Development of a wind turbine for a hybrid solar-wind power system

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ARTICLE INFO

Keywords:
Wind turbine
Renewable energy
Machine design
Local content
Soil moisture

ABSTRACT

Conventional energy supply has not been able to meet the energy needs of most developing nations. This calls for the need to invest in renewable energy systems which are not only sustainable but clean, abundant, and easily assessable. This research presents a study of wind variability by using wind data got from a weather station to design and fabricate a small-scale horizontal axis wind turbine (HAWT). This was done by using locally sourced materials for a Hybrid Solar-Wind power system for irrigation purposes, as a performance evaluation of the turbine. The materials used in the fabrication of the turbine include wood, polyvinyl chloride plastic, acrylic glass, Teflon, and steel all sourced locally. From the evaluation, the power capacity of the wind turbine was derived to be 40 W, 41 W and 43 W from the voltage and current output reading on the multi-meter from three average wind speed variations of 5 m/s, 10 m/s and 15 m/s measured from handheld digital anemometers respectively. A regression analysis of the relationship between the turbine's power capacity and the wind speed showed that the turbine operates best at low speed of 5 m/s, with an R² value of 0.9602. The fabricated wind turbine was connected to a hybrid power system with the second energy source consisting of a 40 W solar tracking system to give a more stable power supply. The system was used for soil monitoring irrigation purposes. The design of the HAWT indicates a cheap, alternative and sustainable energy source that is more stable and suitable for smart solar panel irrigation system.

1. Introduction

Electricity has become an intricate aspect of human life. In most countries, its major sources are non-renewable energy sources such as coal, nuclear power and petroleum products. These resources not only deplete with time but damage the environment from harmful effects of their use. There arises a need for clean and renewable energy, wind energy harnessed using turbine has proven to be a useful source of electricity. In its earlier years, the wind turbine was mostly as a mechanical device, but recently, it is being used to generate large amounts of electricity [1, 2]. Over a millennium, it has been developed to become a main power source in some countries in the world and is now available in different configurations in both onshore and offshore applications.

Wind and solar are the most abundant sources of renewable energy and as such, harnessing these sources should be the main focus in our goal to reach a sustainable energy dependent society. The term “wind turbine” no longer only refers to a rotary propeller but a machine known as an aerofoil powered generator, different types of wind turbines such as vertical and horizontal are manufactured of recent. Small turbines have been implemented to charge batteries for boats and to serve as power source to traffic signs [3, 4, 5]. While large turbines have been implemented to power homes and offices for industrial uses. A collection of large turbines which is otherwise known as wind farms are fast becoming an important source of renewable energy which have been implemented by several countries to reduce absolute dependant on fossil fuels [6].

Since the late 1980s, the growth of wind energy has visibly reduced in the US, while it continues to grow in Europe due to sudden awareness and alertness on the need for urgent environmental response to various research indicating changes to global climate if the use of fossil fuels arises at that rate [7]. Today, wind-powered generators operate in every size, which ranges from small turbines needed to charge batteries to a very large size offshore wind farms that provide electricity to national electric transmission systems [8]. Alternative source of energy such as the wind is gradually becoming known around the world, however, many developing countries are yet to embrace this source of energy. The wind map for a developing nation such as Nigeria can be seen in Figure 1. Today, wind power is not used in Nigeria, what is available are relics pointing to its previous usage.

One challenge faced in wind power as an alternative energy source is the unpredictability of the resource in its availability. Another challenge...
lies in the siting of the wind power plants in suitable locations which have favourable wind speeds. Several studies have been carried out to overcome this challenge. Diffuser Augmented Wind Turbine (DAWT) have been used to improve the efficiency of the wind turbines by increasing the wind speed upstream of the turbine by Ilhan et al 2022 [10]. In their study, a comprehensive review of previous studies on improving or augmentation power of horizontal axis wind turbines (HAWT) have been reviewed in two categories, first related with relative improvement of energy by improving the aerodynamic forces that affects the HAWT at different modifications for blades, and secondly by reviewing techniques to augment the largest possible amount of power from HAWT focusing on DAWTs to gather information, they concluded

Figure 1. Wind speed map for Nigeria [9].

