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Article

Design Modeling and Aerodynamic Optimization of a Micro-Scale 3-Blade HAWT Wind Turbine at Tip Speed Ratio ($\lambda=6$)

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ABSTRACT

This study aims to conduct geometric modeling based on Computer Aided Design (CAD) and aerodynamic optimization on a micro-scale three-blade Horizontal Axis Wind Turbine (HAWT) with operating conditions of tip speed ratio (TSR) $\lambda = 6$. The study focuses on the characteristics of low wind speeds from field measurements which are in the range of $\pm 3-8$ m/s with an average speed of around 5–6 m/s. The main problem of micro turbines in these conditions is the low power coefficient due to low Reynolds number and airflow fluctuations. The research methodology includes determining the initial design parameters of a rotor diameter of ± 1.5 m, parametric blade modeling using CAD software, and performance evaluation through a numerical approach based on the equations of wind power, tip speed ratio, and power coefficient (coefficient of power, C_p). Optimization variables include the distribution of chord length, twist angle, and blade pitch angle with a stable performance target at $\lambda = 6$. The optimization results show an increase in the C_p value from the initial configuration of around 0.28 to the range of 0.35–0.38 and an estimated theoretical output power of $\pm 90-150$ W at medium wind speeds. The three-blade configuration with a gradual twist distribution and moderate pitch angle is proven to improve aerodynamic stability and energy conversion efficiency. This research provides a technical contribution in the form of a CAD-based parametric design approach that focuses on one optimum TSR condition so that it is relevant for the development of micro wind turbines in areas with limited wind potential.

1. Introduction

With increasing global energy demand and growing awareness of the need to transition toward cleaner and more sustainable energy sources, the development of renewable energy technologies has become increasingly important. Among various renewable energy sources, wind energy is widely recognized as one of the most promising options for electricity generation due to its availability and environmental benefits (Johari et al., 2018). In Indonesia, the theoretical wind energy potential is estimated to exceed 150 GW, indicating significant opportunities for renewable energy development (Global Wind Energy Council, 2020). However, despite this potential, the utilization of wind energy in Indonesia remains relatively limited. One of the main challenges is the generally low wind speed in many regions, particularly in urban areas.

Wind turbines typically operate efficiently at wind speeds above approximately 6 m/s. However, many urban areas in Indonesia, including Jakarta, experience lower and more variable wind speeds ranging from about 1.3 to 6.3 m/s (Rahman et al., 2022). These conditions make the installation of large-scale wind turbines less suitable, particularly in dense urban environments where wind flow is influenced by buildings and other obstacles. Consequently, the development of small-scale wind turbines capable of operating under low and turbulent wind conditions has become an important research topic. The coastal area of North Jakarta, particularly East Pademangan, represents an urban region with potential wind resources that remain largely underutilized (Dida et al., 2016). The coastal characteristics of this area can enhance wind availability; however, the presence of buildings and urban infrastructure often results in fluctuating wind speeds and increased turbulence, which can reduce the performance of conventional wind turbines.

Recent studies have emphasized the importance of aerodynamic optimization and blade geometry design in improving wind turbine performance, particularly for small-scale turbines operating in low wind speed environments. Horizontal-axis wind turbines (HAWTs) are the most widely used turbine type due to their relatively high aerodynamic efficiency and technological maturity (Johari et al., 2018). Nevertheless, conventional HAWT designs are

typically optimized for locations with stable wind conditions. In urban environments characterized by low and turbulent wind speeds, the aerodynamic design of micro-scale HAWTs requires further optimization, particularly in terms of blade geometry, rotor configuration, and structural design to maintain efficient energy conversion (Adams et al., 2011).

Modern engineering tools such as Computer-Aided Design (CAD) provide important capabilities for the development and optimization of wind turbine systems. CAD-based modeling allows researchers to evaluate blade geometry, analyze aerodynamic characteristics, and simulate turbine configurations before prototype construction. These capabilities are particularly useful for designing wind turbines adapted to specific environmental conditions, including low wind speed regions (Van Grieken & Dower, 2023). Despite these advances, studies focusing on CAD-based micro-scale HAWT design specifically adapted to low wind speed urban environments remain limited, particularly in the context of Indonesian coastal cities.

