

## Research Article

# Design and Optimization of a Wind Turbine for Rural Household Electrification in Machakos, Kenya

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Machakos is an area characterized by low wind speeds in the range of 0.5 m/s to 5 m/s with an annual average wind speed of 3.5 m/s. Maximum power generation from wind requires the appropriate design of the conversion system. In this study, two HAWT rotor blades were fabricated using Styrofoam and aluminium with a pitching mechanism to maximize power. The system was tested in a wind tunnel environment at a wind speed range of 0 m/s–20 m/s. RPMs and torque were measured and then used to calculate the TSR and power coefficients at different pitching angles. Energy optimization was performed by varying the pitch angles from 0 to 40 degree and rotational speeds, blade shape, and also a variation of blade materials. The analysis of tip speed ratios showed positive skewness implying high potential for significant energy generation at low wind speeds. At the rated wind speed of 5 m/s, Styrofoam blades performed optimally at a pitch angle of 20 degree with a tip speed ratio (TSR) of 2.1 corresponding to a  $C_p$  of 0.465. This translates to 238 W of power. Aluminium type performed optimally at a pitch angle of 15 degree with a TSR of 1.9 corresponding to a  $C_p$  of 0.431, a power estimate of 220 W. These findings showed that Styrofoam blades were more effective and thus suitable for application in wind systems. The understanding gained from this study could be useful to the HAWT research community and can be extended to the turbine designs for small-scale microgrids and utility applications.

## 1. Introduction

The pursuit to attain sustainable development goals has made growth in renewable energy technologies [1]. The world's ever-growing population estimated to be 9 billion by 2050 has led to increased demand for basic necessities like energy, food, and water as well as increased environmental pollution [2, 3]. As a result, a clean and sufficient source of energy is thus the immediate need for today as also indicated by Shankar et al [4]. To minimise this huge energy demand, application of new technology in the exploitation of renewable energy resources offers a viable solution. Renewable energy sources like wind and solar are among the cleanest, most widely distributed, and freely available sources with huge energy reserves. The two energy sources offer better

solutions for the alleviation of energy shortages and environmental pollution. The two renewables also offer the potential to mitigate the ever-increasing demand for clean energy [5, 6]. Of late, wind energy is one of the most developing areas in renewable energy research, accounting for approximately 40% of the total primary energy utilization [7, 8]. Moreover, according to de Falani et al., 2020 [9], wind energy is considered the fastest growing and most promising source of renewable energy with zero direct emissions. Wind systems would thus greatly reduce carbon footprints and hence reduce pollution [10]. As highlighted by Asim et al. [11], global scientific advances in the wind have greatly contributed to a good percentage of the job market. Wind thus remains a better option in the energy sector to supplement other sources of renewable energy. However, of

much interest in this study is the wind energy conversion system (WECS) meant to optimize power generation from the resource.

Wind turbine design and installation are highly dependent on the wind conditions, topological conditions, and energy needs of the site [12]. Wind turbines generate significant power from wind speeds ranging from 3 or 4 m/s up to 15 m/s, 25 m/s, or even 34 m/s. However, as mentioned by Apunda and Nyangoye [5], intermittency makes some regions experience lower speeds than 4 m/s leading to low energy yields. Based on the wind regime characterization performed in the previous study, Machakos region was found to have low wind speeds in the range of 3–4 m/s on average. Weibull's uncertainty analysis gave  $c$  (scale parameter) and  $k$  (shape parameter) values of 3 and 1.9, respectively. A  $k$  value of 1.9 obtained in this analysis showed high variability of the wind speeds raising flags of high variability of wind energy from Machakos. The low  $c$  value of 3 obtained revealed the high probability Machakos has for low wind speeds. These wind characteristics qualified Machakos region to be in the wind class of  $\approx 1$ , which is unsuitable for large-scale wind energy generation. However, with much focus on wind turbine technology advances, wind power generation from the available wind speeds can be maximized for small-scale power applications in rural households with energy loads of less than 1 kWh. These advances lay emphasis on wind turbine aerodynamics and simple designs using light materials like composites [2]. Moreover, high towers and long blades relative to generator capacity allow for installation of wind turbines in low-speed wind sites [9].

Wind energy converters are divided into two categories, namely, the lift and the drag types. Drag machines have their direction of rotor rotation corresponding to the direction of the wind, leading to reduction in their relative speed. As reported by Saoko et al. [3], though widely used, this type has proven to be inefficient. In this study, lift machines were used due to their higher energy harnessing capacity [11, 13]. In this converter, blades rotate faster than the wind increasing efficiency [14]. A lift machine operates on the principle of relative velocity at which the wind strikes the blade at a given radius. The force that can be developed by this type of machine is greater than that developed by using a drag machine at the same surface area. The wind force provides a much higher lift and power coefficient [15]. These facts justify the application of the lift-driven device in this study. In this respect, therefore, to increase the system's reliability and efficiency, knowledge of the aerodynamic variables affecting its performance is critical [11]. Consequently, designers need to explore wind turbine optimization using aerodynamic parameters like blade pitching, twisting, tapering, yawing, rotor area, blade materials, and shape [16, 17]. These parameters enable variations in lift and drag coefficients across the blade surfaces allowing for an increase in wind turbine efficiency [18]. Wind turbine designers use cambered airfoils more often than symmetrical ones since they can work in any direction with a lower drag coefficient [19]. Moreover, cambered blades can generate lift at zero pitching angles and higher lift at higher angles of

attack compared to symmetrical airfoils. In this work, cambered blades were preferred to be symmetrical.