Figure 2. The horizontal axis wind turbine.
that the use of DAWT achieves a quantum leap in increasing the production of wind power, especially in small turbines in urban areas if it properly designed [11]. Mehmet et al 2021 investigated the impact of growth in turbine size on aerodynamic rotor performance of modern commercial large-scale wind turbines. The results reveal that decreasing specific power decreases the rated output wind speed of the wind turbines; hence, the reduction in the rated output of wind speed contributes to the tendency of higher power capacity [12]. A small wind turbine based on wind energy density was assessed by Sohaib et al 2018 [13], energy density is calculated based on the measured wind speed and temperature values. Results of power output of HAWT and VAWT indicate that VAWT is more feasible at some location since it produces more power in that particular location, this method helps to find the best location for the small wind turbine that would yield maximum energy generation. This study aimed at proposing a combined wind energy system with a solar panel system for the stability of electricity which can be transmitted to different locations while considering the suitability of wind energy and converts it to mechanical power for the motor shaft. The material used in this study is the unplasticized Polyvinyl Chloride (PVC-U) 4-inch pipe of schedule 40. The hub serves as an attachment for the blade and generator to be connected. It makes up the rotor with the blade. It is fabricated from poly (methyl methacrylate), commonly known as acrylic glass or Perspex among others. The rotor attachment connects the rotor assembly to the shaft of the electric motor. It is fabricated from a Teflon rod machined to specifications. While the Nacelle serves as the housing of the electrical components of the turbine, and it contains the generator.

2.1. Variability of wind speed at the weather station

An analysis was conducted to understand the wind speed characteristics at the wind station, which is located at Afe Babalola University, Ado, Nigeria. The wind data was got from the institution’s weather station taken for 22 days. The instrument used to collect data is the imetos parameter position at latitude 7.67° E and longitude 5.31° E, and a computer model was used to assess the data. The wind average speeds, and maximum speeds were read every 10 min daily. The average and maximum wind speeds can be seen in Table 1.

2.2. Determination of nature of wind speed

Due to the unfavourable wind conditions, a fan was used to enhance the wind speed supplied to the turbine placed at 0.5 m distance; in order to start the turbine. The wind speed was increased by using an electrical fan of three speed variations (High, Medium and Low) for the purpose of this study. The wind speed is taken into consideration when designing the turbine blade. The wind speed sets the Reynolds Number. Assuming the air density, \( \rho \) as 1.223 kg/m\(^3\), air dynamic viscosity, \( \mu \) as 1.86 \( \times \) \( 10^{-5} \) kg/ms at room temperature and blade chord length as 0.3 m, the Reynolds number for the average wind speeds, \( u \) generated from the rated three fan speeds (5 m/s, 10 m/s and 15 m/s for low, medium and high respectively), can be seen in Table 2.

According to Park et al 2017 [14], the laminar flow over a smooth flat plate begins to transit to the turbulent flow at a Reynolds number of about \( 1 \times 10^5 \) but does not become fully turbulent before the Reynolds number reaches much higher values, typically around \( 3 \times 10^6 \). It can be concluded that the nature of the wind velocity at 5 m/s is laminar while that of 10 m/s and 15 m/s is translational.

The design considerations, methodology and the results will be discussed extensively.

2. Materials selection

Most materials used in this study were locally sourced and cost efficient. The major components used in the development of the small-scale HAWT are Blades, Rotor attachment, Hub, Nacelle, DC motor, Base plate and Booster circuit as shown in Figure 2. The blade is the rotor component that is attached to the hub. By a clockwise rotation, it harnesses the wind energy and converts it to mechanical power for the motor shaft. The nature of average wind speed.