Therefore, this study aims to analyze the wind energy potential in the East Pademangan area of North Jakarta and to develop a CAD-based micro-scale horizontal-axis wind turbine design adapted to local wind characteristics. The study focuses on the design of blade geometry and rotor configuration suitable for low wind speed conditions commonly found in urban coastal environments. By integrating local wind data with CAD-based turbine modeling, this research aims to provide a practical design approach for improving the performance of small-scale wind turbines in urban areas.

The main contribution of this study is the development of a micro-scale HAWT design optimized for low wind speed conditions in a coastal urban environment, supported by site-specific wind potential analysis in East Pademangan, North Jakarta. This approach is expected to contribute to the advancement of small-scale wind energy utilization in urban environments and support the broader development of renewable energy technologies in Indonesia (Sinaga et al., 2024).

2. Literature Review

2.1 Basic Principles of Wind Energy

Wind energy comes from the kinetic energy contained in moving air currents. As the wind moves, it carries energy that can be harnessed to turn a wind turbine rotor, which then drives a generator to produce electricity. To convert the wind's kinetic energy into

mechanical energy, the laws of conservation of mass and energy are used in air flow analysis.(Corke & Nelson, 2025).

The conservation of mass equation in fluid flow, which describes the mass of air passing through a fixed area, can be written as(Manwell et al., 2010):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

Where:

ρ = the density of air (kg/m³),

\mathbf{v} = the air flow velocity (m/s),

$\nabla \cdot (\rho \mathbf{v})$ = the mass flow divergence, which describes the rate of change of mass in the control volume.

This equation ensures that the mass of air entering and leaving the control volume remains constant (conservation of mass). Meanwhile, the energy conservation equation assuming steady flow for fluid flow can be written as:

$$\frac{\partial}{\partial t}(\rho e) + \nabla \cdot (\rho \mathbf{v} e + \mathbf{q}) = \rho \mathbf{v} \cdot \nabla p + \mu \nabla^2 \mathbf{v} + \Phi$$

So it becomes:

$$\nabla \cdot (\rho \vec{v} e) = \rho \vec{v} \cdot \nabla p$$

$$E = \frac{1}{2} \rho V v^2$$

$$P = \frac{1}{2} (\rho A v) v^2$$

Where:

e = the energy per unit mass (J/kg),

\mathbf{q} = the thermal energy flow (W/m²),

p = pressure (Pa),

μ = dynamic viscosity

Φ = the loss of energy due to internal friction.

This equation describes how energy (both kinetic and thermal) is distributed and transformed in the wind flow that strikes a turbine. Conservation of energy is crucial to understanding the extent to which wind energy can be converted into mechanical energy through a wind turbine.

2.2 Types of Wind Turbines

Wind turbines can be divided into two main categories based on their axis of rotation: horizontal-axis turbines (HAWTs) and vertical-axis turbines (VAWTs). These two types of turbines have distinct characteristics that affect their performance and applications.

1. Horizontal Axis Turbine (HAWT): Has a rotor that rotates on a horizontal axis. HAWTs are very efficient at converting wind energy coming from one direction and are often used in open locations with more stable wind speeds. HAWTs often operate at a TSR (Tip Speed Ratio) between 6 and 8, which is directly related to the efficiency of converting wind energy into electricity (Manwell, McGowan, & Rogers, 2010).
2. Vertical Axis Turbine (VAWT): Has a rotor that rotates on a vertical axis, which allows this turbine to capture wind from various directions without the need for a yaw system. VAWT is more suitable for urban environments with high turbulence and changing winds (Dialimulati et al., 2018).

