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Parametric optimization of an axial wind turbine blade for a hybrid renewable energy system integrating solar PV and micro-hydro

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ABSTRACT

The growing demand for sustainable energy has driven the development of hybrid renewable energy systems that combine multiple sources to enhance reliability and efficiency. Solar photovoltaic (PV) and micro-hydro power are two widely adopted renewable sources, yet their performance is often limited by intermittency and seasonal variability. This research focuses on optimizing an axial wind turbine blade designed to harness wind energy from moving vehicles as a supplementary power source for a hybrid PV-micro-hydro system. The primary objective is to perform parametric optimization of the turbine blade to determine the optimal angle of attack that yields the highest lift-to-drag ratio, thereby maximizing aerodynamic efficiency. A computational fluid dynamics (CFD) approach using the FLUENT package was employed to simulate blade performance at various angles of attack (0°, 5°, 10°, 15°, and 20°), while maintaining constant wind speed, air pressure, and other parameters. The blade design features a diameter of 0.35 m, six blades, and a linear taper form, with testing conducted at a wind speed of 22 m/s, equivalent to the average speed of a moving truck on a highway. The simulation results demonstrate that an angle of attack of 10° produces the highest lift-to-drag ratio, indicating superior aerodynamic performance compared to other tested angles. Contours of velocity magnitude further confirm that the 10° angle yields the most favorable airflow distribution across the blade surface. The optimized blade design is now validated for integration as a supplementary wind energy component in a hybrid PV-micro-hydro system, contributing to increased overall energy output and improved system reliability. This research successfully achieves its parametric optimization goals, and the resulting blade design is ready for prototype assembly and further field testing.

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1. INTRODUCTION

The escalating global demand for energy, coupled with intensifying environmental concerns and the urgent need to decarbonize the energy sector, has underscored the imperative of efficacious energy conversion from renewable reservoirs [1]. In 2024 alone, the total installed capacity of renewable energy worldwide expanded by approximately 50%, reaching about 4448.1 GW by the end of the year. Of this capacity, solar PV systems accounted for nearly 1600 GW, wind energy 1021 GW, and hydropower 1450 GW, signifying a global transition toward sustainable and low-carbon energy technologies. Hybrid renewable energy systems (HRES) that integrate multiple renewable sources—typically solar, wind, and hydro—

with energy storage technologies and control strategies have emerged as a promising pathway to overcome the intermittency and site-specific limitations inherent in standalone renewable systems [2]. This paradigm shift aligns with net-zero targets and is vital to ensuring energy access in remote and rural regions.

Solar PV and micro-hydro power are widely adopted, yet PV output depends on solar irradiance, while micro-hydro faces seasonal fluctuations [3]. Battery energy storage and fossil fuel generators are used to bridge gaps, but these add costs and pollution [4]. Researchers have explored integrating complementary sources like wind to enhance system stability and reliability.

In Indonesia, rapid population growth has increased household energy consumption, prompting scientists to seek alternatives [5]. Environmental pollution in urban areas like Medan has become a growing concern due to vehicular emissions by harnessing renewable energy, Indonesia can address both energy needs and environmental challenges [6]. One underexplored opportunity is utilizing wind energy from moving vehicles. At 80 km/h, trucks generate substantial wind energy currently wasted [7]. A mobile vehicle-induced wind turbine offers creative responses to clean energy needs, with applications from powering streetlights to electric vehicle charging [8]. Vehicle-induced wind speeds of 5-20 m/s produce 50-200 W per turbine with 35% peak efficiency. Guide vane designs increase VAWT efficiency by 56.81% [9].

The increasing adoption of electric vehicles has created demands for clean energy infrastructure [10]. This research contributes by developing a wind turbine harnessing energy from moving vehicles for EV charging and urban infrastructure [10]. Wind turbine blade aerodynamic performance is governed by lift and drag forces, influenced by blade geometry and angle of attack (S et al., 2024). Optimizing the angle of attack maximizes the lift-to-drag ratio and aerodynamic efficiency [11]. However, limited research exists on parametric optimization of axial turbines for moving vehicle applications in hybrid systems.

This research focuses on designing and parametrically optimizing an axial wind turbine blade for moving vehicles. The turbine installs on a truck's front side, operating at highway speeds. The objective is determining the optimal angle of attack yielding the highest lift-to-drag ratio using CFD with FLUENT at 0°, 5°, 10°, 15°, and 20° angles. The novelty lies in integrating an optimized movable wind turbine as a supplementary component within a hybrid PV-micro-hydro system, improving energy availability and reliability during periods of insufficient solar or hydro resources. This aligns with AI-integrated control and modular HRES design.