Table 1. Wind data at the weather station.

| DAY | Average Speed, Uavg (m/s) | Maximum Speed, Umax (m/s) |
|-----|--------------------------|--------------------------|
| 1   | 0.4                      | 0.5                      |
| 2   | 0.2                      | 0.2                      |
| 3   | 0.1                      | 0.2                      |
| 4   | 0.2                      | 0.3                      |
| 5   | 0.3                      | 0.4                      |
| 6   | 0.2                      | 0.3                      |
| 7   | 0.4                      | 0.5                      |
| 8   | 0.3                      | 0.4                      |
| 9   | 0.4                      | 0.4                      |
| 10  | 0.3                      | 0.4                      |
| 11  | 0.4                      | 0.5                      |
| 12  | 1.6                      | 1.8                      |
| 13  | 1.2                      | 1.3                      |
| 14  | 0.3                      | 0.4                      |
| 15  | 0.4                      | 0.6                      |
| 16  | 0.8                      | 0.9                      |
| 17  | 1.0                      | 1.2                      |
| 18  | 1.6                      | 1.9                      |
| 19  | 1.6                      | 1.9                      |
| 20  | 0.9                      | 1.0                      |
| 21  | 0.7                      | 0.9                      |
| 22  | 0.6                      | 0.7                      |

Table 2. Nature of average wind speed.

| S/N | Wind Speed (m/s) | Reynolds Number |
|-----|------------------|-----------------|
| 1   | 5                | \( 9.86 \times 10^4 \) |
| 2   | 10               | \( 1.97 \times 10^5 \) |
| 3   | 15               | \( 2.96 \times 10^5 \) |
3. Material design

To ensure the functionality of the HAWT, a detailed analytical estimation of the blade parameters was carried out. Horizontal Axis Wind turbines are very sensitive to changes in blade profile and design. The number of three blades for the turbine design was selected. Fewer blades are used to achieve a desirable reduction in rotor nacelle weight and manufacturing costs. Although, it is apparent that there exist dynamic structural and balancing difficulties of the polar asymmetrical rotor [15]. Problem such as increased wear and inferior aesthetic qualities of one and two bladed rotors are evident. Hence, a three-blade configuration was adopted as the most efficient design to meet environmental, commercial and economic constraints.

3.1. Blade width

The blade width was derived from the diameter of the PVC pipe used (4-inch). The following calculations were done to arrive at the desired width:

3.1.1. Perimeter of pipe

Let the diameter of 4-inch pipe, \( d \) = 10 cm.

The radius of the pipe, \( r \) (Eq. (1)) will be:

\[
r = \frac{d}{2} \]

\[ r = \frac{10}{2} = 5 \text{ cm} \] (1)

Therefore, the perimeter of the pipe will become Eq. (2)

\[
p = 2\pi r = 2 \times \pi \times 5 = 31.4 \text{ cm} \] (2)

The perimeter of the pipe, approximately 30 cm is used to calculate the width of the three blades (Eq. (3)).

\[
Width, b = \frac{p}{3} \]

\[ b = \frac{30}{3} = 10 \text{ cm} \] (3)

The blade width was taken as 9 cm.

3.2. Rotor diameter

Assuming blade chord length, \( L \) of 30 cm and hub diameter of 10 cm, the rotor diameter can be seen in Eq. (4).

\[
D = 2l + h \text{ub diameter}
\]

\[
D = (2 \times 30) + 10 = 70 \text{ cm} = 0.7 \text{ m} \] (4)

The rotor diameter is used to calculate the wind power and the swept area.

3.3. Swept area

The swept area \( A \) of the turbine can be calculated from the rotor diameter using the equation for the area of a circle. And the swept area is calculated as 0.385 m².

3.4. Tip speed ratio

The tip speed ratio (TSR) is defined as the relationship between blade tip speed and relative wind speed. Eq. (5) gives the parameters for calculating TSR.

\[
\lambda = \frac{\omega R}{v}
\] (5)

This design considers a tip speed ratio of 6 for the three-blade rotor. This ratio has been found to produce efficient conversion of the wind’s kinetic energy into electrical power.