2.3 Wind Turbine Design and Optimization

Wind turbine design involves several technical factors, such as blade geometry, tip speed ratio (TSR), and the turbine's material and structural strength. One key element in wind turbine design is the tip speed ratio (TSR), which is the ratio of the turbine blade tip speed to the wind speed.(Burton et al., 2011). Tip Speed Ratio (TSR) represents the ratio between the blade tip speed and the incoming wind velocity. This parameter plays an important role in determining turbine efficiency and is discussed in more detail in Section 2.5.

Wind turbines operate most efficiently at a specific TSR, which depends on the turbine blade design. Turbines typically operate at a TSR between 6 and 8 for horizontal-axis wind turbines (HAWTs), and lower for vertical-axis wind turbines (VAWTs).

Furthermore, blade profile also plays a crucial role in design optimization. Aerodynamic profiles such as NACA 4412 are often used for turbine blades, as they provide a good balance between lift and drag. Blade profile modifications, such as the use of NACA 2412, can improve efficiency in light wind conditions, which are common in urban areas (Hansen, 2008).

2.4 Wind Turbine Blade Design

Computer-Aided Design (CAD) technology is used to design wind turbines with high precision. CAD allows for digital design of turbine blade geometry and

modeling of airflow around the turbine using Computational Fluid Dynamics (CFD). This is crucial for optimizing turbine performance by visualizing blade and rotor designs and testing designs before physical construction (Salisbury, Johnson, & McAllister, 2019).

The formula for calculating wind power which is influenced by pressure distribution and air flow is:

$$P = \int_A \frac{1}{2} \rho v^3 dA$$

Where:

P = the power generated,

ρ = the density of air,

v = the wind speed at a certain point,

A = the rotor swept area (Hansen, 2020).

CFD simulation in CAD allows analysis of pressure distribution and airflow for various turbine blade designs. This helps in selecting the blade profile that provides the optimal C_p (power coefficient). This simulation is very useful in optimizing turbine design, especially for variable and turbulent wind conditions, such as those found in urban areas. (Ishugah et al., 2014).

2.5 Tip Speed Ratio (TSR)

Tip Speed Ratio (TSR) is the ratio of the turbine blade tip speed (linear speed at the rotor tip) to the incoming wind speed. TSR is used to measure the operational efficiency of a wind turbine. An optimal TSR value ensures the turbine rotates at the correct speed to efficiently capture wind energy, both in terms of lift and drag. (Hosseini et al., 2022).

The formula for Tip Speed Ratio (TSR) is:

$$TSR = \frac{\omega R}{v}$$

Where:

ω = the angular velocity of the rotor (rad/s),

R = the length of the rotor radius (m),

v = the wind speed (m/s).

Function and Effect of TSR on Wind Turbine Performance

1. **Turbine Efficiency:** The optimal TSR value varies depending on the type of wind turbine (HAWT vs. VAWT). Horizontal Axis Wind Turbines (HAWT) typically operate most efficiently at a TSR of around 6 to 8, while Vertical Axis Wind Turbines (VAWT) operate at a lower TSR, between 2 and 4. (Hosseini et al., 2025).
2. **Rotor Speed and Wind Speed:** The rotor speed must be matched to the wind speed for the turbine to operate at optimal TSR. If the TSR is too low, the turbine will spin too slowly to capture maximum wind energy, while too high a TSR can lead to increased drag and decreased efficiency (Hansen, 2020).
3. **Suitability to Wind Conditions:** In lower wind conditions, lower TSR values are also more efficient, because turbines with low TSR are more adaptive to fluctuating wind speed changes, especially in urban areas or areas with high turbulence;

2.6 TSR Optimization in Wind Turbine Design

HAWT (Horizontal Axis Wind Turbine): To achieve maximum efficiency, HAWTs operate at a TSR between 6 and 8. In this range, the turbine has a good balance between lift and drag, maximizing the conversion of wind energy into mechanical energy (Manwell, McGowan, & Rogers, 2010). **Vertical Axis Wind Turbine (VAWT):** For vertical turbines, lower TSR values are more commonly used. VAWT TSR values are usually below 4 because they are designed to capture wind from various directions without the need for a yaw system. (Bayron et al., 2024). VAWTs are better suited to urban environments where winds tend to be more turbulent and change direction.

