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Design and Implementation of a Renewable Energy System for Wind Turbine Power Analysis at Ikot Akpaden Community

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Abstract: *Renewable energy plays a crucial role in sustainable development by enhancing human development and economic productivity. Analyzing the pipeline of installed wind farms across Africa reveals that the continent has substantial wind resources, with the potential to expand capacity by over 900% through the addition of 140 planned projects. The design and implementation of a renewable energy system for wind turbine power analysis in Ikot Akpaden Community serve as a valuable demonstration of wind energy's effectiveness in mitigating high carbon flaring and other environmental pollutants, benefiting both the present and future environment. The analysis evaluates wind velocity and its significant power output based on the design parameters of the system in used. The experiment is carried out between the hours of 8:00 am to 9:00 pm for 7 days. Results show that wind velocity of Akpaden community varies between 2.67 m/s to 4.57 m/s with an average wind velocity of 4.03 m/s, there are limitation of some hours of the day without significant wind velocity but there is no complete 24 hours of a day that could be without free flow of wind energy. Using a wind turbine with a minimum sweep area of 0.283* m^2*, the power output produced by the available wind velocity ranges from 3.0 W to 8.82 W in a second, therefore by comparison with the theoretical power output of 11.32 W using the system designed parameters, there is 78 percent efficiency in the system design. Also, there is significant drop in power output between the hours of 3:00 pm and 4:00 pm as it is shown on the graphical representation which is as a result of decrease in the wind velocity of the area within that time. It is therefore seen that there is a useful power available in the wind velocity of the study region in which when it is collected and stored, can serve as a useful energy for student during their experiment and research purpose. The wind turbine's output power can be improved to a desired percent using turbine with larger blade radius and sweep area.*

Keywords: *Efficiency, Power, Renewable, Turbine, Velocity, Wind energy.*

1. INTRODUCTION

Wind energy is one of the most important resources for generating electricity and is used extensively throughout the world among the different renewable energy sources, including solar, wind, hydro, geothermal, biomass, and ocean thermal power [1]. Due to its many benefits, wind energy is one of the energy sources with the quickest rate of growth in the world [2]. Researchers are tackling technical and socioeconomic issues to promote a future with decarbonised power in order to maximise its potential and societal benefits across the globe [3]. Through 2026, it is anticipated that the world's energy demand would increase at an average annual rate of 3.4% due to better economic conditions that will speed up the use of power in both developed and developing nations.

Renewable energy sources are predicted to overtake coal and other fossil fuels as the primary source of electricity generated worldwide by early 2025. It is projected that the proportion of renewable energy sources in the production of electricity will increase from 30% in 2023 to 37% in 2026, with the expansion of solar photovoltaic (PV) systems playing a significant role in this increase. Renewables are anticipated to reduce dependency on fossil fuels during this time by offsetting demand increases in developed economies such as the US and the EU. Regions with significant levels of variable renewable generation are establishing new markets and implementing certain operational measures to guarantee the stability of the power system. Increasingly, battery storage systems are being used to increase system flexibility and stabilize grid frequency, which is crucial for incorporating renewable energy sources [4].

Countries with significant wind energy potential are leveraging this resource to address electricity demand, particularly in regions with energy resource constraints. In areas where electricity access is below 50%, wind power, combined with solar energy, biomass, and hydro, offers a viable low-carbon solution [4].

1.1 Cumulative Wind Power Capacity Worldwide

Figure 1 gives a list of the largest onshore global wind farms that are currently operational, rated by generating capacity [5].

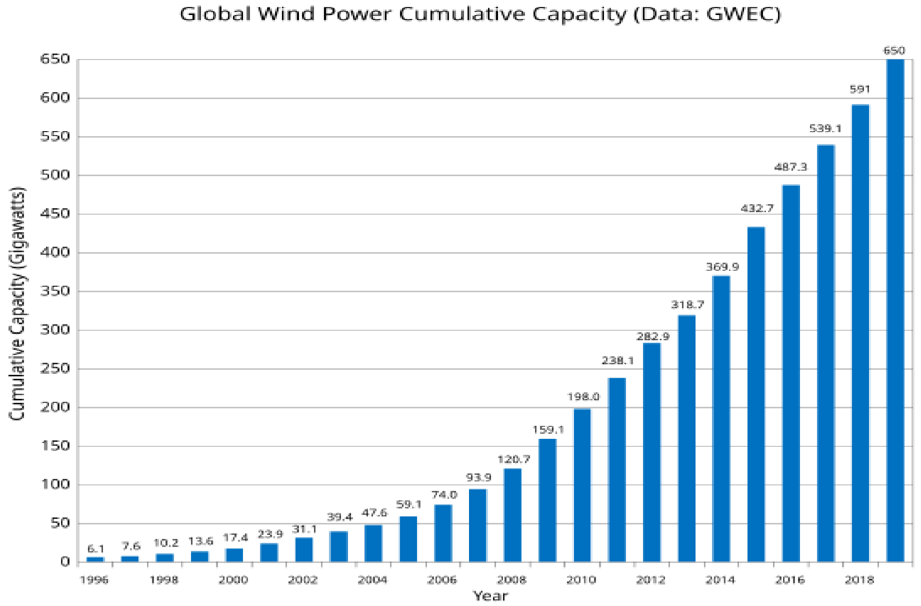

Figure 1: Cumulative wind power capacity worldwide [5]

1.2 Electric Wind Generator

By converting mechanical energy into electrical energy, a wind turbine also referred to as an electric wind generator produces electricity. It neither generates energy nor generates more electrical energy than the rotor blades' mechanical energy. More mechanical power is needed to turn the rotor of a generator when the electrical demand, or "load," is higher.