3.5. Blade twist

This is an important factor for determining the coefficient of power obtained at each segment of the blade. Eq. (6) was used to determine the designed blade twist:

\[
\tan \varphi = \frac{2}{\lambda + \frac{2}{3}}
\] (6)

Assuming the TSR, \( \lambda \) as 6, the blade twist will be given as

\[
\tan \varphi = \frac{2}{6 + \frac{2}{3}} = 0.1091
\]

The angle of twist, \( \varphi = \tan^{-1}(0.1091) = 6^\circ \)

3.6. Blade pitch

This refers to the angle between the rotor blade chord line and the plane of rotation of the rotor. It is commonly known as the pitch, \( \Theta \) is often described as the distance travelled by a blade in one rotation in 100% efficiency. Pitch control is a very important aspect in turbine operation as the angles of blades must be controlled to keep wind speed

### Table 4. Turbine rated revolution speeds.

| S/N | Wind Speed (m/s) | Rated Revolution Speed (rpm) |
|-----|------------------|------------------------------|
| 1   | 5                | 818.9                        |
| 2   | 10               | 1637.9                       |
| 3   | 15               | 2456.8                       |

### Table 5. Theoretical wind and turbine power capacities for three fan speed variations.

| S/N | Low Wind Speed (m/s) | Low Wind Power (W) | Low Turbine Power (W) | Medium Wind Speed (m/s) | Medium Wind Power (W) | Medium Turbine Power (W) | High Wind Speed (m/s) | High Wind Power (W) | High Turbine Power (W) |
|-----|----------------------|--------------------|-----------------------|-------------------------|------------------------|------------------------|-----------------------|----------------------|----------------------|
| 1   | 6.5                  | 38.34              | 12.08                 | 10.1                    | 143.84                 | 45.31                  | 16.2                  | 593.55               | 186.97               |
| 2   | 6.3                  | 34.91              | 11.00                 | 10.3                    | 152.55                 | 48.05                  | 15.4                  | 509.89               | 160.61               |
| 3   | 6.2                  | 33.27              | 10.48                 | 11.4                    | 206.84                 | 65.15                  | 16.5                  | 627.14               | 197.55               |
| 4   | 6.8                  | 43.90              | 13.83                 | 10.9                    | 180.80                 | 56.95                  | 16.2                  | 593.55               | 186.97               |
| 5   | 6.5                  | 38.34              | 12.08                 | 10.6                    | 166.28                 | 52.38                  | 16.2                  | 593.55               | 186.97               |
| 6   | 5.6                  | 24.52              | 7.72                  | 10.2                    | 148.15                 | 46.67                  | 16.3                  | 604.61               | 190.45               |
| 7   | 5.4                  | 21.98              | 6.92                  | 10.0                    | 139.61                 | 43.98                  | 16.9                  | 673.86               | 212.27               |
| 8   | 5.3                  | 20.78              | 6.55                  | 11.4                    | 206.84                 | 65.15                  | 15.3                  | 500.02               | 157.51               |
within limits. In this study, the pitch is kept constant as a constant range of wind speed is employed.

3.7. Blade tip speed

The speed at the tip of the blade can be calculated from the turbine’s tip speed ratio and the wind speed as seen in Eq. (7).

\[ \mu = \lambda \times \nu = \omega R = 2sfR \]  

(7)

Assuming \( \lambda \) as 6, the blade tip speed values are calculated for all wind speeds recorded for the three fan speed variations as shown in Table 3.

3.8. Rated revolution speed

The rated revolution speed can be derived from Eq. (8).

Rated revolution speed (rpm) = \( \frac{60 \mu}{6.28R} \)  

(8)

Assuming the average rated fan speeds (\( \nu \)) are 5 m/s, 10 m/s and 15 m/s respectively, the turbine rated revolution speed can be seen in Table 4.

3.9. Power capacity

The power in the wind hitting a wind turbine is responsible for the generation of electrical power by the turbine. According to Adetunla 2021 [16], under constant acceleration, the kinetic energy of a body having mass \( m \) and velocity \( v \) is equal to the work done \( W \) in displacing that object from rest to a distance \( s \) under a force \( F \). According to newton’s law, power can be calculated as shown in Eq. (9).

\[ P = \frac{1}{2} \rho A \nu^3 \]  

(9)

This wind power calculated is known as the extracted theoretical wind power by the turbine blades under ideal conditions.

