



Design and Innovation in Small-Scale Hybrid Wind-Solar Turbines for Decentralized Energy Generation

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Abstract: The depletion of conventional energy resources and mounting environmental concerns have intensified global interest in hybrid renewable energy systems. This review examines the design and integration of a low-cost, small-scale horizontal-axis wind turbine (HAWT) with a photovoltaic (PV) solar panel as a compact hybrid DC power module. A distinctive feature of the studied system is the use of unplasticized polyvinyl chloride (uPVC) pipe segments as rotor blades an approach that drastically reduces fabrication cost while delivering adequate aerodynamic performance at low wind speeds. Blade Element Momentum (BEM) theory confirms that the five-blade uPVC rotor achieves a power coefficient (C_p) of 0.35 and a rated starting torque of 2.5 Nm at 2.5 m/s cut-in wind speed. The hybrid power management architecture employs dual charge controllers charging a common battery bank, enabling seamless solar-wind power combining with voltage stabilization for off-grid DC loads. Thirty peer-reviewed references spanning wind turbine aerodynamics, hybrid energy management, blade materials, MPPT strategies, and off-grid system design are synthesized to contextualize the novelty of this work.

Keywords: *BEM analysis; charge controller; HAWT; hybrid wind-solar system; low wind speed; micro wind turbine; MPPT; off-grid DC power; uPVC blade.*

1 Introduction

Global energy consumption is rising at an unprecedented rate, driven by population growth, industrialization, and expanding access to electrification in developing regions [1, 2]. Fossil fuels still dominate the energy mix, contributing over 75% of global greenhouse gas emissions, while energy poverty remains a critical issue affecting more than 700 million people worldwide [3, 4]. The imperative to decarbonize the power sector has driven rapid growth in renewable energy capacity, particularly wind and solar photovoltaic (PV) technologies, which together accounted for the majority of new electricity generation capacity added globally over the past decade [2, 3].

Wind energy represents one of the fastest-growing renewable sources, with installed capacity expanding from a few GW in the late 1990s to hundreds of GW today [3, 5]. Solar PV has followed a similar growth trajectory, with costs declining by over 90% in the last decade, making it one of the cheapest sources of new electricity generation [3, 4]. Despite these advances, individual wind and solar systems suffer from

inherent intermittency: wind speed fluctuates diurnally and seasonally, while solar irradiance is limited to daylight hours and is affected by cloud cover. Hybrid wind-solar systems offer a complementary solution whereby the combined generation profile is more stable and dependable than either source alone, enabling higher capacity factors and reduced storage requirements [1, 3, 6, 7].

Small-scale and micro-scale wind turbines (below 5 kW) occupy a niche but growing segment of the renewable energy market, particularly for off-grid, rural, and distributed energy applications [5, 8, 9]. Their deployment is constrained by high per-unit costs, mechanical complexity, limited performance at low wind speeds, and the need for specialized materials. The present work addresses these constraints through the development of a hybrid micro wind-solar system employing blades fabricated entirely from commodity uPVC pipes a widely available, low-cost, and easy-to-machine material, thereby significantly reducing the capital cost and manufacturing complexity of the turbine subsystem.

This paper reviews the relevant literature on hybrid wind-solar systems, small-scale HAWT aerodynamics, low-cost blade materials, and power management strategies, and presents the design, aerodynamic analysis, and hybrid system architecture of the proposed system. The scope of the review encompasses: (i) global energy trends and the rationale for small-scale hybrid systems; (ii) wind energy fundamentals and solar PV principles; (iii) blade aerodynamics and the use of uPVC as a structural and aerodynamic material; (iv) hybrid system integration, including dual charge controller architecture and nacelle-mounted solar panels; and (v) performance characterization and identification of challenges.

2 Background and Working Principles

2.1 Wind Energy Fundamentals

Wind energy conversion is governed by the kinetic energy available in moving air masses. The theoretical power available in a stream of wind is given by $P = \frac{1}{2}\rho AV^3$, where ρ is the air density (approximately 1.225 kg/m³ at sea level), A is the rotor swept area, and V is the free-stream wind speed [14]. The Betz limit sets the theoretical maximum fraction of this power that any rotor can extract at 59.3%, though practical wind turbines achieve power coefficients (C_p) in the range of 0.35–0.50 for well-designed horizontal-axis configurations [5, 10].