As seen in the wind electric farm depicted in Figure 2, wind power is used to produce mechanical power or electricity, providing energy to residences, workplaces, schools, and laboratories. Wind energy is initially transformed into mechanical energy by the wind turbine's generator, which subsequently turns that mechanical energy into electrical power [6].

Figure 2: Wind electric farm [7]

2. REVIEW OF RELATED LITERATURE

One of the most dependable renewable energy sources in the world is wind energy. Seasons, the time of day, and general weather patterns all affect average wind speeds, though. Periods of relatively weaker winds are often followed by multiple days of strong wind speeds at a particular place. Together, the United States, China, India, and Europe have 93% of the world's installed wind power capacity. Between 2000 and 2013, more than 100 GW of wind power capacity was built in Europe. Even though coal, natural gas, and oil account for more than 80% of the US's energy consumption, by the end of 2013, more than 61.1 GW of wind generating capacity had been constructed. China became the world leader in wind energy, adding over 91 GW of capacity in just eight years to fulfil the demands of its tremendous industrialization, while India reached about 21 GW of cumulative wind power capacity by 2014 [4].

With average wind speeds ranging from 3.5 to 10 meters per second at elevations of 10 to 20 meters, Africa has a significant potential for wind energy. Significant progress is being made by the continent in the development of renewable energy [8]. For example, in Senegal and Kenya, wind energy accounts for 15% and 17% of total power output, respectively. The first Status of Wind in Africa report, released by the Global Wind Energy Council's Africa Wind Power program, gives a broad overview of the continent's wind business and forecasts substantial development. There are currently 83 wind farms operating in Africa, generating 9 GW of clean energy. With 140 projects scheduled to add an additional 86 GW of installed capacity, the project pipeline indicates that capacity might increase by more than 900% [8, 9].

Several major wind energy projects illustrate global developments in the area. The 522.8 MW Sagamore Wind Farm is an onshore wind project located in New Mexico, USA. Constructed in stages, the farm was put into operation in December 2020 after construction started in 2019 [10]. In response to a presidential mandate on renewable energy pilot projects released in December 2019 [11], ACWA Power developed the Azerbaijan 240 MW Wind Farm, a greenfield Independent Power Project (IPP). Similar to this, private IPPs are able to sell energy directly to consumers via the national grid thanks to Morocco's Khalladi 120 MW Wind Farm, which was built under the Renewable Energy Law. In 2014, ACWA Power purchased a majority interest in this project [11].

The Australian Renewable Energy Hub, originally known as the Asian Renewable Energy Hub, will be located in Australia's Pilbara region. This updated proposal, which was approved in January 2023, consists of seven projects with a combined wind and solar capacity of 26 GW with the goal of producing green hydrogen [12, 13].

Early vertical-axis windmills were employed for grain processing in the Seitan region of Iran and Afghanistan, which is where windmills first appeared. Horizontal-axis windmills, like the post or trestle mill, first appeared in Dutch Normandy around 1180 and swiftly expanded across Europe. With a mill house with a revolving tower cap and rotor blades, these ideas developed into the tower mill in the 14th century and, in the 16th century, the famous Dutch windmill, which is still in use today for conventional milling operations [14].

Wind turbines capture wind energy, which is the kinetic energy of flowing air, and transform it into mechanical energy and subsequently electrical energy. These gadgets, which are sometimes called wind generators, are crucial for supplying changing energy needs [15]. Understanding the energy, mechanical, structural, and construction aspects of wind turbine design, building, and operation is essential to creating efficient wind turbines. The sector's consistent advancement is demonstrated by Figure 3, which shows the expansion of wind energy capacity and production in the United States from 1999 to 2009 [16].

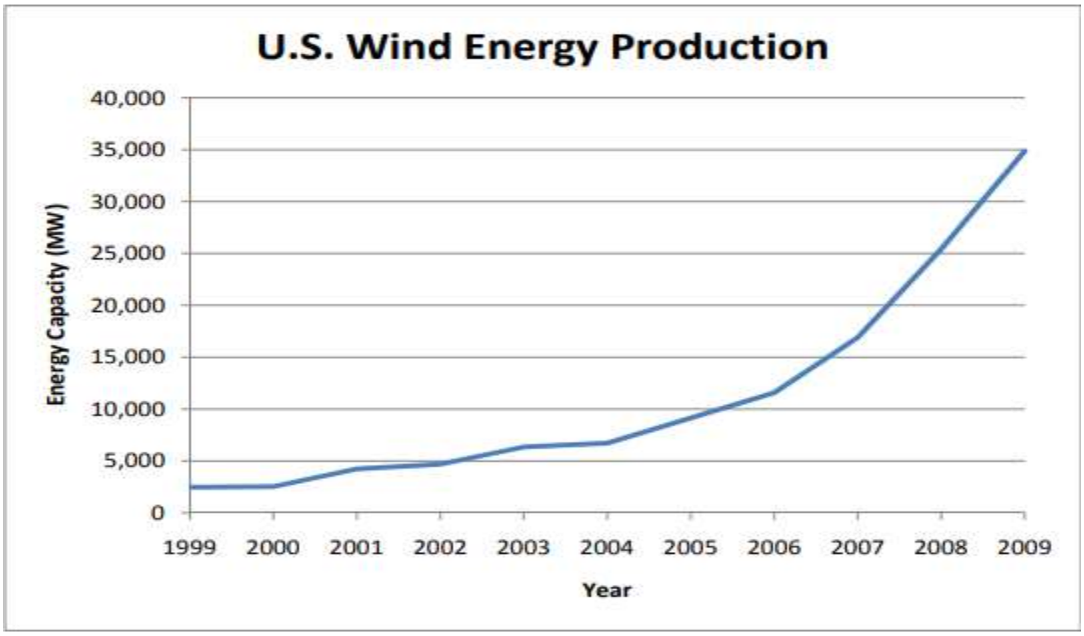

Figure 3: U.S. wind production [17]