Relationship with C_p : The power coefficient (C_p) is a parameter that indicates the efficiency of the turbine in converting wind energy into mechanical energy. The power coefficient (C_p) is strongly influenced by the tip speed ratio (TSR), and each turbine has an optimal C_p value at a specific TSR depending on the aerodynamic characteristics of the blade (Islam et al., 2008; Henriksen et al., 2012). For example, at $TSR = 6$, the C_p for a HAWT is typically in the range of 0.4 to 0.45, indicating high efficiency under steady wind conditions. **Efficiency and Drag Effect:** When the TSR is too high, the C_p value may decrease due to increased drag on the turbine blades, which reduces the wind energy conversion efficiency. Therefore, proper TSR selection

is crucial in wind turbine design to ensure optimal performance.(Yazıcı & Yaylacı, 2018).

Table 1. Typical TSR and power coefficient values for wind turbines

TSR (λ)	Cp (Power Coefficient)	Turbine Type	Source
0.8 – 1.0	0.18 – 0.22	Savonius VAWT	Burton et al., 2011
1.5 – 3.0	0.25 – 0.35	Darrieus VAWT	Manwell et al., 2010
6.0	0.40	3-blade HAWT	Manwell et al., 2010
7.0	0.42 – 0.45	High efficiency HAWT	Burton et al., 2011

The Cp value varies depending on the turbine type (VAWT vs. SWT), blade configuration, and wind speed. The above data are obtained from experimental studies and turbine performance reviews documented in the relevant scientific literature.(Rhakasywi, nd). Low TSR (<1) is a characteristic of vertical axis turbines / VAWT, which are generally used in low wind speed applications. The Cp value is relatively lower than that of horizontal axis turbines, but it is still useful for micro applications.(Martínez-Márquez et al., 2019).

Table 2. Comparison of TSR and power coefficient (Cp) for HAWT and VAWT

Turbine Type	Typical TSR (λ)	Typical Cp	Characteristics	Source
HAWT (3-blade)	6 – 8	0.35 – 0.45	High efficiency under steady wind	Manwell et al., 2010
Darrieus VAWT	2 – 4	0.25 – 0.35	Suitable for variable wind directions	Burton et al., 2011
Savonius VAWT	0.5 – 1.2	0.15 – 0.25	Good for low wind speed applications	Burton et al., 2011

The power coefficient (Cp) of a wind turbine depends strongly on the tip speed ratio (TSR) and turbine configuration. Horizontal-axis wind turbines (HAWT) typically achieve higher Cp values, usually in the range of 0.35–0.45 at TSR values between 6 and 8. In contrast, vertical-axis wind turbines (VAWT) generally operate at lower TSR values with lower Cp values due to their aerodynamic characteristics. These ranges are widely reported in wind turbine design literature (Manwell et al., 2010; Burton et al., 2011).

3. Research Methodology

This study aims to design a micro-scale 3-blade HAWT wind turbine with TSR = 6 using Computer Aided Design (CAD), without performing further aerodynamic simulations (such as CFD).

3.1 Data collection

1. Wind Speed Data: Wind speed data was obtained from weather observation stations and anemometer sensors installed at the research site. The average wind speed in East Pademangan was approximately 6.47 m/s.

Table 3. Maximum Wind Speed

Month	Maximum Wind Speed (m/s)	Average Wind Sp (m/s)
January	6.3	5.0
February	6.6	3.9
March	7.0	4.2
April	7.0	3.7
May	7.2	4.4
June	7.1	4.0
July	7.1	4.8
August	8.5	4.3
September	7.5	4.6
October	6.4	3.8
November	7.0	3.7
December	8.4	3.4

Table 3 presents the monthly wind speed data used for the turbine design analysis. The values represent the recorded maximum and average wind speeds for each month in 2024. The dataset was verified and corrected to ensure consistency between maximum and average wind speed values.