As earlier highlighted, this study focuses on exploring the feasibility of the low wind speed regime in Machakos for small-scale wind energy generation. This will create access to an alternative source of renewable energy other than the vast solar resource. In view of the discussed facts and possibilities in wind energy technology, a site-specific wind energy system has been designed and characterized to maximize the energy conversion in the area. Optimization was achieved by comparing the performance of Styrofoam and aluminium whose shapes were tapered and cambered to minimize drag. Variation of the rotor speed and blade pitch angles was also performed to have the rotor performance approach the upper Betz limit of 59.3%.

## 2. Wind Turbine Aerodynamics

In wind resources, the wind energy content that is dependent on the density and air velocity is of much interest. Density varies with pressure and temperature, both of which depend on altitude. The conversion of the kinetic energy of the wind resource into electricity is performed by the use of a wind turbine [8]. In wind turbine design and fabrication, key issues that affect aerodynamic characteristics of the wind turbine need to be addressed to optimize power extraction from wind resources [11]. According to Erick et al. [20], the conversion efficiency of turbines majorly depends on the blade airfoil, where the aerodynamic forces contributing towards torque occur. Since turbines make the most out of the wind by subtracting the amount of movement of the wind current, it is necessary to know the upper limit of the extractable energy from wind resources [4, 20]. This knowledge gives light in designing for utmost perfection to minimize all effects that reduce energy due to the number of blades, wake rotation, and aerodynamic drag. The wind turbine experimental models fabricated in this study were blades and the hub where the blades were designed in accordance with the blade element and momentum theories [20, 21]. At the design stage aerodynamic parameters such as rotor power, tip speed ratio (TSR), torque, Reynolds number, solidity, lift, draft, and power coefficients are important. These parameters can be determined using equations (1)–(10) [1, 11, 20, 22].

$$\text{Wind Power: } P = \frac{1}{2} \rho A U^3, \quad (1)$$

$$\text{Rotor Power: } P = \frac{1}{2} \rho A U^3 C_p, \quad (2)$$

$$\text{Reynolds number: } Re = \frac{\rho U c}{\mu} = \frac{U c}{\nu}, \quad (3)$$

$$\text{Tip speed ratio } \lambda := \frac{\omega R}{U}, \quad (4)$$

$$\text{Solidity : } \sigma = \frac{BA}{\pi R^2}, \quad (5)$$

TABLE 1: Wind turbine configuration.

Rotor radius (mm)	1450
Swept area (m <sup>2</sup> )	6.6
Number of blades	3
Solidity	0.2
Airfoil type	NACA 4418
Reynolds number	100000
Design tip speed ratio	2.3
Assumed power coefficient (cp)	0.46
Design system efficiency	85%
Rotor speed (RPM)	75
Rotor power rating (W)	235
Chord (mm)	300
Rated wind speed (m/s)	5
Generator rating (W)	200

$$\text{Power coefficient: } C_p = 4a(1-a)^2 - \frac{Bc}{2R}c_d\lambda^3, \quad (6)$$

$$\begin{aligned} \text{Lift and drag forces: } dL &= C_l(\alpha) \frac{1}{2} \rho U^2 cdr, \\ dD &= C_d(\alpha) \rho U^2 cdr, \end{aligned} \quad (7)$$

$$\begin{aligned} \text{Torque and Power: } P &= Q\omega, \\ C_p &= C_Q\lambda, \end{aligned} \quad (8)$$

where  $B$  is the number of rotor blades,  $A$  is the blade area,  $C_l$  is the lift coefficient,  $C_d$  is the drag coefficient,  $R$  is the radius of the rotor,  $c$  is the chord,  $\omega$  is the angular velocity,  $U$  is the free stream wind speed,  $\rho$  is the fluid density,  $\mu$  is dynamic viscosity,  $\nu$  is kinematic viscosity,  $\alpha$  is the angle of attack,  $\lambda$  is the tip speed ratio,  $\sigma$  is solidity,  $P$  is wind power,  $Q$  is torque,  $C_p$  is the power coefficient, and  $C_Q$  is the torque coefficient. The power coefficient of a turbine is the measure of the turbine's energy conversion ability from the wind. It is majorly dependent on the tip speed ratio and blade pitching angle. Equation (9) and (10) show the power coefficient ( $C_p$ ) and the tip speed ratio ( $\lambda$ ) [1, 11, 20, 22].

$$C_p = \frac{2\pi nQ/60}{1/2\rho AV^3}, \quad (9)$$

$$\lambda = \frac{2\pi Rn/60}{V}, \quad (10)$$

where  $C_p$  is the power coefficient,  $n$  is the rotational speed,  $\rho$  is the air density,  $V$  is the wind speed,  $A$  is the swept area,  $R$  is the radius of the rotor,  $\lambda$  is the tip speed ratio, and  $Q$  is torque.