2.1 Different Turbine Types

Wind turbines come in two main varieties: horizontal-axis wind turbines (HAWT) and vertical-axis wind turbines (VAWT) [18, 19]. Both types are illustrated in Figure 3. Among these, horizontal-axis wind turbines are more commonly used and widely available. Due to the abundance of information regarding their construction, the HAWT model will be utilized in this project.

The components of a horizontal-axis wind turbine (HAWT) are depicted in Figure 4. The essential elements of a basic HAWT include blades, rotor, shaft, a simple transmission system, generator, vane, nacelle (casing), and tower, as shown in Figure 5 [20].

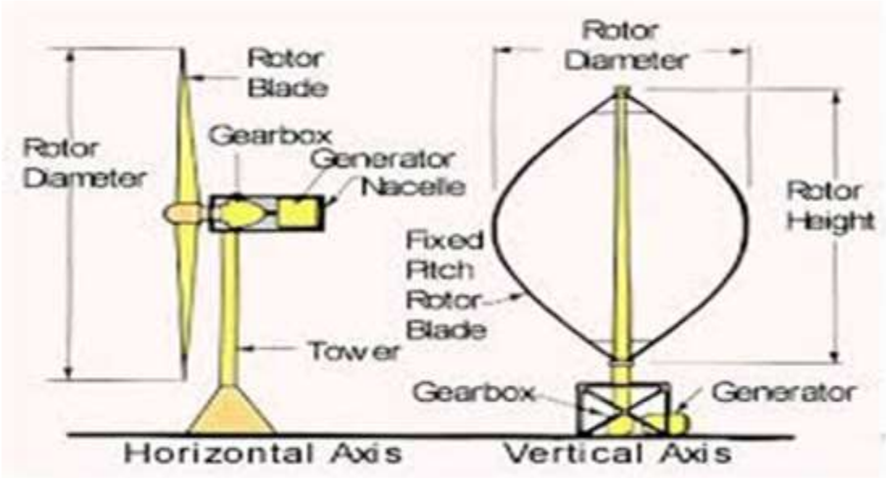

Figure 4: Horizontal and vertical wind turbine [20]

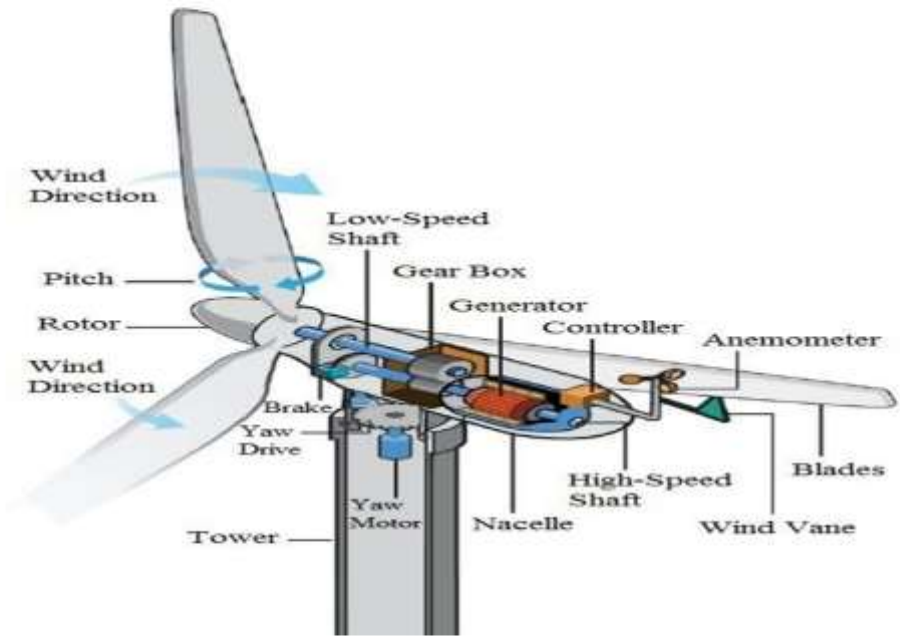

Figure 5: Horizontal Axis wind turbine (HAWT) [20]

2.2 Power Law of a Wind Turbine

The usable power (P) of a wind turbine, which is represented by the power flow law cylinder in Figure 6, is the ratio of the kinetic energy received over time. Typically, a wind turbine transforms the kinetic energy in the wind's moving mass into rotational energy and are govern by Equations 1-9 [21, 22].

