.7628	152.4478

Table 19 is the results of thrust, moment and available wind power for Enugu Metropolis. Muyiwa (2014) conduct an evaluation on Rotor Blade Performance Analysis with Blade Element Momentum Theory. He used computational model to predict wind power which depends on optimised chord length, twisted angle and pitch angle. He also deduces a relationship between axial induction and tangential induction against extractible wind power. Firstly in this study we calculate the total thrust force exerted on each blade element, which can be obtained by summation of $dF_{T1} to\ dF_{T10}$. the total thrust force of each blade element F_T is $21.5354N$ and for three blade wind turbine is$64.6062N$.

Secondly, the total moment force exerted on each blade element can be obtained by summation of$dF_{M1} to\ dF_{M10}$. Total moment force of each blade element, F_M is $34.3168\ N$ and for three blade wind turbine is$102.9504\ N$.

Thirdly, the total moment exerted on each section of the blade element can be obtained by the summation of dM_1 todM_{10}. The total moment of each blade element, dM is $16.7001Nm$ and for three blade wind turbine is $50.1003Nm$.

Fourthly, the total power extracted by each blade can be obtained by the summation of dP_1 todP_{10}. Total power of each blade element, P is $441.7921W$ and for three blade wind turbine is $1325.376W$ or $1.3254kW$.

CONCLUSIONS

In this research, we have estimated the performance of a horizontal axis wind turbine blade for some stations in Nigeria based on blade element momentum (BEM) theory. In this method, the blade of a wind turbine is divided into several element where by each sections of the blade element is acted upon by forces. The coefficient of lift and drag were selected at an optimum angle of attack for the purpose of aerodynamic analysis using airfoil design workshop. The aerodynamic characteristics of each selected stations across six geopolitical zones such as the Incremental Lift force, Incremental drag force, velocity component, thrust force, moment force and extractible wind power were all investigated and calculated. Maiduguri Metropolis was found to be best fit for surface wind electrification due to it semi-arid region.

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