### 3. Methodology

In this section modified turbine parameters, rotor fabrication, and wind tunnel experimental tests are presented.

**3.1. Wind Turbine Design Parameters and Fabrication.** The turbine configuration parameters recorded in Table 1 were determined using Equations (1)–(10). Considering aerodynamic forces which depend on free-stream velocity

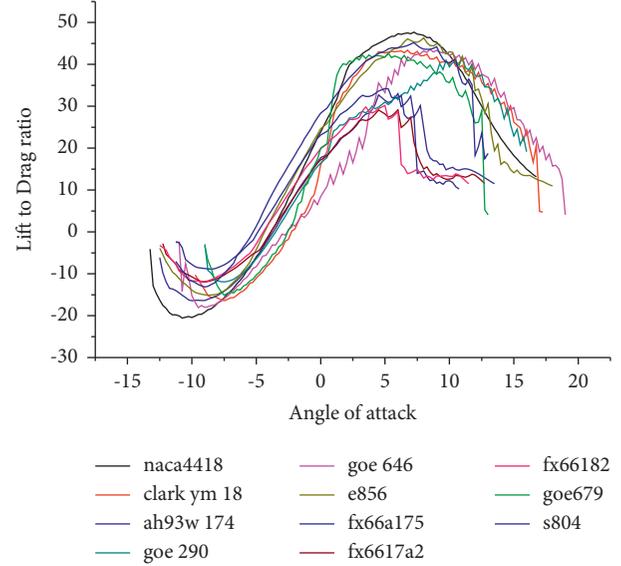


FIGURE 1: Lift-to-drag ratio against the angle of attack for different airfoils.



FIGURE 2: Fabricated aluminium blades.

plus the distance from the axis, wind turbine blades were designed based on the blade element momentum theorem. The fabrication was performed using two sets of light materials: aluminium and Styrofoam. The rotor was then assembled for aerodynamic tests in a wind tunnel environment to characterize its optimum performance.

In the selection of the most appropriate blade airfoil in this study, analysis of the lift-to-drag ratio at different angles of attack shown in Figure 1 was used. The wind regime in Machakos was found to have a Reynolds number of approximately  $1 \times 10^5$  and thus classified as a turbulent flow zone. Based on this flow regime, NACA 4418 was selected as the most suitable airfoil due to its high lift-to-drag ratio of 47 compared to other airfoils. This ratio was found to be in agreement with Smulder's proposal that stated a good choice of an airfoil for use in a lift-driven machine ought to have a lift-to-drag ratio of at least 30 [13, 19].

**3.1.1. Aluminium Blade Design.** A 4 mm thick aluminium sheet was used to fabricate a 1300 mm span blade with a straight leading edge and the trailing edge tapered at an angle of 10 degree. The blade strength was enhanced by the use of three folds of 20 degree, 15 degree, and 15 degree parallel to

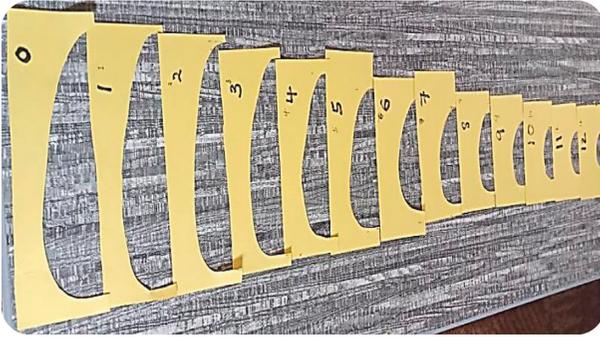


FIGURE 3: Styrofoam blade element cross sections.

the leading edge, which also ensured much fluid dynamic contact with the blade surface. The blade pitching angle was varied manually to determine the maximum angle at which the rotor has the maximum lift. Figure 2 shows the fabricated aluminium blades.

**3.1.2. Styrofoam Blade Design.** Based on blade element theory, 13 sections cut from Manila paper were used to size and shape Styrofoam into a tapered blade design. The sections are shown in Figure 3.

Shaping and sizing of the Styrofoam blades adopted the NACA 4418 model properties that gave a uniformly tapered blade as shown in Figure 4. Fiber-reinforced plastic was glued to form the primary cover layer which was further reinforced using resin with 2% methyl ethyl ketone peroxide to harden. The blades were then molded using body filler to make them stronger, smooth, and waterproof.

**3.1.3. Rotor Hub.** A three-blade rigid hub of diameter 300 mm was designed and fabricated using aluminium cast as shown in Figure 5. It was fitted with bearings for smooth rotation and three pipes 150 mm long and 30 mm in diameter located at an interval of 120 degree. This hub design was to allow for variable pitching of the blades to maximize power capture. Energy optimization through pitching allowed for lift variation at different angles of attack at a testing stage in the wind tunnel environment.