3.10. Turbine power

The wind power extracted loses some efficiency before it is converted to electrical power to be used through friction, drag, heat, blade configuration, mechanical transmission, and electrical generation losses. The actual turbine electrical power can be derived as seen in Eq. (10).

\[ P_t = \frac{1}{2} \rho A \nu^3 c_p n_d n_g \]  

(10)

Assuming the density of air, \( \rho = 1.223 \text{ kg/m}^3 \), drive train efficiency, \( n_d = 0.35 \), generator efficiency, \( n_g = 0.9 \) and Maximum coefficient of power, \( C_p = 0.593 \); the wind power and generator power were calculated for the recorded wind speed of the three fan speed variations in Table 5.
Figure 6. Schematic diagram of a DC-DC booster converter.

Figure 7. Waveform of full bridge rectifier.

Figure 8. Assembly of the wind turbine.
3.11. Drag and lift

The most important component of a wind turbine rotor is the airfoil, which is the element that produces the forces that make the turbine rotate. The forces are the lift and drag forces and are given by Eqs. (11) and (12) respectively. The parameters of utmost importance are the coefficients of lift ($C_L$) and drag $C_d$.

\begin{align*}
L &= \frac{1}{2} \rho A v^2 c C_L \quad \text{(11)} \\
L &= \frac{1}{2} \rho A v^2 c C_d \quad \text{(12)}
\end{align*}

where: $s =$ airfoil span, $v =$ air velocity, $c =$ airfoil chord.

3.12. Wind tower

The wind tower height is an important factor to be considered in the design of wind turbines. The higher the tower length, the higher the wind speed as there will be more wind stability and fewer obstructions. In this design, the height effect was negated due to the size of the turbine and its experimental purpose. The height of the tower is defined as 90cm, thrice the blade length of 30cm. The tower was tapered to improve the balancing of the turbine.

3.13. Taper angle

This refers to the angle between the taper and the center axis of the tower represented as $\alpha$, as shown in Figure 3. The taper angle can be calculated by using Eq. (13).
\[
\tan \alpha = \frac{D_1 - D_2}{2L}
\]  
(13)

where \(D_1\) as 13 cm and \(D_2\) as 10 cm, the half taper angle is given as 1° while the full taper angle is given as 2°.

3.14. Electrical components

The electrical circuits in Figures 4 and 5 are responsible for the generation and stabilization of electrical power. The turbine generator converts the mechanical power of the rotor to electrical power. The generator used in this study is a 12 V DC motor rated at 350 rpm speed, with ball bearings at the front and the rear. The output is an alternating current. A peak to peak ripples of 16 V-DC output cannot be directly connected to the load. A filter capacitor is however implemented in order to remove ripples from the supply. A 1000 uF and 25 V rated filter capacitor is used as shown in circuit diagram. The connection of the capacitor is such that it is connected directly to the output of the bridge rectifiers to get charged up in order to produce pure dc output by eliminating the ripples from the dc supply. However, the output of both capacitors are not regulated. The filter capacitor is connected to a regulator integrated circuit (IC) so as to regulate the output voltage of the capacitors which will otherwise be varying as per input voltage change. Depending on the output voltage requirement, different types of regulator ICs are used. In this case, a pure and regulated output voltage of +12 V is needed so IC 7812 is used. A red LED of 2 V voltage is used to signify that output is being produced by the electrical circuit.

3.15. DC-DC booster converter

The booster converter used in this study is rated at an input voltage of DC 8.5–50 V, output voltage of DC 10–60 V and direct current of 15 A. The booster consists of an inductor, a semiconductor switches a diode and a capacitor as shown in the schematic diagram in Figure 6.

3.16. Rectifier

A bridge rectifier circuit is used to connect the two output terminals of the motor. The rectifier circuit serves as a converter that converts AC into DC supply. The circuit is made of diode switches as shown in the Electric circuit diagram. Therefore, four diodes are used to produce an input voltage (8 VAC) and output voltage of 16 VDC with ripples in it. For a full bridge rectifier, the output voltage is given by Eq. (14).

\[
V_{DC} = \frac{2V_{AC}}{\pi}
\]  
(14)

Figure 7 presents the waveform of the input and output voltage of a full bridge rectifier.