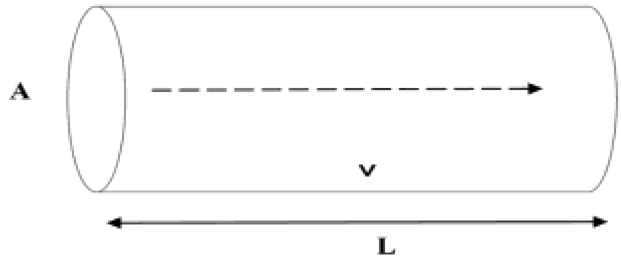

Figure 6: Power flow law cylinder [21]

$$\text{Kinetic Energy (K.E)} = \frac{1}{2}mv^2 \quad (1)$$

$$\text{Power (P)} = \frac{K.E}{t} = \frac{\frac{1}{2}mv^2}{t} = \frac{1}{2} \times v^2 \times \frac{m}{t} \quad (2)$$

$$\text{As Mass flow rate} = \frac{m}{t} \quad (3)$$

$$\text{Distance (L)} = \text{Velocity} \times \text{Time} \times vt \quad (4)$$

$$\text{Time (t)} = \frac{L}{v} \quad (5)$$

$$\text{Density } (\rho) = \frac{\text{mass}}{\text{volume}} = \frac{m}{v} \quad (6)$$

$$\text{Mass} = \text{density} \times \text{volume} = \rho \times v = \rho \times A \times L \quad (7)$$

$$\text{Power} = \frac{\frac{1}{2} \times v^2 \times \rho \times A \times L}{\frac{L}{v}} = \frac{1}{2} \times v^2 \times \rho \times A \times v \quad (8)$$

$$\text{Power (P)} = \frac{1}{2} \times A \times \rho \times v^3 \quad (9)$$

where $A = \pi R^2$ = Area of the circle swept by the rotor blades (m2), V = Wind velocity in m/s, and ρ = Air density in kg/m3 = 1.223 kg/m. Therefore, the air density (often around 1.223 kg/m3), the swept area of the turbine blades (imagine a large circle formed by the spinning blades), and the wind speed determine how much power a wind turbine can produce. Wind speed is undoubtedly the most significant variable input among these. Since wind speed is cubed, it is the most significant variable; the other inputs are also significant, but not as much as wind speed [23, 24].

2.3 Turbine Performance Characterization

A wind turbine's power curve, which shows the electric power output as a function of wind speed at the hub height, is commonly used to describe its performance. Without needing specific knowledge about the wind turbine or its parts, this curve makes it possible to forecast the power output and energy production of a wind turbine [6, 25].

Two wind turbine models—ATB Riva Calzoni 500 kW and Enercon3 500 kW—were chosen for this investigation because they closely match the typical wind speeds of the sites that were picked. The 3500 kW wind turbine's power curve is shown in Figure 7 [26].

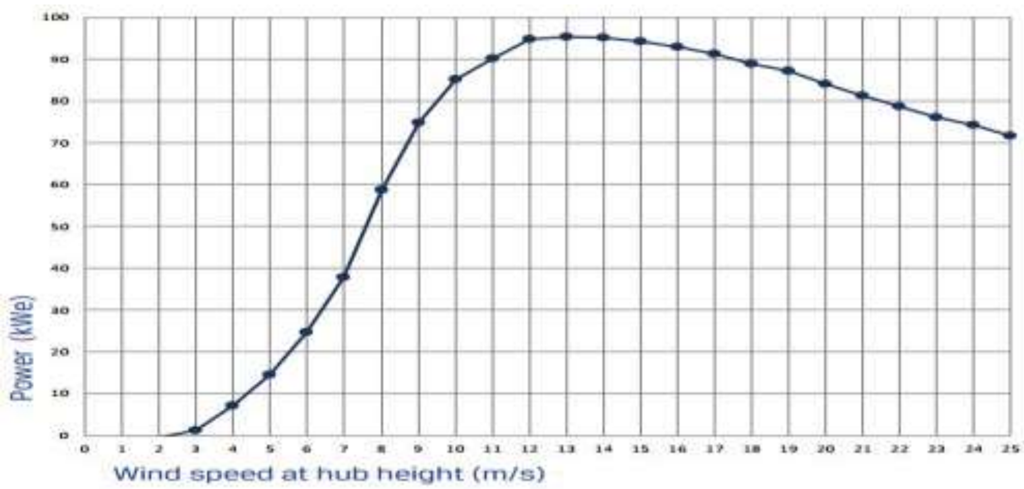

Figure 7: Power curve of a wind turbine [26]

2.4. Lift and Drag Forces on Wind Turbine

Aerodynamic forces like lift and drag are influenced by an object's size, form, air quality, and speed. Lift is the force that operates at a right angle to the direction of travel in the air and is produced by variations in air pressure. It is directed perpendicular to the flight path, as shown in Figure 8. Drag is the force acting against the direction of motion and is directed along the flight path [27, 28].

2.5 Tip-Speed Ratio

The link between a wind turbine blade tip's rotational speed and the free-stream wind's velocity is known as the tip-speed ratio (TSR). Achieving the perfect TSR is essential for effective turbine performance since the maximum lift-to-drag ratio is ensured by an optimal angle of attack, which is dependent on wind speed. The following formula of Equation (10) defines the TSR [29].

$$\text{TSR} = \frac{\Omega R}{v} \quad (10)$$

Where: Ω is the rotational speed in radians per second, R is the rotor radius, and v is the free-stream wind velocity.

The placement of the turbine determines the wind speed. A example wind speed distribution curve that adheres to a Weibull distribution is shown in Figure 9. The probability function for 800 wind speed intervals (bins), each with a width of 0.025 m/s, is shown by the curve [29, 30].