**3.2. Wind Turbine System Testing.** Wind tunneling was performed in the fluid lab at Jomo Kenyatta University engineering workshops to investigate the aerodynamic performance of the turbine rotor. Figure 6 shows the experimental test setup in the Fluid Mechanic Lab of the Jomo Kenyatta University of Agriculture and Technology.

The wind blower used in this study had 440 mm square exit duct and variable wind speeds in the range of 0.5 m/s to 10 m/s to drive the rotor. An induction motor was used as a load, and an inverter was used to regulate the frequency from high speed to low speed. Torque and rotational speed were measured using a torque meter as shown in Figure 6.

**3.3. Wind Turbine Optimization.** Wind turbine design and optimization parameters have a momentous impact on the



FIGURE 4: Styrofoam blades reinforced in fiber material.



FIGURE 5: Three-blade rigid rotor hub.

turbine energy output. In this view, it is important when specifying turbine parameters to take into account the wind distribution and energy potential at the site. In this view, optimization of energy capture was performed based on the low wind speed regime in Machakos. Figure 7 shows a flowchart indicating how power optimization was achieved.

The rotor design specifications were determined to enable it extractable the maximum possible energy from the wind resource. This enabled the generator to produce its maximum rated power of 200 W at the rated wind speed of 5 m/s. This state was achieved through iterations of the parameters affecting wind power which include rotor area, rotational speed, torque, tip speed ratio, blade material, blade geometry, and pitching angles. Parameters like rotational speed, blade material, and pitch angles were variable and thus were used to determine the optimum point for both Styrofoam and aluminium blades.

Using the turbine specifications in Table 1 and the simulated wind speeds, the wind power was calculated using equation (1), while the rotor output power was determined using equation (8). The two power outputs were compared to determine the power coefficient used to determine the optimum power point of the turbine. This process was repeated at different pitch angles starting from 0 degree to 40 degree at intervals of 5 degree until the maximum power was achieved at 20 degree and 15 degree for both Styrofoam and aluminium blades, respectively, as presented in the next section.

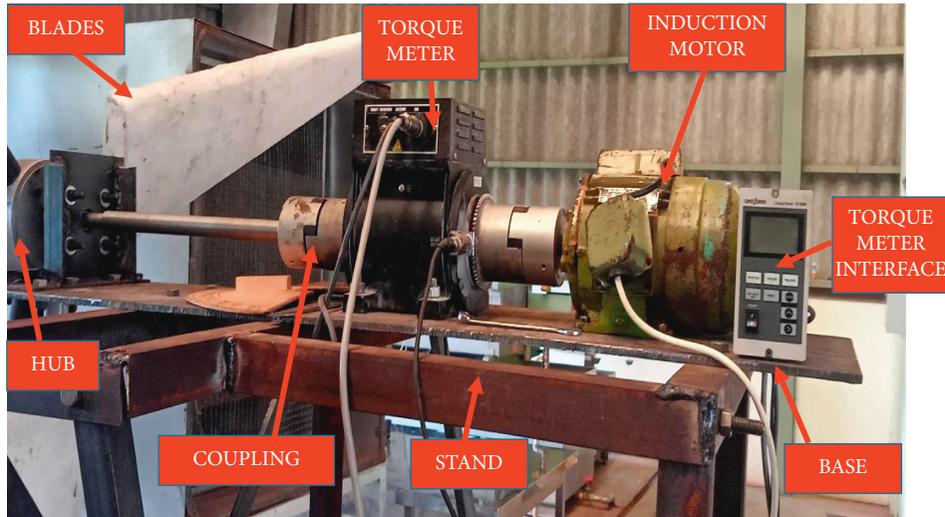


FIGURE 6: Wind turbine experimental setup.

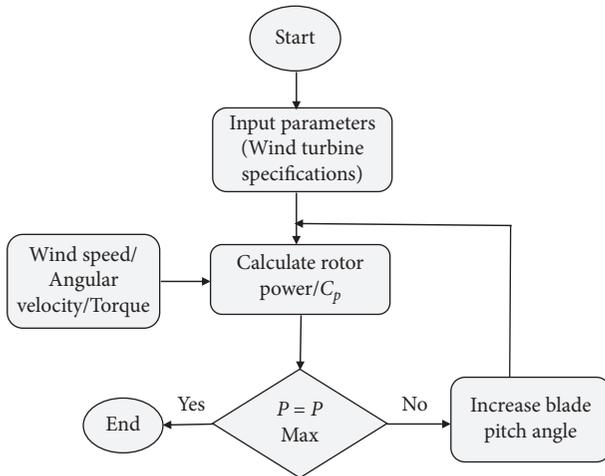


FIGURE 7: Wind turbine optimization flowchart.