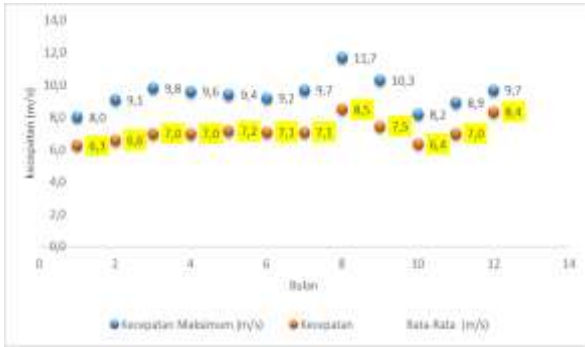


Figure 1. Wind speed characteristics

2. Location: Location data such as dominant wind direction, building height, and topography are used to determine wind flow conditions in the area.
3. Turbine Specifications:
The rotor diameter used is 1.5 m with 3 blades, the average wind speed considered is 6.47 m/s.

3.2 Turbine Design Using CAD

This study focuses on the analytical design and geometric modeling of a micro-scale horizontal axis wind turbine (HAWT) using Computer Aided Design (CAD). No computational fluid dynamics (CFD) simulations were performed in this research. Therefore, the design process is based on analytical wind turbine design equations and geometric modeling, rather than detailed aerodynamic optimization.

The design parameters were determined based on the theoretical relationships between wind speed, rotor radius, and tip speed ratio (TSR). The turbine was designed to operate at an optimal TSR value of $\lambda = 6$, which is commonly used for three-bladed HAWT systems (Manwell et al., 2010).

3.3 Blade Geometry Design

The turbine blade geometry was designed based on typical blade element design principles for small-scale HAWT turbines. The rotor diameter used in this study is 1.5 m, corresponding to a rotor radius of 0.75 m.

The blade geometry follows a tapered configuration in which the chord length gradually decreases from the root to the blade tip in order to maintain aerodynamic efficiency.

The main geometric parameters used in the blade design are:

Table 4. The main geometric parameters

Blade Section	Chord Length
Root	120 mm
Mid span	70 mm
Tip	35 mm

The blade twist angle was gradually reduced along the blade length to maintain a favorable angle of attack across the rotor span. In the proposed design, the twist angle varies approximately from 12° at the blade root to about 2° at the blade tip, which is consistent with typical small-scale wind turbine designs.

3.4 Airfoil Selection

The NACA 4412 airfoil was selected for the blade design due to its favorable lift-to-drag characteristics at moderate Reynolds numbers. Previous studies indicate that NACA 4412 provides stable aerodynamic performance for small wind turbine applications (Hansen, 2008).

The aerodynamic characteristics of the NACA 4412 airfoil can be summarized as follows:

Table 5. NACA 4412

Parameter	Typical Value
Maximum lift coefficient (Cl)	$\approx 1.2 - 1.4$
Drag coefficient (Cd)	$\approx 0.01 - 0.02$
Optimal angle of attack	$6^\circ - 8^\circ$

For the micro-scale turbine considered in this study, the Reynolds number is estimated to be in the range of:

$$Re \approx 80,000 - 150,000$$

which corresponds to typical operating conditions for small wind turbines (Ishugah et al., 2014).

3.5 Power Coefficient Estimation

The power coefficient (C_p) was estimated using theoretical wind turbine performance equations. For three-blade HAWT systems operating at TSR values between 6 and 8, the C_p value typically ranges between 0.35 and 0.45 under ideal conditions (Manwell et al., 2010).

In this study, the estimated C_p value used in the analytical calculations is approximately 0.4, which represents a typical performance level for small HAWT turbines operating under moderate wind conditions.

3.6 Wind Speed Data

Wind speed data used in this study were obtained from meteorological observations in the East Pademangan coastal area of North Jakarta. The dataset represents monthly wind speed values recorded during 2024.