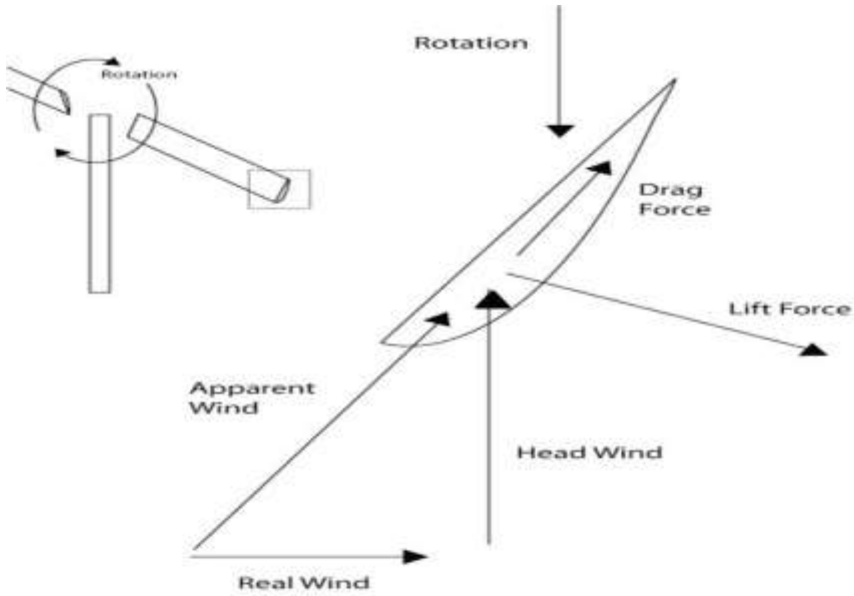

Figure 8: Lift/Drag forces experienced by turbine blades [27]

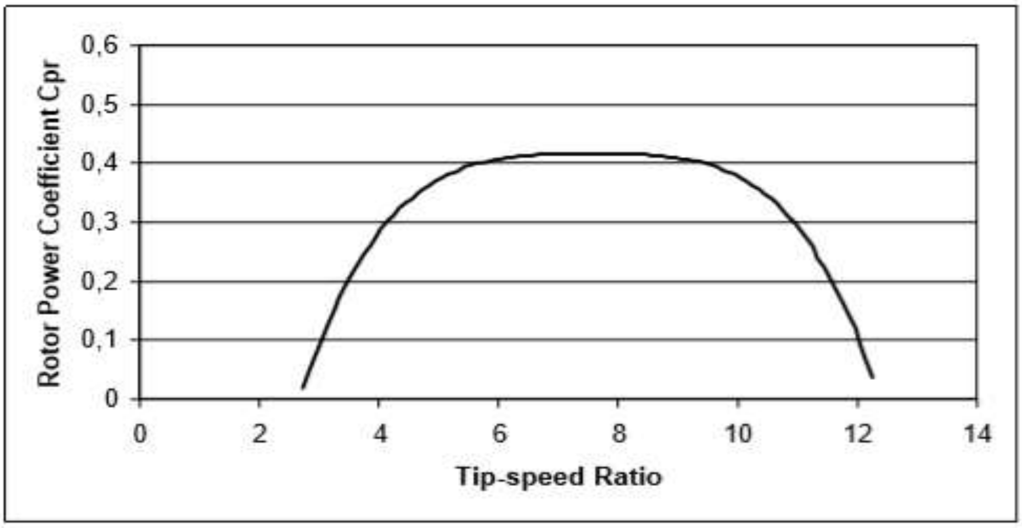

Figure 9: Power flow curve vs blade tip speed/wind speed [31]

2.6 Anemometer

Various types of anemometers are used to measure wind speed, including portable hand-held models and stationary ones, such as cup anemometers, which are typically installed at weather stations. Anemometers are widely used in areas such as weather monitoring, ship navigation, aviation, weather buoys, and wind turbine operations. They also have applications in measuring wind pressure, flow, and direction. Three or four hemispherical cups fastened to horizontal arms positioned on a vertical shaft make up a cup anemometer. The shaft rotates at a speed roughly proportionate to the wind speed when airflow from any horizontal direction passes over the cups. For a wide variety of speeds, the average wind speed can be computed by counting the shaft's revolutions over a given time period [32]. Modern hand-held anemometers, like the one shown in Figure 10, feature a rotating fan and a digital display screen, which shows the measured wind speed in meters per second.

Figure 10: A cup and a hand-held anemometer [33]

3. MATERIALS AND METHOD

The study evaluates wind velocity and its significant power output based on the design parameters of the system in used. Values of the wind velocity and the corresponding power output are tabulated between 8:00am and 9:00pm with the use of Anemometer, Voltmeter and Ammeter for seven days, the power output is obtained by multiplying an intermittent measured voltage quantity (V) by a measured current quantity (A) of the system. The results obtained is analyzed graphically. Fig. 3.0 below represent Akwa Ibom State University Ikot Akpaden Community, the area in which the experiment was carried out at a Longitude and Latitude (4.6280 N, 7.5000 E). (a) represent Nigeria as a country, (b) represents Akwa Ibom State, (c) is the study area, Ikot Akpaden Community.

3.1 Design Specification of the Wind Turbine System.

From equation (1);

$$\text{Power (P)} = \frac{1}{2} \times A \times \rho \times v^3$$

where, $\boldsymbol{\rho}$ = 1.223 kg/m^3, R = Radius of the blade tip to rotor = 0.3 m, **A** = πR^2 = Area of the circle swept by the rotor blades (m^2), $A = 3.142 \times 0.3 \times 0.3 = 0.283\ m^2$, v = velocity of the wind in m/s . Therefore, from Table 1, the overall average wind velocity of the study area is 4.03 m/s.