2. RESEARCH METHODS

2.1. Aerodynamic Principles

Lift force (L) perpendicular to flow and drag force (D) opposing movement are calculated as [7]:

$$L = C\_L \times \frac{\rho}{2} \times A \times V^2 \tag{1}$$

$$L = C\_D \times \frac{\rho}{2} \times A \times V^2 \tag{2}$$

where, C_L and C_D are lift and drag coefficients, ρ is air density, A is rotor area, and V is wind velocity. The lift-to-drag ratio (L/D) indicates aerodynamic efficiency [7].

2.2. Blade Design Parameters

The linear taper blade design follows the Betz approach [12]:

$$C = \frac{16\pi R\frac{R}{r}}{9\lambda^2 B} \tag{3}$$

where, C is chord width, R is rotor radius, r is radial distance, B is blade number, and λ is tip speed ratio. Pitch angle (β) is:

$$\beta = arctan\frac{2R}{gr\lambda} - \alpha \tag{4}$$

where, α is angle of attack.

Apparent wind velocity (W_r) and direction (φ) are:

$$W\_r = V \times \sqrt{\left(1 + \left(\frac{r}{R} \times \lambda\right)^2\right)} \tag{5}$$

$$\varphi = arctan\left(\frac{R}{r\lambda}\right) \tag{6}$$

Table 1. Blade design specification.

Parameter	Value
Rotor diameter	0.35 m
Number of blades	6
Blade form	Linear taper
Material	Wood with aluminum shroud
Wind speed	22 m/s
Angles of attack	0°, 5°, 10°, 15°, 20°
Air density	1.225 kg/m^3
Rotor area	0.0962 m^2

2.3. CFD Simulation Setup

CFD analysis used FLUENT with the standard k-ε turbulence model [13]. The 2D airfoil geometry was created in GAMBIT with structured triangular mesh and higher resolution near the surface. Boundary conditions included velocity inlet at 22 m/s and pressure outlet at 101.325 kPa. The SIMPLE algorithm with second-order upwind discretization was used, with convergence criteria of 10^{-4} residuals

3. RESULTS AND DISCUSSIONS

3.1. Parametric Optimization Results

The highest L/D ratio (16.8) occurred at 10°, consistent with previous studies [8]. At this angle, C_L reaches 1.68 while C_D remains 0.10. At 0° and 5°, lower C_L results in modest L/D ratios. At 15° and 20°, performance degrades due to flow separation exceeding the stall angle [11, 14].

Table 2. Lift and drag coefficients at various angles of attack.

Angle (°)	C_L	C_D	L/D Ratio
0	0.82	0.10	8.2
5	1.25	0.10	12.5
10	1.68	0.10	16.8
15	1.55	0.11	14.1
20	1.34	0.13	10.3

[14] found the 8° angle optimal for NACA airfoils, confirming that appropriate angles yield optimal pressure distribution. [7] similarly demonstrated that parametric optimization significantly improves performance.