3.17. Assembly of the HAWT

The turbine blades were marked out and cut from a 4-inch pipe and twisted using a hot hair blower to desired curves. The hub, nose and nacelle parts were marked out and cut out from the acrylic glass. A 90 cm wood was cut out from \(\frac{6}{2}\)6 wood and tapered with diameters \(D_1 = 13\) cm and \(D_2 = 10\) cm respectively. The base plate was marked out and cut out of wood. The tower was mounted and screwed to the base plate and a hole was drilled through tower-base plate assembly. The rotor attachment was machined using the lathe machine. The blades were bolted to the hub and the blade-hub assembly was fitted to the shaft of the dc motor, using the rotor attachment. The electrical circuit was built, connected to the wind generator (d. c. motor) and tested. The motor and circuit assembly were mounted and screwed to the nacelle bottom plate using steel L clamps. The nacelle and rotor were assembled and screwed to the turbine tower. The wooden surfaces were polished and lacquered for finishing Wire was connected from motor through Nacelle and tower.

Table 6. Wind speeds at three fan speed variations (m/s).

| S/N | Low (m/s) | Medium (m/s) | High (m/s) |
|-----|-----------|--------------|------------|
| 1   | 5.3       | 10.0         | 15.3       |
| 2   | 5.4       | 10.1         | 15.4       |
| 3   | 5.6       | 10.3         | 15.9       |
| 4   | 5.6       | 10.4         | 16.1       |
| 5   | 5.7       | 10.6         | 16.2       |
| 6   | 5.8       | 10.9         | 16.2       |
| 7   | 5.9       | 11.1         | 16.3       |
| 8   | 6.2       | 11.3         | 16.3       |
| 9   | 6.3       | 11.4         | 16.3       |
| 10  | 6.4       | 11.4         | 16.4       |
| 11  | 6.5       | 11.4         | 16.5       |
| 12  | 6.7       | 11.4         | 16.7       |

Table 7. Experimental turbine power capacities.

| Voltage (V) | Power (W) | Voltage (V) | Power (W) | Voltage (V) | Power (W) |
|-------------|-----------|-------------|-----------|-------------|-----------|
| S/N         | Low       | Medium      | High      |
| 1           | 12.6      | 37.8        | 13        | 39.0        | 13.3      |
| 2           | 12.7      | 38.1        | 13.1      | 39.3        | 13.4      |
| 3           | 12.7      | 38.1        | 13.1      | 39.3        | 13.6      |
| 4           | 12.8      | 38.4        | 13.2      | 39.6        | 13.7      |
| 5           | 12.9      | 38.7        | 13.3      | 39.9        | 13.8      |
| 6           | 13.0      | 39.0        | 13.5      | 40.5        | 14.0      |
| 7           | 13.3      | 39.9        | 13.7      | 41.1        | 14.3      |
| 8           | 13.3      | 39.9        | 13.9      | 41.7        | 14.5      |
| 9           | 13.4      | 40.2        | 14        | 42.0        | 14.6      |
| 10          | 13.5      | 40.5        | 14.1      | 42.3        | 14.6      |
| 11          | 13.7      | 41.1        | 14.2      | 42.6        | 14.7      |
| 12          | 13.7      | 41.1        | 14.3      | 42.9        | 14.8      |

Figure 11. Wind speed distribution for 40 days.
assembly to the power options box of the Hybrid power irrigation system as shown in Figure 8.

3.18. Water storage and soil moisture control system

The water storage is achieved by the tank system designed and painted with an anticorrosion agent to prevent rusting. The tank supplies water for irrigating the farm. However, control of water supply is required to prevent water logging or uncontrolled irrigation. This is achieved by attaching a control valve to the supply line outlet from the tank. The solenoid valve used in this study is a 12 V DC system capable of receiving control signals from 12 V rated switching devices. The central control system handles the signal sending for valve open and closure as shown in Figure 9a. While the system features a soil moisture sensor that jointly controls the irrigation process based on the dryness of the soil. The soil moisture provides an analog stream of data that shows the volumetric moisture contents at various depths as shown in Figure 9b.