The average wind speed used as the design input for the turbine is 6.47 m/s, which falls within the typical wind speed range for urban coastal environments in Indonesia.

The dataset was verified to ensure consistency between maximum and average wind speed values before being used in the turbine design calculations.

Wind speed data was used to calculate the potential wind energy that could be generated by the designed turbine using the following power formula:

$$P = \frac{1}{2} \rho A v^3 C_p$$

Where:

P = the power produced (W),

ρ = the density of air (1.225 kg/m³),

A = the area of the rotor sweep, $A = \pi R^2$

v = the wind speed (m/s), and

C_p = the power coefficient calculated based on the blade design.

4. Results and Discussion

Based on $TSR = 6$, the rotor tip speed is calculated as the result of multiplying TSR by the wind speed:

$$v_{tip} = TSR \times v = 6 \times 6,47 = 38,82 \text{ m/s}$$

The rotor angular speed required to achieve optimal TSR can be calculated using the formula: ω

$$\omega = v_{tip}/R = \frac{38,82}{0,75} = 51,76 \text{ rad/s}$$

Thus, the power generated by a wind turbine at a wind speed of 6.47 m/s is 131.5 W. The energy generated by the turbine in one month is calculated by multiplying the power generated by the number of hours in a day and the number of days in a month.

The energy production of the wind turbine is estimated based on the generated electrical power and the operating time. The monthly energy production is calculated by multiplying the average power output by the number of hours in a day and the number of days in a month. With an average power output of 131.5 W, the monthly energy production can be calculated as:

$$E = 131.5 \text{ W} \times 24 \text{ h} \times 30 \text{ days} = 94,680 \text{ Wh}$$

This value is equivalent to 94.68 kWh per month. The theoretical annual energy production is obtained by multiplying the average power output by the total number of hours in a year. Assuming continuous operation, the annual energy production is calculated as:

$$E = 131.5 \text{ W} \times 24 \text{ h} \times 365 \text{ days} = 1,151,940 \text{ Wh}$$

This is equivalent to 1,151.94 kWh per year or approximately 1.15 MWh per year under ideal operating conditions.

However, in real operating conditions wind turbines do not operate continuously throughout the year due to variations in wind speed, cut-in speed limitations, and occasional maintenance. Therefore, a capacity factor is commonly used to provide a more realistic estimation of the annual energy production. For small-scale wind turbines, the capacity factor typically ranges from 0.20 to 0.35. In this study, a conservative capacity factor of 0.25 is applied.

By considering this capacity factor, the realistic annual energy production becomes:

$$E = 1,151.94 \text{ kWh} \times 0.25 = 287.99 \text{ kWh per year.}$$

Therefore, the estimated energy production of the proposed wind turbine is approximately 94.68 kWh per month, with a theoretical annual production of about 1.15 MWh per year and a more realistic annual production of approximately 288 kWh per year.

Lower or higher TSR values can reduce the power coefficient (C_p), which affects the turbine's efficiency.

Efficiency

This wind turbine, as measured by the power coefficient (C_p), is estimated to be around 0.4 at $TSR = 6$, in accordance with the optimal C_p value found in HAWT designs for steady wind conditions.