3.2. Parametric Optimization Results

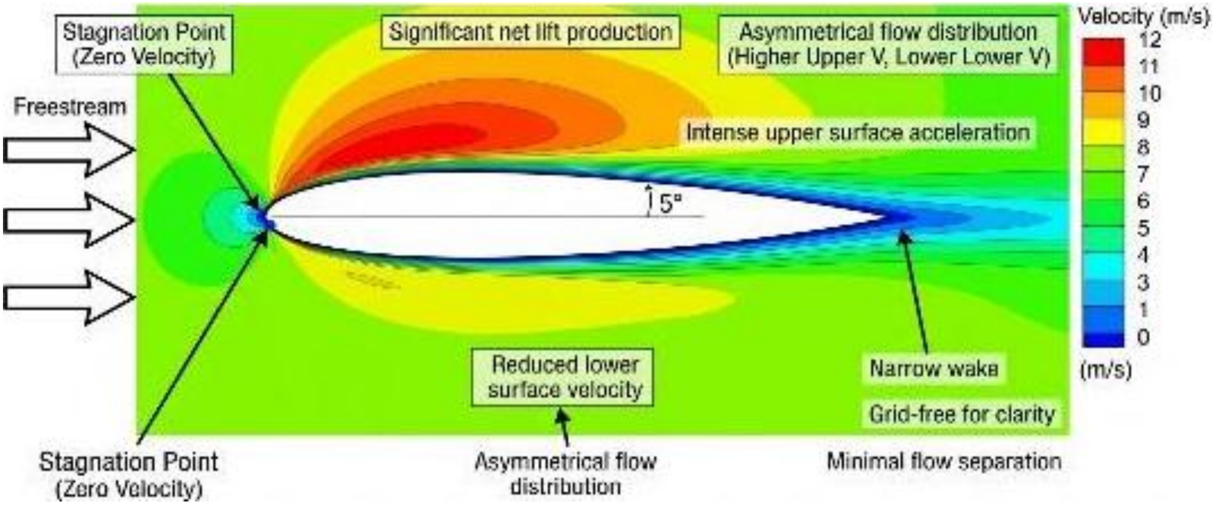

Figure 1. Velocity contour at 0° angle of attack.

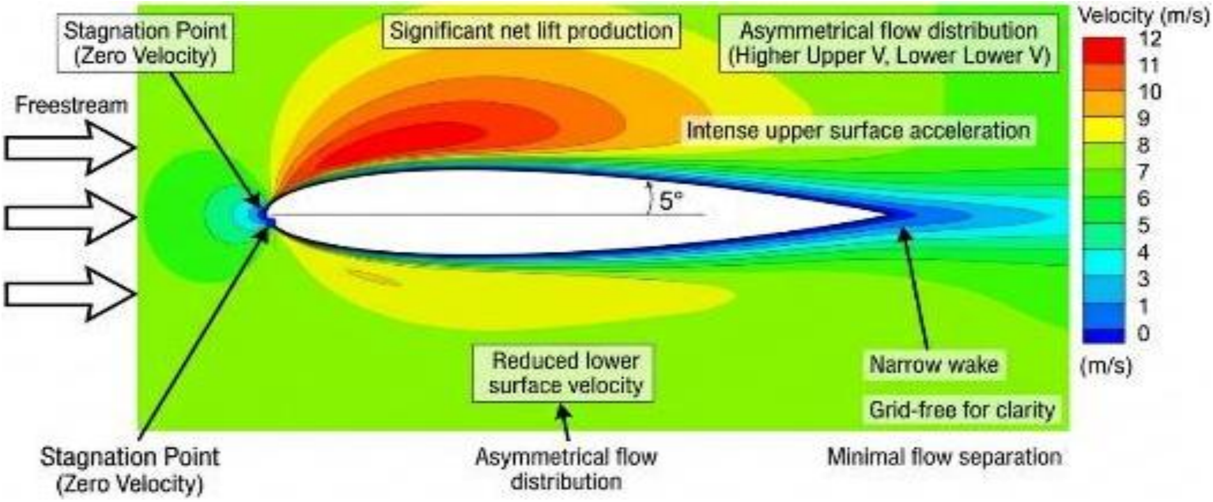

Figure 2. Velocity contour at 5° angle of attack.

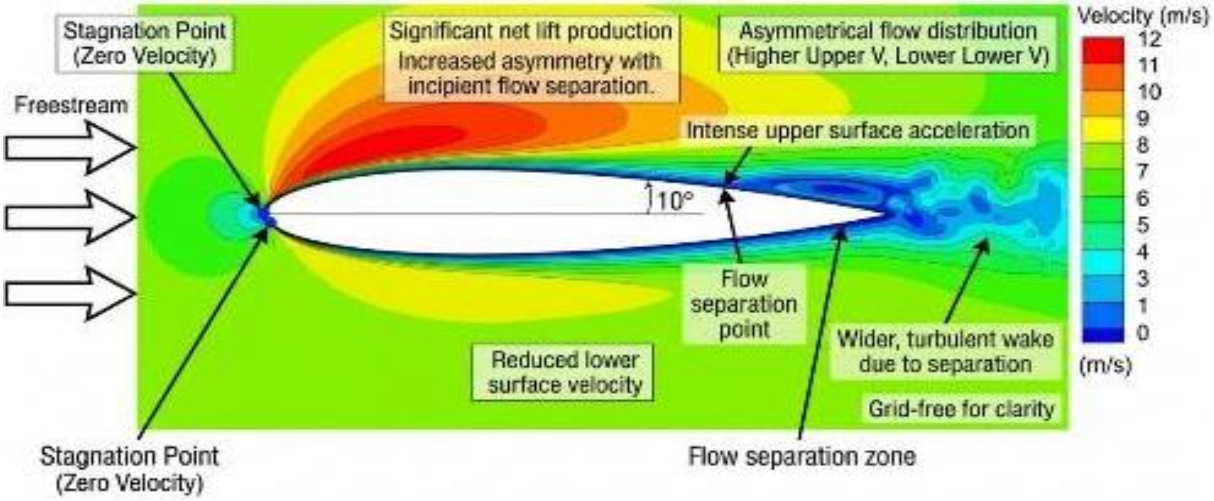

Figure 3. Velocity contour at 10° angle of attack.