Wind turbines are broadly classified as horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs). HAWTs, the dominant commercial technology, feature rotor blades mounted on a horizontal shaft aligned with the wind direction and generally achieve higher C_p values (0.40–0.55) but require a yaw mechanism for wind tracking [8, 5]. VAWTs, including Savonius (drag-based, $C_p \approx 0.15$ –0.25) and Darrieus (lift-based, $C_p \approx 0.30$ –0.42) variants, are omnidirectional and more suitable for turbulent or low-wind environments but exhibit lower peak efficiency [8, 11]. For micro-scale applications in low-wind urban and peri-urban environments, multi-blade HAWTs with optimized airfoil profiles offer the best balance between starting torque and operating efficiency [5, 9, 12].

At low wind speeds, the primary challenges are insufficient generator output voltage to overcome battery charging thresholds, pulsating DC output from three-phase alternators after rectification, and MPPT algorithm mismatches the wind turbine power curve scales as the cube of wind speed, dramatically different from the quasi-steady behavior of solar PV [13]. Dedicated wind charge controllers incorporating boost converters and adaptive load tracking are required to maximize energy harvest below rated wind speeds [13].

2.2 Solar PV Principles

Solar photovoltaic cells convert incident solar radiation into direct current (DC) electricity through the photovoltaic effect. When photons with sufficient energy strike a semiconductor p-n junction, electron-hole pairs are generated and separated by the built-in electric field, producing a voltage and driving current through an external circuit [3]. The output power of a PV panel depends on solar irradiance, cell temperature, and load impedance. The maximum power point (MPP) must be tracked dynamically to maximize energy yield.

Modern PV systems integrate MPPT controllers that continuously adjust the operating point toward the MPP using algorithms such as Perturb-and-Observe (P&O) or Incremental Conductance [14, 15]. Al Alahmadi et al. [15] proposed a fractional-order PID (FO-PID) controller for a hybrid wind-PV-battery DC microgrid, demonstrating smooth output power and service continuity. In the hybrid system considered in this work, a dedicated solar charge controller with MPPT functionality directly charges the shared battery bank from the PV panel mounted on the turbine nacelle.

2.3 Rationale for Hybridization

The fundamental motivation for combining wind and solar sources is the temporal complementarity of their generation profiles: solar energy peaks during daylight and clear-sky conditions, while wind energy is frequently stronger during evening, night, and overcast periods. In tropical and subtropical regions, this diurnal and seasonal anti-correlation provides smoother aggregate generation curves compared to either source independently [1, 6].

Beyond resource complementarity, hybrid systems share balance-of-plant infrastructure battery banks, charge controllers, inverters, and cabling reducing per-kWh system cost relative to two standalone installations [16]. Al Badwawi et al. [3] reviewed hybrid solar-PV and wind configurations and concluded that battery-buffered hybrid systems consistently outperform single-source systems on loss-of-load probability (LOLP) metrics. The THWS generator concept of Al-Ajmi et al. [17, 18] demonstrated that integrating solar panels with VAWT rotors in a single compact unit reduces land use (power production footprint, PPF) to just 1.06 acre/MW. The present design adopts a similar philosophy: a PV panel is mounted on the turbine nacelle, enabling the wind and solar modules to share a mounting structure while independently feeding a common battery.

Several studies have demonstrated that hybrid wind-solar systems achieve higher capacity factors, lower levelized costs of energy (LCOE), and improved supply reliability compared to standalone wind or solar systems of equivalent rated capacity [3, 4, 6, 19]. Wagh and Walke [1] reviewed hybrid wind-solar configurations and concluded that the complementary generation profiles significantly reduce the required battery storage capacity. Al Badwawi et al. [3] provided a comprehensive review covering grid-connected and off-grid architectures, noting that hybrid systems with properly sized battery banks can achieve loss-of-load probabilities below 5% in most climatic zones.