Theoretically, the estimated Maximum Power of the system using the design parameters is:

$$\text{Power (P)} = \frac{1}{2} \times A \times \rho \times v^3 = \frac{1}{2} \times 0.283 \times 1.223 \times 4.03^3 = 11.32\ W$$

3.2 Calculation of Gear Ratio

Simple gear trains, (in) $t_A = 12$, (out) $t_B = 60$, t = number of gear teeths, N = rotational speed (rpm), T = torque (Nm).

$$GR = \frac{\text{Drive (B)}}{\text{Drive (A)}} \tag{11}$$

$$GR = \frac{60}{12} = \frac{5}{1} = 5:1$$

Note: For every 1 rotation of the driving gear, the driven makes 5 rotations

$NA = rpm = 5 \times 60 = 300\ rpm$

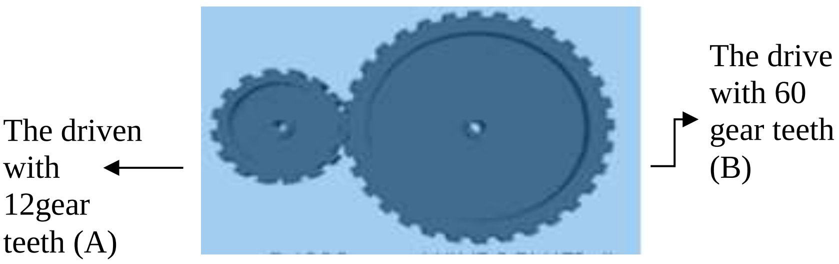

Figure 11: Gearboxes [33]

4. RESULTS AND DISCUSSION

4.1 Average Wind Velocity and Power Output of the System

The average wind velocity of Ikot Akpaden Community is tabulated in Table 1 using Anemometer. The results show the variation in wind velocity of the study area for seven days between the hours of 8:00am and 9:00pm. The power output of the system is obtained by multiplying an intermittent measured voltage quantity (V) by a measured current quantity (A) using Voltmeter and Ammeter. The average wind velocity V = 28.21/7 = 4.03m/s. The results of the wind electric generator are given in Tables 2 to 5. These give the data of measured voltage, current and power of the wind electric generator at a height of 3 m. The results of the tabulated data are analyzed graphically using line graphs as presented in Figures 12 to 18. Average power output = 569.2/(14x7) = 5.8 W

Table 1: Average wind velocity on turbine of the study area

DAYS	Average Wind Velocity
Day 1	4.27m/s
Day 2	3.93m/s
Day 3	2.67m/s
Day 4	4.17m/s
Day 5	4.57m/s
Day 6	4.40m/s
Day 7	4.20m/s