3.19. Hybrid solar–wind system connection

After fabrication of the small-scale HAWT, it is connected to the smart solar panel irrigation system. The solar power system consists of two 20 W solar panels that can be repositioned using the solar tracker to produce an output of 40 W. The two output wires from the turbine are connected to the microprocessor of the irrigation system which automatically controls the switch between the wind and solar power. The irrigation system uses a solenoid valve to control water supply through monitoring of soil moisture content using switching devices connected to the microprocessor control system. Codes were written on Arduino Uno microcontroller to be able to read out the soil moisture content.
The charge controller employed here is a 12 A Pulse Width Module (PMW) charge controller and a 7.5 Ah/12 V lead acid battery. The schematic diagram of the Hybrid Power Irrigation System can be seen in Figure 10.

4. Result and discussion

4.1. Experimental wind speed variation

From the wind data collected, an analysis carried out on the collected wind to give a wind speed distribution for 22 days as shown in Figure 11. From the graph, the average wind speed distribution average is given as 0.7 m/s, the lowest recorded wind speed was 0.1 m/s and the highest recorded wind speed is 1.9 m/s. This range is not capable of running a wind turbine as it is below the starting wind speed of 3 m/s; therefore, a fan was employed in conducting the turbine experiment. From the topology and population of the weather station located within the University campus, this location is not suitable for the construction of a Hybrid Wind-Solar Farm. The small-scale horizontal wind turbine has the power capacity of 40 W. The wind speeds measured and recorded for the duration of 2 min at an interval of 10 s at three fan variations: low, medium, and high can be seen in Table 6. This table gives an average speed of 5 m/s, 10 m/s and 15 m/s as our low, medium, and high wind speed variations respectively.

Figure 14. Wind turbine power capacity at medium wind speed.

Figure 15. Screenshot of the serial monitor for soil moisture sensing.
Table 8. Soil volumetric moisture contents of the sensor.

| Predicted Depth (cm) | $R^2$ | RMSE |
|----------------------|-------|------|
| 20                   | 0.85  | 1.76 |
| 30                   | 0.88  | 0.88 |
| 50                   | 0.95  | 0.39 |

4.2. Wind turbine performance

The wind turbine electrical circuit was connected to an LED of power 1 W to read and record the current and voltage outputs from the multimeter for the three fan variations at an interval of 10 s for 2 min. It was noted that some time was taken for the output to stabilize, and the current was consistent at 3 A. Table 7 shows the voltage and corresponding turbine power at current of 3 A, these wind speeds are expected to produce an average of 40 W, 41 W and 43 W respectively.

Figures 12, 13, and 14 shows the relationship between the wind speed and experimental turbine power at the three fan variations. The $R^2$ value was used to evaluate the scatter-plot of the turbine power values around the fitted regression line and draws comparison between the figures. It can be interpreted that the low wind speed is the most suitable to produce a stable power of 40 W as the wind turbine power distribution $R^2$ value is the highest at 0.9602; so as to avoid damage to wind turbine components from uncontrolled wind speed.

4.3. Run-time results of soil moisture

The serial monitor facility on the integrated development environment provides an added feature to view experimental run-time results. Serial monitor screen results for sun-light intensity sensor and soil moisture sensor can be seen in Figure 15.

A soil volumetric moisture content monitoring was evaluated based on results from the sunlight intensity sensor and the soil moisture sensor. The root mean square error (RMSE) was used as the index of accuracy of the model (Equation 15) [17];

$$RMSE = \sqrt{\frac{(R^2 - Yi)^2}{n}}$$ (15)

where $R^2$ is the measured volumetric moisture content of the ith soil sample and $Xi$ is the volumetric moisture content obtained by the ith soil sample's using the existing sun-light intensity sensor. The volumetric moisture content of 20, 30, and 50 cm soil depth is shown in Table 8.