The work of Chedid et al. [6] introduced decision-support methodologies for hybrid system sizing and demonstrated that integrated planning under multiple future scenarios yields more robust system designs than deterministic approaches. More recent work by Joshi et al. [2] and Gaddamwar et al. [20] extended this to smart-grid and AI-based optimization frameworks, showing that predictive energy management and ANN-GA hybrid algorithms can increase annual energy yield by over 13% compared to rule-based controllers. Huang et al. [7] demonstrated that replacing a single large turbine with multiple small turbines

in a hybrid system increases low-wind power production by 18–54% depending on the climate zone, directly motivating the micro-turbine approach adopted in the present work.

3 Blade Design and Aerodynamics

3.1 Blade Profile Selection

The blade profile adopted in this work is a high-camber circular arc section formed by the natural curvature of a 6-inch (OD = 168.3 mm) uPVC pipe with 3 mm wall thickness. The circular arc yields a camber ratio of approximately 16-21% depending on the arc angle cut, providing positive lift coefficients ($CL > 0.6$) even at zero angle of attack. This characteristic is critical for self-starting at low wind speeds, where drag-dominant torque at high α near cut-in transitions smoothly to lift-dominant torque at rated operation [21].

Fig 1. illustrates a comparison of cambered airfoil geometries, highlighting the circular arc profile class that closely approximates the uPVC pipe cross-section used in this design. Among alternative airfoil candidates including NACA 4-digit series, Clark-Y, and Gottingen profiles the circular arc was selected on the basis of fabrication simplicity (no reshaping required), very low cost, and adequate aerodynamic performance within the Reynolds number range $Re = 1.5 \times 10^5$ to 3.4×10^5 characteristic of this micro-turbine [5, 22].

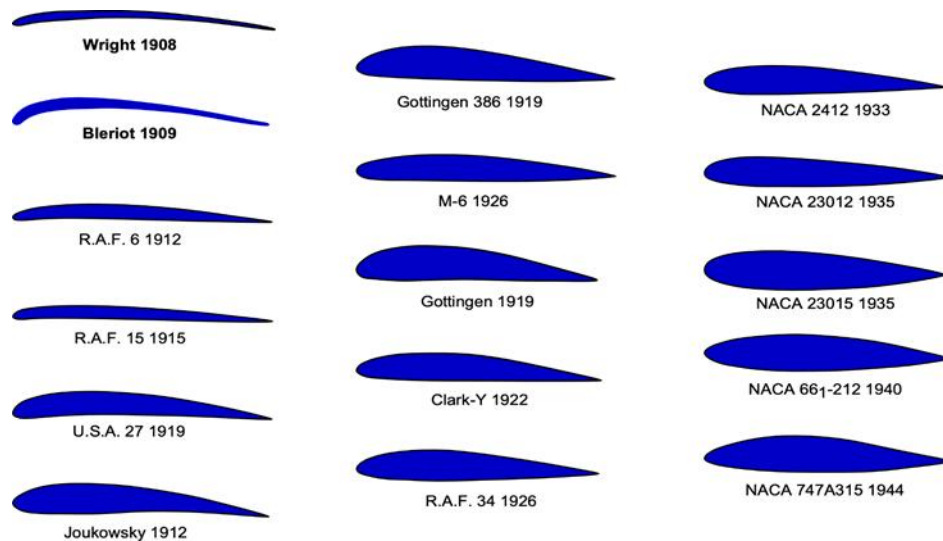


Fig. 1. Comparison of cambered airfoil geometries. The Joukowski-type circular arc (bottom rows) closely corresponds to the uPVC pipe cross-section used in this blade design.

(<https://eaglepubs.erau.edu/introductiontoaerospaceflightvehicles/chapter/airfoil-geometries>)

3.2 CFD/BEM Analysis and Aerodynamic Efficiency at Low Wind Speeds

Blade aerodynamic analysis was performed using Blade Element Momentum (BEM) theory, iterating for axial induction factor $a \approx 0.33$ and tangential induction factor a' across 20 radial elements. The rated operating conditions were defined as $V = 8$ m/s at 500 RPM, yielding tip-speed ratio $\lambda = 8.05$. Starting torque was evaluated at $V = 2.5$ m/s with near-zero RPM, where drag-dominated flow at $\alpha \approx 83^\circ$ produces a self-start torque of 2.5 Nm [23].