#### 4. Results Discussion and Validation

This section presents the optimization results which include the analysis of rotational speeds, tip speed ratios, and the power coefficients at different wind speeds and blade pitch angles. Figure 8 shows the RPMs at different wind speeds for aluminium and Styrofoam blades, respectively. Comparatively, Styrofoam blades recorded slightly higher speeds than aluminium blades in the range of 60 and 102 rev/min. High speeds were realized at pitch angles of 12 degree, 15 degree, and 18 degree for the aluminium rotor blades with the peak attained at a pitch angle of 15 degree. Angles higher than 18 degree recorded low speeds. These low speeds can be attributed to an increase in drag forces as the blade approaches the stalling point. Near the stalling point, lift decreased drastically for some blades, a condition that led to a decreased lift-to-drag ratio and hence a low coefficient of power. Styrofoam blades recorded higher RPMs at pitch angles of 18 degree, 20 degree, 23 degree, and 25 degree which reduced at angles higher than 25 degree. The highest RPM was realized at a pitch angle of 20 degree.

According to [23], an optimum pitching angle exists at which two-thirds of the wind speed is converted to kinetic energy by using the rotor. With this fact, aluminium and Styrofoam blades were set at 15 degree and 20 degree, respectively below which much wind was blurred increasing drag. Tests beyond these angles showed that more than one-third of the wind spilled past the blades reducing the amount of wind power available for conversion. Thus, pitch angles of 15 degree and 20 degree gave the optimum condition of operation for the two types of rotor blades in this study.

Figure 9 shows the tip speed ratios versus wind speeds for Styrofoam and aluminium blades, respectively. The tip speed ratio was a key parameter that influenced the turbine power coefficient. From the analysis, higher tip speed ratios were skewed towards low wind speeds showing good prospects of energy conversion by the turbine at low wind speed regimes.

The aluminium blades recorded a maximum TSR of 2.9 at the optimum pitch angle of 15 degree, whereas Styrofoam recorded a slightly higher TSR of 3.1 at the optimum pitch angle of 20 degree. The high TSR from the Styrofoam type can be attributed to their difference in a density of  $2.7 \text{ g/cm}^3$  and  $0.96 \text{ g/cm}^3$  for aluminium and Styrofoam, respectively. Styrofoam therefore proved to be the better option in blade fabrication than aluminium even though their performance was comparably close. Power coefficients with the corresponding TSR were calculated and compared for both blade types. According to Wekesa et al. [6], the power coefficient ( $C_p$ ) is a dimensionless quantity, which is often used to compare the power performance of wind turbine rotors. In this study,  $C_p$  has been used to give measure of the magnitude of power extractable in wind using Styrofoam and aluminium rotor blades. Figure 10 shows the graphs of the power coefficient against TSR, while Figure 11 shows the graphs of the extractable wind power calculated at the optimum  $C_p$  of 0.465 for aluminium and Styrofoam blades, respectively. A maximum  $C_p$  of 0.431 corresponding to a  $C_p$  of 2.0 at the optimum pitch angle of 15 degree was obtained for the aluminium blades. As indicated in the graph in

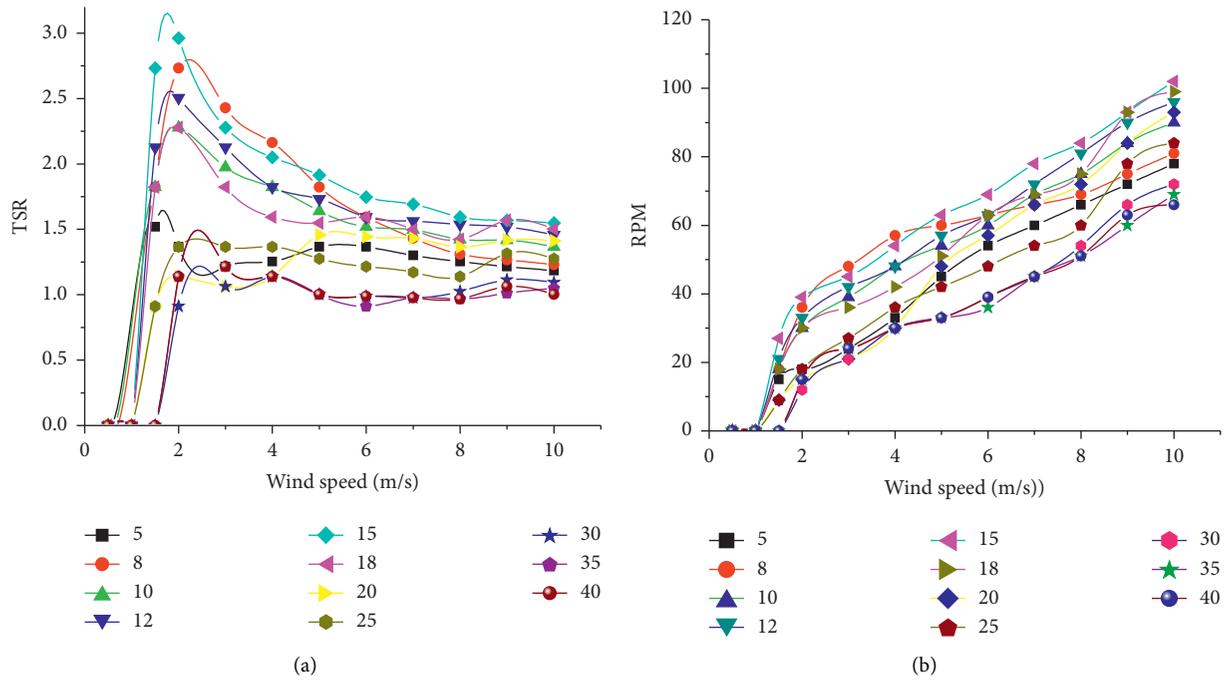


FIGURE 8: (a) RPM versus wind speeds for Styrofoam and (b) aluminium blades, respectively.