5. Conclusion

The small-scale horizontal axis wind turbine (HAWT) was constructed with the sole aim of enhancing the power capacity of renewable energy system through a hybrid connection with the solar panel, used to power a soil monitoring irrigation system. From the performance evaluation of the developed HAWT, the power capacity of the wind turbine was derived to be 40 W, 41 W and 43 W from the voltage and current output reading from three average wind speed variations of 5 m/s, 10 m/s and 15 m/s measured from handheld digital anemometers respectively. A regression analysis of the relationship between the turbine's power capacity and the wind speed showed that the turbine operates best at low speed of 5 m/s, with an $R^2$ value of 0.9602. The developed HAWT was subsequently deployed to an irrigation system, and the soil volumetric moisture content has been determined at different depths of 20, 30 and 50 cm of $R^2$ of 0.85, 0.88 and 0.95 respectively. From this study, it has been demonstrated that with sufficient wind speed at acceptable tower height, the wind turbine has the capability of providing an alternative, sustainable, and cost-effective power source.

Declarations

Author contribution statement

Adedotun Adetunla, PhD: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Oluwasina Rominyi: Conceived and designed the experiments; Performed the experiments.

Bernard Adaramola: Analyzed and interpreted the data.

Adeyinka Adeoye: Contributed reagents, materials, analysis tools or data.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] O.O. Aanuoluwapo, A.C. Ohis, Biomimetic strategies for climate change mitigation in the built environment, Energy Proc. 105 (2017) 3868–3875.
[2] S. Patil, N. Jain, G.P. Komula, Development of automated grid monitoring and control system using IoT, A Review 6 (1) (2021) 368–371.
[3] S.B.T. Raj, Advanced material for front fan blade manufacturing, Variations 1 (2017) 2.
[4] S. Khan, V. Paliwal, V.V. Pandey, V. Kumar, Biomass as Renewable Energy,” No. March 2015, 2017.
[5] M. Gavrilescu, Biomass Power for Energy and Sustainable Development 7, 2008, pp. 617–640.
[6] K. Khoshmanesh, A.Z. Kouszani, S. Nahavandi, A. Abbasi, Reduction of fuel consumption in an industrial glass melting furnace,” no. June 2014, 2007.
[7] M. Medojevic, D.E. Initiative, I. Cosic, A. Rikalovic, Energy Management in Industry 4.0 Ecosystem: a Review on Possibilities and Concerns,” No. January 2019, 2018.
[8] I. Environment, Energy-Efficient Through-Life Smart Design, Manufacturing and operation of ships in an industry 4.0 Environment 2012, 2017, pp. 1–13.
[9] M.Z. Ibrahim, A. Albani, R. Energies, The Status of the Development of Wind Energy in Nigeria,” na. November, 2020.
[10] A. Ihan, B. Sahin, M. Bilgili, A review : diffuser augmented wind turbine technologies, Int. J. Green Energy 19 (1) (2022) 1–27.
[11] B.A.J. Al-qarashi, N. Zelawati, B. Asmuni, Review on Diffuser Augmented Wind Turbine (DAWT), No. June, 2019.
[12] M. Bilgili, S. Tumse, M. Tontu, B. Sahin, Effect of growth in turbine size on rotor aerodynamic performance of modern commercial large - scale wind turbines, Arabian J. Sci. Eng. 46 (8) (2021) 7185–7195.
[13] S. Gayas, R.E. Engineering, M. Mathews, Feasibility Assessment of Small Wind Turbines Based on Wind Energy Density, 2018, pp. 8–12.
[14] J.H. Park, K. Yoon, Designing a Biomimetic Ornithopter Capable of Sustained and Controlled Designing a Biomimetic Ornithopter Capable of Sustained and Controlled Flight 6239, 2017.
[15] S. Akande, A. Adeyun, T. Olunrewaju, and A. Adeoye, “UAV and its Approach in Oil and Gas Pipeline Leakage Detection,”, vol. 2021, 2021.
[16] A. Adetunla, N. Madonsela, Harnessing Industry 4.0 technology to improve productivity in manufacturing industries: a case of CNC based welding factory, Proc. 2021 IEEE 12th Int. Conf. Mechatron. Technol. ICMMT 2021 (2021) 180–185.
[17] Z. Gao, Y. Zhu, C. Liu, H. Qian, W. Cao, J. Ni, Design and test of a soil profile moisture sensor based on sensitive soil layers, Sensors 18 (5) (2018) 1648.