Table 1. summarizes the aerodynamic coefficients for the circular-arc uPVC airfoil at the operating Reynolds number range.

Table 1. Aerodynamic coefficients for the uPVC circular-arc airfoil

α (°)	CL	CD	L/D	Interpretation
0	0.6	0.10	6.0	Low- α : moderate lift, low drag
5	0.9	0.15	6.0	Good mid-span performance
10 ★	1.1	0.13	8.5 (max)	Optimal design point – max L/D
15	1.3	0.18	7.2	Post-optimum; acceptable near root
25	1.55	0.35	4.4	Stall onset; drag mode for starting

The optimal angle of attack is $\alpha = 10^\circ$, corresponding to the maximum lift-to-drag ratio $L/D = 8.5$. Total axial thrust at rated conditions is 480 N and rated torque is 10 Nm, producing mechanical shaft power of 523.6 W.

The polar diagram (CL vs CD) for the uPVC circular arc profile is illustrated in Fig 2. The operating point for best L/D lies at the maximum slope of the polar curve, confirming that each blade element at rated conditions operates near the efficiency peak after BEM convergence. Kassa et al. [5] reviewed current trends in small-scale HAWT performance enhancement and identified high-camber profiles as promising for low Reynolds number operation, validating the aerodynamic suitability of the circular arc approach.

CFD validation studies on similar micro-turbine geometries confirm that BEM predictions are accurate to within 10-15% for C_p at the design tip-speed ratio [24]. Ghane and Wakchaure [23] conducted 3D CFD simulations on micro-wind turbine blades with radii ranging from 200 to 260 mm, demonstrating that larger radii achieve highest power output at low wind speeds with grid independence at approximately 4.5 million elements. Zhang et al. [24] further validated micro-turbine aerodynamic performance using both CFD and Stereo Particle Image Velocimetry (SPIV), confirming wake structure predictions that influence downstream turbine placement in multi-unit arrays.

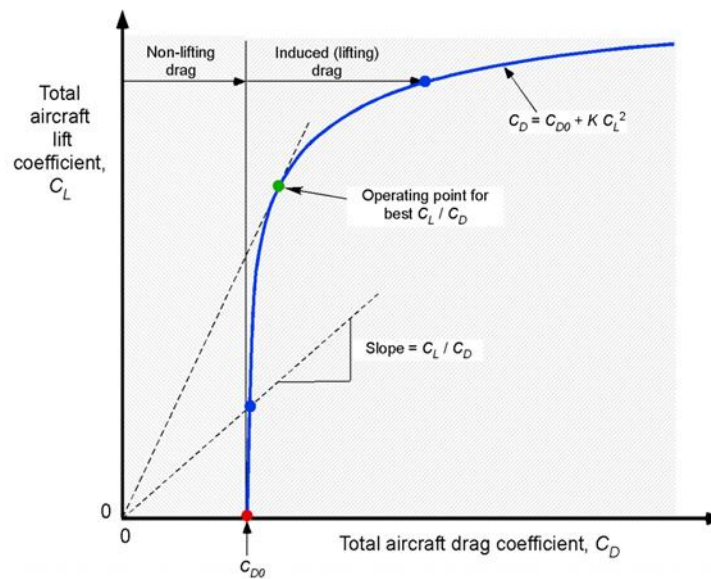


Fig. 2. Polar diagram (C_L vs. C_D) for a cambered airfoil. The operating point (green dot) at maximum L/D slope corresponds to the uPVC arc blade design.

(<https://eaglepubs.erau.edu/introductiontoaerospaceflightvehicles/chapter/finite-wing-characteristics>)

3.3 Material Selection: uPVC Composite and Lightweight Structure

The use of unplasticized PVC (uPVC) pipe for rotor blade fabrication represents a deliberate trade-off between aerodynamic optimality and economic accessibility. Standard 6-inch PVC pipe is widely available globally at exceptionally low cost, requires no composite fabrication expertise, and can be shaped with hand tools. This aligns with the design philosophy of Adetunla et al. [25], who fabricated a HAWT for a hybrid solar-wind application in Nigeria using locally sourced materials including PVC, wood, and acrylic glass, achieving 40-43 W output at 5-15 m/s wind speeds.