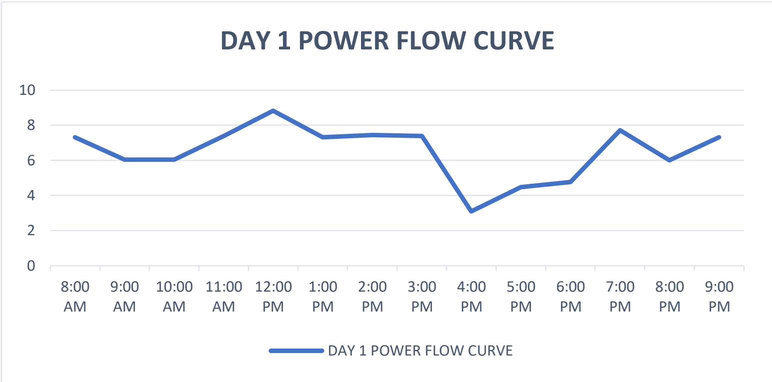

Figure 12: Graph of wind turbine power output against time for day 1

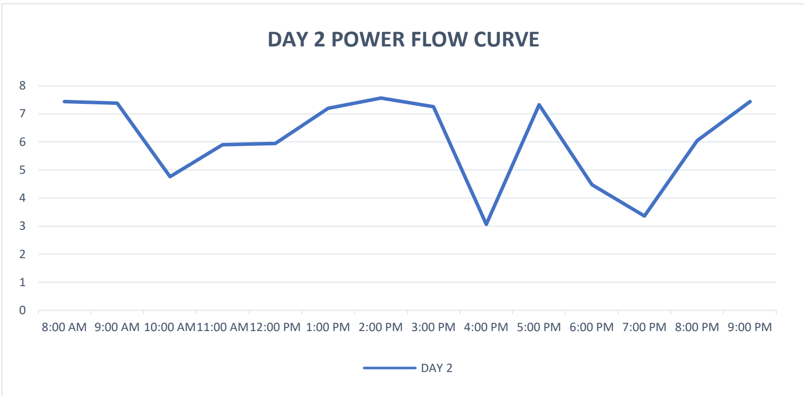

Figure 13: Graph of wind turbine power output against time for day 2

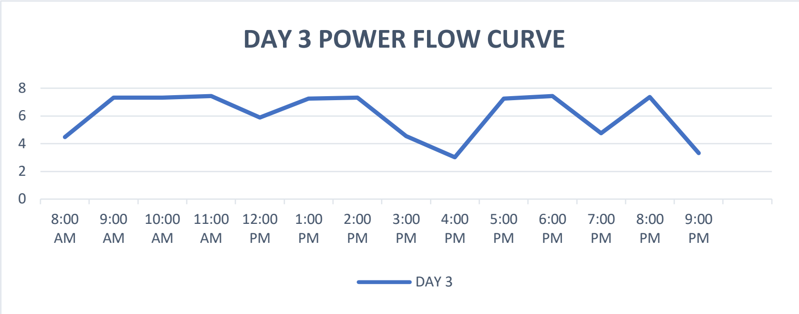

Figure 14: Graph of wind turbine power output against time for day 3

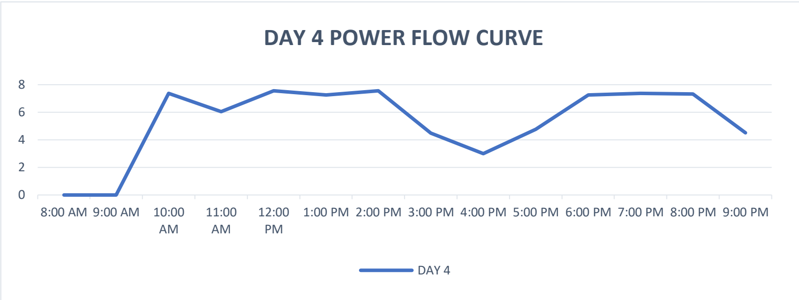

Figure 15: Graph of wind turbine power output against time for day 4

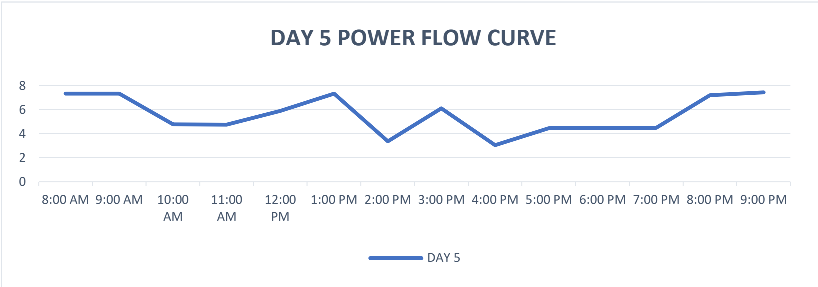

Figure 16: Graph of wind turbine power output against time for day 5

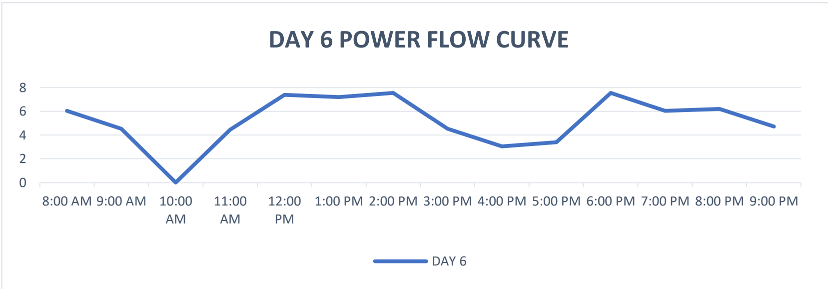

Figure 17: Graph of wind turbine power output against time for day 6

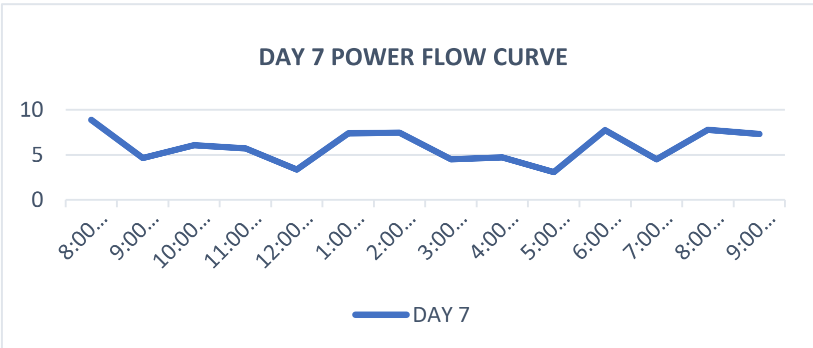

Figure 18: Graph of wind turbine power output against time for day 7

Table 2: Voltage, current and power output of the wind electric generator from day 1 to day 7 (morning)

DAY/TIME	**8:00 AM**			**9:00 AM**			**10:00 AM**			**11:00 AM**			**12:00 PM**		
	V	**A**	**W**	**V**	**A**	**W**	**V**	**A**	**W**	**V**	**A**	**W**	**V**	**A**	**W**
DAY 1	12.2	0.6	7.32	12.1	0.5	6.05	12.1	0.5	6.05	12.3	0.6	7.38	12.6	0.7	8.82
DAY 2	12.4	0.6	7.44	12.3	0.6	12.9	11.9	0.4	4.76	11.8	0.5	5.9	11.9	0.5	5.95
DAY 3	11.2	0.4	4.48	12.2	0.6	7.32	12.2	0.6	7.32	12.4	0.6	7.44	11.8	0.5	5.9
DAY 4	0.00	0.0	0.00	0.00	0.0	0.00	12.3	0.6	7.38	12.1	0.5	6.05	12.6	0.6	7.56
DAY 5	12.4	0.6	7.32	12.2	0.6	7.32	11.9	0.4	4.76	11.9	0.5	4.74	11.8	0.5	5.9
DAY 6	12.1	0.5	6.05	11.3	0.4	4.52	0.00	0.0	0.00	11.3	0.4	4.45	12.3	0.6	7.38
DAY 7	12.6	0.7	8.89	11.4	0.4	4.56	12.1	0.5	6.05	11.8	0.4	5.72	11.2	0.3	3.36

Table 3: Voltage, current and power output of the wind electric generator from day 1 to day 7 (afternoon)