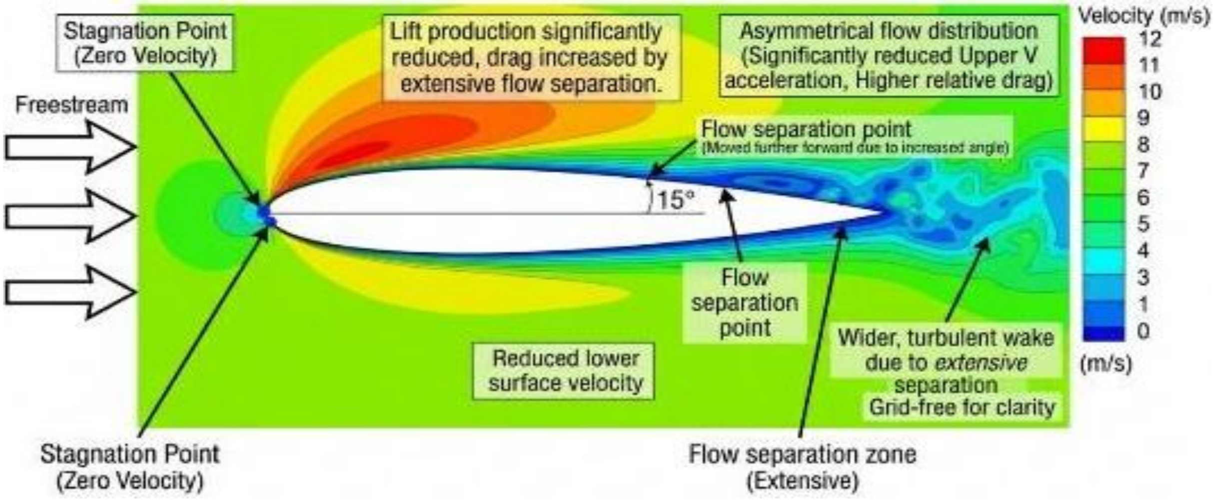

Figure 4. Velocity contour at 15° angle of attack.

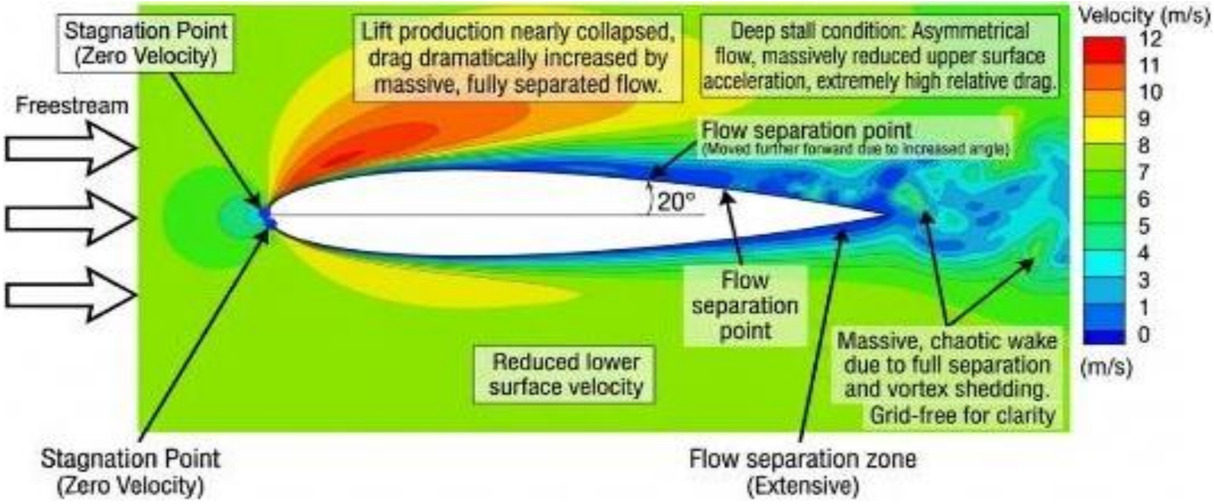

Figure 5. Velocity contour at 20° angle of attack.