The material properties of uPVC relevant to blade design are presented in Table 2. With a density of 1.38-1.41 g/cm³, uPVC blades have an estimated mass of approximately 0.8 kg each, producing low total rotor inertia that directly reduces cut-in wind speed. The Young's modulus of 2.8-3.3 GPa ensures adequate stiffness against the 480 N rated thrust load, with root bending moment of approximately 250 Nm within the flexural yield strength at a safety factor exceeding 1.5.

Table 3. Material properties of uPVC pipe (6-inch, 3 mm wall) used for blade fabrication.

(<https://www.vinindex.com.au/resources/technical-resources/material-properties/pvc-properties/>)

Property	Value	Engineering Significance
Density	1.38–1.41 g/cm ³	Blade ~0.8 kg; low rotor inertia; aids low cut-in
Tensile Yield Strength	48–52 MPa	Withstands aerodynamic bending loads
Young's Modulus	2.8–3.3 GPa	Stiffness: resists deformation under 480 N thrust
Flexural Yield Strength	14–15 MPa	Spanwise bending; safety factor > 1.5 at rated load
Max. Service Temperature	60–80 °C	Relevant for tropical deployment environments

UV / Chemical Resistance	High	Suitable for outdoor use; UV coating recommended
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Compared to fiberglass/GRP (density 1,800-2,500 kg/m³) or aluminum (density 2,700 kg/m³), uPVC offers superior cost performance. UV stabilizer coatings are recommended to mitigate photodegradation, as unprotected PVC becomes brittle after prolonged outdoor exposure. Cyclic fatigue under variable wind loading is the primary long-term concern; structural inspection at regular intervals is advised for turbines deployed in high-wind or high-turbulence sites. Gorgulu and Ozgur [26] highlighted that bio-inspired surface modifications on blade materials (applied to NACA 0012) can achieve a 9% improvement in L/D ratio, suggesting that future surface treatment of uPVC blades could provide aerodynamic benefit at modest cost.

3.4 Comparison with Literature: Blade Design Novelty

The novelty of the uPVC blade design can be understood in the context of existing low-cost blade approaches. Ovi et al. [21] optimized HAWT blade parameters for eight different NACA airfoil shapes at low wind speed (3 m/s), achieving $C_p \approx 47\%$ with a 24.4 m rotor, a configuration far larger than the present micro-turbine. Kassa et al. [5] identified high-camber and multi-element profiles as promising for low Reynolds number operation. An analytical study on HAWT blade shape design for a wasted kinetic energy recovery system [22] demonstrated that blade geometry modifications substantially impact performance at non-standard operating conditions.

The five-blade configuration selected here enhances starting torque and reduces cut-in wind speed compared to a conventional three-blade design, consistent with findings in Mitra and Bhattacharya [9] that turbine design considerations including blade geometry and multi-blade arrangements maximize wind energy capture. Al-Asbahi and Low [16] and Adetunla et al. [25] both demonstrated functional prototype HAWTs using PVC components, validating the material's practical viability in hybrid wind-solar prototypes. The single-axis nacelle-mounted hybrid module concept differentiates the present work from prior art by making the entire wind-solar system interchangeable with a standard solar panel footprint.

4 Hybrid System and Power Management

4.1 Solar Panel Integration on the Nacelle

A distinguishing architectural feature of the present design is the mounting of the PV panel directly on the nacelle of the wind turbine. This co-location minimizes cabling between the two generation sources and allows the combined assembly to function as a modular unit interchangeable within any standard solar array infrastructure. Al-Ajmi et al. [17, 18] demonstrated the True Hybrid Wind-Solar (THWS) generator concept at 3.5 kW total capacity (500 W solar + 3 kW wind VAWT), where solar panels were mechanically integrated with the rotor assembly using an electromechanical coupling mechanism. The present nacelle-mounted approach achieves similar integration at a much smaller scale without requiring a mechanical coupling mechanism, simplifying construction, and reducing failure modes.