DAY/TIME	**1:00 PM**			**2:00 PM**			**3:00 PM**			**4:00 PM**			**5:00 PM**		
	V	**A**	**W**	**V**	**A**	**W**	**V**	**A**	**W**	**V**	**A**	**W**	**V**	**A**	**W**
DAY 1	12.2	0.6	7.32	12.4	0.6	7.44	12.3	0.6	7.38	10.3	0.3	3.09	11.3	0.4	4.48
DAY 2	12.0	0.6	7.2	12.6	0.6	7.56	12.1	0.6	7.26	10.2	0.3	3.06	12.3	0.6	7.32
DAY 3	12.1	0.6	7.26	12.2	0.6	7.32	11.4	0.4	4.56	10.1	0.3	3.03	12.1	0.6	7.26
DAY 4	12.1	0.6	7.26	12.6	0.6	7.56	11.3	0.4	4.48	10.0	0.3	3.0	11.9	0.4	4.76
DAY 5	12.2	0.6	7.32	11.2	0.3	3.36	12.2	0.5	6.1	10.3	0.3	3.03	11.4	0.4	4.45
DAY 6	12.0	0.6	7.2	12.6	0.6	7.56	11.2	0.4	4.52	10.2	0.3	3.06	11.3	0.3	3.39
DAY 7	12.3	0.6	7.38	12.4	0.6	7.44	11.3	0.4	4.48	11.8	0.4	4.72	10.2	0.3	3.06

Table 4: Voltage, current and power output of the wind electric generator from day 1 to day 7 (night)

DAY/TIME	6:00 PM			7:00 PM			8:00 PM			9:00 PM		
	V	A	W	V	A	W	V	A	W	V	A	W
DAY 1	11.9	0.4	4.76	11.8	0.4	7.72	12.0	0.5	6.00	12.6	0.6	7.32
DAY 2	11.3	0.4	4.48	11.2	0.3	3.36	12.1	0.5	6.05	12.4	0.6	7.44
DAY 3	12.4	0.6	7.44	11.9	0.4	4.76	12.3	0.6	7.38	12.2	0.6	3.32
DAY 4	12.1	0.6	7.26	12.3	0.6	7.38	12.2	0.6	7.32	11.3	0.4	4.52
DAY 5	11.2	0.4	4.48	11.3	0.4	4.48	12.0	0.6	7.2	12.4	0.6	7.44
DAY 6	12.6	0.6	7.56	12.1	0.5	6.05	12.4	0.5	6.2	11.8	0.4	4.72
DAY 7	11.8	0.4	7.72	11.2	0.4	4.48	12.6	0.6	7.76	12.6	0.6	7.32

Table 5: The power output of the wind electric generator from day 1 to day 7

TIME	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5	DAY 6	DAY 7
8:00 AM	7.32	7.44	4.48	0	7.32	6.05	8.89
9:00 AM	6.05	7.38	7.32	0	7.32	4.52	4.65
10:00 AM	6.05	4.76	7.32	7.38	4.76	0	6.05
11:00 AM	7.38	5.9	7.44	6.05	4.74	4.45	5.72
12:00 PM	8.82	5.95	5.9	7.56	5.9	7.38	3.36
1:00 PM	7.32	7.20	7.26	7.26	7.32	7.20	7.38
2:00 PM	7.44	7.56	7.32	7.56	3.36	7.56	7.44
3:00 PM	7.38	7.26	4.56	4.48	6.10	4.52	4.48
4:00 PM	3.09	3.06	3.03	3.00	3.03	3.06	4.72
5:00 PM	4.48	7.32	7.26	4.76	4.45	3.39	3.06
6:00 PM	4.76	4.48	7.44	7.26	4.48	7.56	7.72
7:00 PM	7.72	3.36	4.76	7.38	4.48	6.05	4.48
8:00 PM	6.00	6.05	7.38	7.32	7.20	6.20	7.76
9:00 PM	7.32	7.44	3.32	4.52	7.44	4.72	7.32
TOTAL	**91.13**	**85.16**	**84.79**	**74.53**	**77.90**	**72.66**	**83.03**

The results obtained was taken by measuring voltage (V) output using Voltmeter and Current (A) output using Ammeter of the wind generator, the product of the two quantities gives Power (W) output from the wind electric generator per hour from 8am to 9pm each day for 7 days.

From the results, the power output of the system varies between the time intervals due to non-steady nature of the wind velocity. The maximum power output of 8.82w was achieved, however, a steadier state of the power output is gotten in the evening hours between 6pm to 9pm most days than the morning, this shows that there is more wind pressure on the fan blades which gives more torque to the rotor shaft and which increases the revolution per minute (r.p.m) of the system, which gives a better output voltage and current from the generator.

Graph 1 to 7 illustrate power (w) output of the wind electric generator against time (hour) from day 1 to day 7. The power of the system is measured by multiplying an intermittent measured voltage quantity (V) by a measured current quantity (A) at a stipulated time since the wind energy fluctuates. The result when compared with the theoretical value as calculated using design parameters from equation 1.0 proves the validity of the experiment. Power output of the system ranges from 3.0W to 8.82W, there is a significant fall in power between the hours of 3:00 Pm and 4:00 this is as a result of low wind velocity in all the days of measurement and a maximum accumulated power of 91.13W was achieved in a particular day of the series.

5. CONCLUSION

The experimented values of the system correspond with the theoretical value as the power generated by the system from the tables does not exceed the theoretical value of 11.31W, however, the variation in the wind velocity is indicated in the graph with the rise and fall of the power flow curve plotted, a significant zero value power is seen due to condition that there is no availability of wind pressure at the stipulated time of the day, therefore, if the system parameters is expanded, larger value of power can be obtained, and when it is stored over a certain period of time, becomes a useful energy for the society.

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