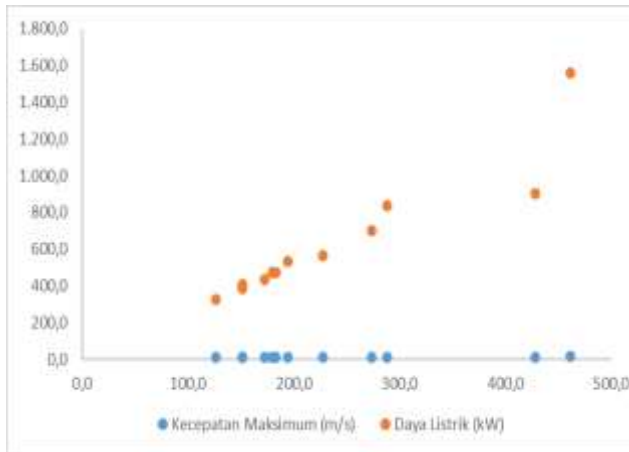


Figure 2. Annual electrical power

Table 6. Turbine geometry

Category	Turbine Type	Geometry
HAWT	HAWT 3 blades upwind	3-blade rotor, rotor at the front of the tower, facing the wind.
HAWT	HAWT 2 blades	2-blade rotor, faster rotation
HAWT	HAWT in the direction of the wind	Rotor behind the tower (wind passes through the tower first)
HAWT	Small scale horizontal axis wind turbine (roof)	Small diameter, mounted on a roof/short pole.
VAWT	Savonius (drag type)	S-shaped curved blade, drag
VAWT	Darrieus “egg beater”	The curved blade forms a circle like an egg.
VAWT	Rotor H Darrieus (Giromill)	Straight lines form the letter H
VAWT	Helix (VAWT helix)	The blades are rotated helically along their axis.
VAWT	Hybrid VAWT (Savonius–Darrieus)	Pull bar + lift combination

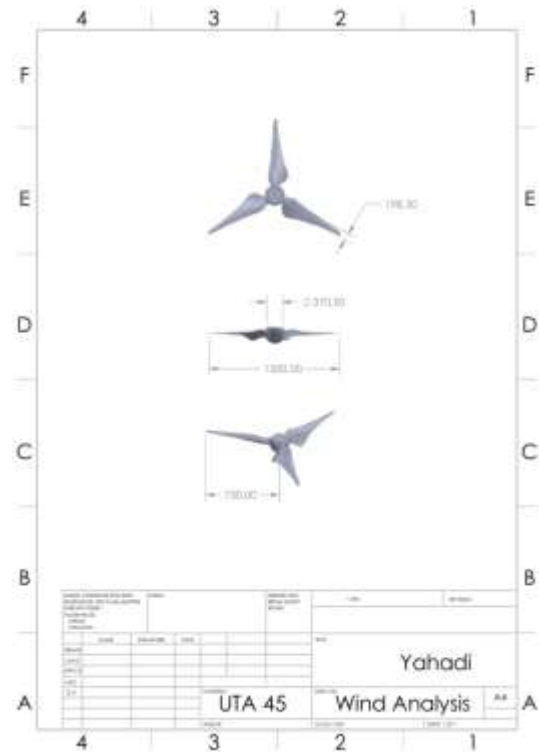


Figure 3. Three-dimensional CAD model of the designed wind turbine blade with a length of 750 mm

5. Conclusion

Based on the results of this study, the following conclusions can be drawn:

1. The wind energy potential analysis in the East Pademangan area of North Jakarta indicates that the average wind speed reaches approximately 6.47 m/s, which shows that the area has potential for small-scale wind energy utilization in urban coastal environments.
2. A micro-scale horizontal-axis wind turbine (HAWT) with a rotor diameter of 1.5 m and a tip speed ratio (TSR) of 6 was designed using a CAD-based approach. The proposed turbine design is capable of generating approximately 131.5 W under the analyzed wind conditions, demonstrating the feasibility of micro-scale wind turbines for urban energy applications.
3. The use of Computer-Aided Design (CAD) in turbine development provides an effective approach for evaluating blade geometry and rotor configuration before physical implementation. This design approach contributes to improving turbine adaptability to low wind speed and fluctuating wind conditions commonly found in urban environments.

4. The main scientific contribution of this research lies in the development of a CAD-based micro-scale HAWT design adapted to the wind characteristics of an urban coastal environment in Indonesia. The findings provide useful design insights for improving the performance of small-scale wind turbines operating under low wind speed conditions.
5. Despite these findings, this study has several limitations. The turbine performance evaluation is mainly based on theoretical calculations and CAD-based modeling, and experimental validation has not yet been conducted. Therefore, future research should focus on prototype development, experimental testing, and aerodynamic analysis under real urban wind conditions to further optimize turbine performance.

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