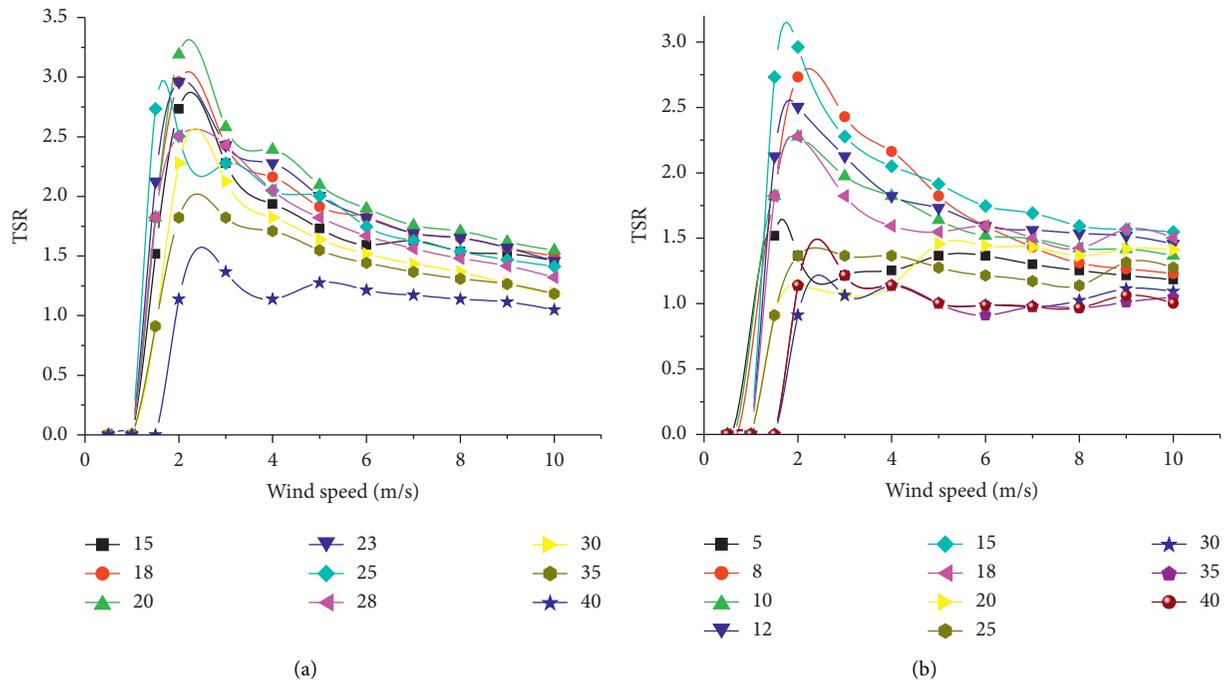


FIGURE 9: (a) TSR versus wind speeds for Styrofoam and (b) aluminium blades, respectively.

Figure 11(a),  $C_p$  of 0.431 translated to a maximum extractable power of 220 W from the wind resource. Styrofoam blades recorded a slightly higher  $C_p$  peak of 0.465, which corresponds to a TSR of 2.1 at the optimum pitch angle of 20 degree. As presented in Figure 11(b), a TSR of 0.465 translates to a maximum power of 238 W down from the maximum available power of 300 W at the Betz limit of

0.593. Below and after the optimum TSR, a low  $C_p$  was recorded in both rotors due to an increase in drag forces that led to a sharp decrease in lift. The TSR obtained in this study was comparable to the values obtained by Nashiziwa et al. [2] on tapered type wind turbine blades. Similar results were reported by Nishizawa with a maximum  $C_p$  of 0.39 for three-bladed rotor at a tip speed ratio of 4.06 [24]. Moreover, Saoko