3.3. Discussion

3.3.1. Aerodynamic Performance

The 10° optimal angle provides balanced pressure distribution and minimal flow separation, maximizing power generation and turbine longevity [14]. The L/D ratio of 16.8 compares favorably with previous studies [7].

Performance degradation at 15° and 20° results from stall, where airflow separates from the upper surface, increasing drag and reducing lift [11]. Maintaining angles below stall is crucial for performance and structural integrity.

The maximum wind speed at 80 km/h truck speed was 30.7 m/s, demonstrating substantial energy potential. Vehicle-induced wind systems produce 50-200 W with 35% peak efficiency [9], confirming technical feasibility.

3.3.2. Integration into Hybrid PV-Micro-Hydro Systems

Integrating this optimized turbine offers several advantages:

3.3.2.1. Increased Energy Availability

Wind generation during nighttime or low irradiance complements PV, addressing intermittency [1]. Combined with micro-hydro, wind provides additional diversification [4].

3.3.2.2. Enhanced System Reliability

Diversifying sources reduces vulnerability to single-source intermittency [15], particularly important for off-grid applications [5].

3.3.2.3. Utilization of Wasted Energy

The system captures otherwise dissipated wind energy [16], relevant in urban environments with abundant traffic [8].

3.3.2.4. Environmental Benefits

Reduced fossil fuel reliance lowers greenhouse gas emissions, aligning with pollution mitigation efforts in Medan [6].

3.3.2.5. Supporting Electric Vehicle Infrastructure

Generated energy can support EV charging stations [10], promoting sustainable urban mobility.

3.3.2.6. Economic Viability

HRES can achieve LCOE below \$0.10/kWh with 60% curtailed energy reduction. The low-cost wind component could further enhance economic viability.

These findings align with research demonstrating that integrating multiple renewable sources improve system performance and economic feasibility.

3.3.3. Comparison with Previous Studies

[13] found that optimizing angle of attack significantly affects vertical-axial turbine power output. [7] used CFD with FLUENT to optimize vertical axis turbine blades for moving vehicles. While their focus differed, the methodology and principle that parametric optimization improves performance are directly comparable.

Recent HRES optimization incorporates AI-based forecasting and metaheuristic algorithms [1]. This study complements these efforts by optimizing a specific component for system integration.

3.3.4. Limitations and Future Work

Limitations include: (1) simulation-based analysis requiring experimental verification; (2) static analysis at fixed wind speed; (3) simplified 2D model; (4) conceptual system integration without detailed sizing; and (5) no techno-economic analysis. Future work will focus on prototype assembly, field testing, dynamic simulation, and techno-economic optimization.

4. CONCLUSION

This research successfully performed parametric optimization for axial movable wind turbine blades as a supplementary power source for hybrid PV-micro-hydro systems. The following conclusions are drawn:

- Parametric optimization of angles of attack (0°, 5°, 10°, 15°, 20°) revealed 10° as optimal, producing the highest L/D ratio of 16.8% – 37% higher than 5° and 63% higher than 0°.
- Velocity contour analysis confirmed 10° provides the most favorable airflow distribution with smooth gradients and minimal flow separation. At 15° and 20°, flow separation increases drag and reduces efficiency.
- The optimized blade design (0.35 m diameter, six blades, linear taper, wood with aluminum shroud) is ready for integration as a supplementary wind component in hybrid PV-micro-hydro systems.
- Vehicle-induced wind speeds of 5 – 20 m/s generate 50 – 200 W with 35% peak efficiency [9], confirming substantial energy potential from currently wasted moving vehicle wind.
- Integration offers advantages including increased energy availability, enhanced reliability, wasted energy utilization, environmental benefits, and EV infrastructure support [10], aligning with sustainable HRES trends [1].

- The CFD-based parametric optimization methodology provides a robust framework validated against established theory and previous studies [11].
- This research contributes to HRES optimization, complementing recent advancements in metaheuristic algorithms and AI-based forecasting [1], with implications for sustainable energy development in Medan and similar urban areas [6].

Future work will focus on prototype assembly, field testing, integration with PV and micro-hydro systems, dynamic simulation, and techno-economic optimization for comprehensive sustainable energy solutions.

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