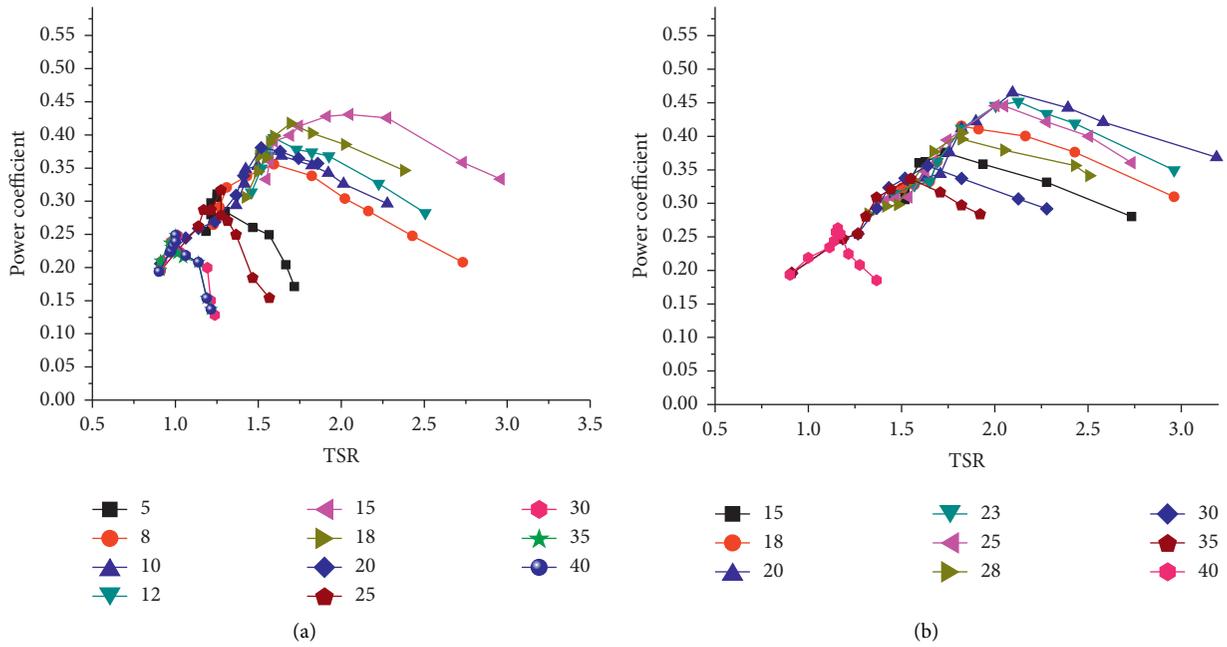


FIGURE 10: (a) Power coefficient versus TSR for aluminium and (b) Styrofoam blades, respectively.

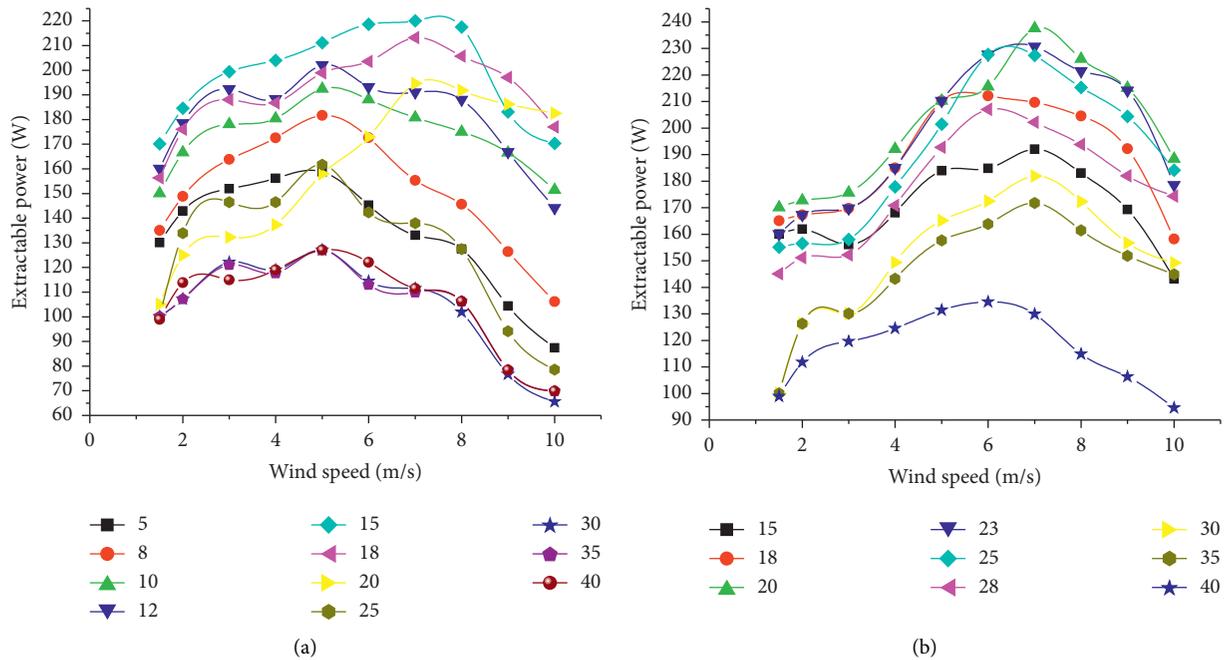


FIGURE 11: (a) Extractable power versus wind speeds for aluminium and (b) Styrofoam blades, respectively.

et al. [3] reported on power coefficients which were comparable to the findings in this study. They reported on small tapered blades at different pitch angles, which recorded a maximum  $C_p$  of 0.372. Below the optimum TSR, it was noted that the blade rotated at low speed. As a result wakes increased and more wind spilled through the blade gaps leaving less wind for energy conversion. Above the optimum TSR, the rotor rotated at high speed making it behave like a solid wall that blurred the wind flow. This state increased

drag leading to a decreased lift force. According to Wen et al. [25],  $C_p$  decreases with an increase in TSR. Such a state is detrimental to the structure of the wind turbine and ought to be avoided by ensuring that the system works at its optimum conditions. Large values of pitch angles made the rotor experience stall, deteriorating its aerodynamic performance.

The expected energy output at the design  $C_p$  of 0.465 was analyzed in comparison with the maximum available power as per the Betz limit of 0.593 at the rated wind speed of 5 m/s.

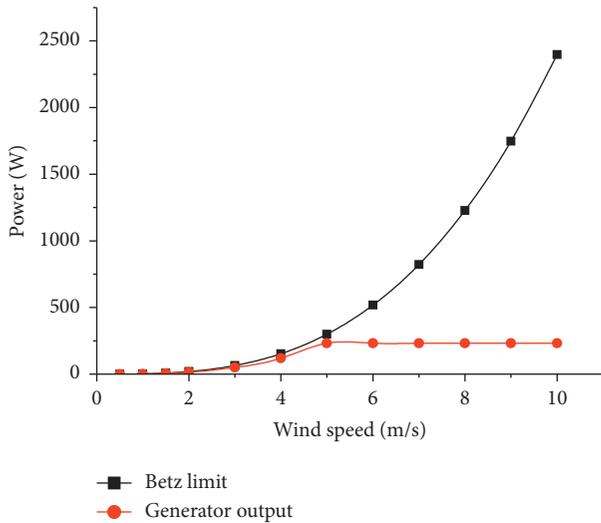


FIGURE 12: Expected wind turbine generator power output.

Figure 12 presents a graph of expected power against wind speeds of the wind turbine generator in comparison to the maximum Betz limit. According to the findings, low wind speed regimes with average annual wind speeds of 3.5 m/s have the capacity to produce power on small scales. The fabricated wind turbine set at its optimum operating conditions has proved to be suitable for converting wind energy into electrical energy at a maximum rate of 46%. This energy of 238 W for Styrofoam blades and 220 W for aluminium is sufficient to bridge the energy demand gap in rural households with an average daily load of 0.588 kWh. These two rotor power outputs are a true reflection of the expected wind turbine output value of 235 W as per the configurations shown in Table 1.

## 5. Conclusion

A site-specific wind turbine mimicking the low wind speed of the wind regime in Machakos has been designed and optimized. The turbine is made to provide a power output of 200 W at a rated wind speed of 5 m/s to rural households with an average daily load of 0.588 kWh. The rotor blades had a solidity of 20% which is within the range of prescribed values for a three-bladed rotor based on blade element techniques. This value of solidity ensured a reduction in fluid flow resistance raising the rotor efficiency. Analysis of the tip speed ratios revealed positive skewness implying high capabilities of energy production at low wind speeds. The Styrofoam blades performed optimally at a pitch angle of 20 degree and a TSR of 2.1. These values corresponded to a  $C_p$  of 0.465 at the rated wind speed. Comparatively, aluminium blades performed closely with a TSR of 1.9 obtained at a pitch angle of 15 degree. The power coefficients obtained translated to 238 W and 220 W of extractable power from Styrofoam and aluminium rotor blades, respectively. These findings revealed that Styrofoam is a more suitable material for rotor blade fabrication due to its low density. This is justified by the fact that Styrofoam rotor blades captured more wind energy than aluminium rotor blades at low wind

speeds. According to the obtained results, the optimized turbine rotors at 20 degree or 15 degree can sufficiently meet the daily load demand for an average rural household in Machakos. Moreover, the findings from this study can be extended to the designs of HAWT for small-scale microgrids and utility-scale applications.

**5.1. Future Work.** The optimized wind turbine will be installed on a tower for hybridization with a solar PV system. The two interfaced energy systems will then be subjected to field tests to determine their effectiveness in providing constant power supply to the loads at night and day time.

## Data Availability

The data supporting this research paper are taken from the previously conducted and reported studies and datasets. The other processed data on the wind tunnel test are available in the supplementary files.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgments

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## Supplementary Materials

Supplementary materials SM 1 to SM 13 show tables of datasets used in this study. SM 1: tables of the rotational speeds recorded during the wind tunnel test at the fluid lab in JKUAT. SM 2, SM 3, and SM 4: the calculated rotor frequencies, tip speeds, and tip speed ratios of both Styrofoam and aluminium-type rotor blades. SM 5 and SM 6: plot of the NACA 4418 airfoil and the coordinates used to implement the sketch used in the fabrication of the rotor blades. Tables SM 7, SM 8, and SM 9: data on the lift coefficients, drag coefficients, and lift-to-drag ratios of NACA 4418 in comparison to the other related airfoils. Analysis of this data was used in the determination of the most appropriate blade airfoil for application in this study. Tables SM 10 and SM 11: the power coefficients and the rotor power calculated at different tip speed ratios of the Styrofoam-type rotor blades. Tables SM 12 and SM 13: the power coefficients and the rotor power determined at different TSRs of the aluminium-type rotor blades. These analyses aided in the establishment of the optimum conditions for blade installation to ensure maximum wind power extraction by using rotors. (*Supplementary Materials*)

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