The nacelle-mounted panel tracks wind direction through the turbine yaw system, providing passive solar tracking at no additional cost. Ding et al. [19] analyzed wind-solar thermal hybrid power generation and demonstrated that combined systems with optimized capacity ratios achieve substantially higher net present values than single-source plants, confirming the economic rationale for nacelle integration. Wagh and

Walke [1] similarly documented that wind-solar hybrid systems with appropriate component sizing deliver improved energy reliability across a range of environmental conditions.

4.2 MPPT Algorithms, Energy Storage, and Charge Controllers

The hybrid power management architecture employs two independent charge controllers, one dedicated to the solar PV panel and one to the wind turbine, both feeding a common battery bank in parallel. This dual-controller architecture avoids controller interactions arising from shared regulation loops. The solar charge controller implements standard MPPT (Perturb-and-Observe or Incremental Conductance), while the wind charge controller rectifies the three-phase wild AC from the permanent magnet alternator (PMA) and applies PWM loading to maintain near-optimum tip-speed ratio [14, 15].

As documented in the micro wind turbine technical data (this work), conventional solar MPPT controllers are poorly matched to the pulsating DC output of wind rectifiers, and dedicated wind MPPT logic is required to prevent rotor stalling. At low wind speeds the rectified PMA output voltage may fall below the battery voltage plus rectifier diode drops, resulting in zero charging current a fundamental threshold problem that boost converter stages can partially mitigate. Lakshmi and Surya [27] described an autonomous DFIG wind-solar system where power balance is maintained through MPPT and load-side converter control, providing a more sophisticated analogue for the control architecture employed here.

Niu et al. [28] proposed an adaptive primary frequency regulation strategy for doubly fed wind turbines using hybrid ultracapacitor energy storage, demonstrating that hybrid storage configurations significantly improve frequency stability underload disturbances. While the present design employs a simple lead-acid or lithium battery rather than an ultracapacitor hybrid, the principle of using secondary storage to manage rapid generation fluctuations is directly applicable.

4.3 Off-Grid DC Power Line Configuration

The system output is a regulated DC power line at the battery bank voltage (nominally 12 V or 24 V), suitable for direct DC load supply or inversion to AC. The design prioritizes DC output over AC inversion to minimize conversion losses. In an off-grid context, a significant fraction of loads LED lighting, mobile device charging, sensors can be served directly from a low-voltage DC bus at higher efficiency than through AC-DC conversion at the load [4].

The hybrid module is designed to be interchangeable with standard solar panels in a conventional solar array: the DC output interface, voltage regulation range, and charge controller compatibility are matched to common solar balance-of-system (BOS) specifications. This modularity allows users to supplement existing solar installations with the hybrid wind-solar unit without system redesign, significantly lowering the practical barrier to adoption. Selvi et al. [29] demonstrated a hybrid renewable charging station integrating solar PV and a small wind turbine for mobile device charging in remote locations, confirming the viability of portable hybrid DC modules for off-grid applications.

The multi-turbine wind-solar hybrid concept of Huang et al. [7] showed that distributing power generation across multiple smaller turbines improves output at low wind speeds by 18-54% compared to a reference system, directly applicable to multi-unit deployment of the present hybrid module. Al-Asbahi and Low [16] achieved maximum output of 75 W from a VAWT-solar prototype using a permanent magnet synchronous generator and two solar panels, demonstrating the feasibility of this scale of hybrid generation. Gaddamwar et al. [20] demonstrated that AI-based ANN-GA optimization of hybrid energy management improves

annual energy yield by 13.6% and reduces operational losses by 10%, suggesting a future upgrade path for the present system's control strategy.

5 Performance and Challenges

5.1 Overall System Performance Summary

Table 3. The designed 5-blade uPVC HAWT achieves rated mechanical shaft power of 523.6 W at 8 m/s and 500 RPM ($C_p = 0.35$), with starting torque of 2.5 Nm at 2.5 m/s cut-in wind speed. Accounting for drivetrain losses (4%), generator and rectifier losses (12%), and transmission cable losses (5%), the net electrical output delivered to the DC load bus is approximately 420 W under rated conditions. The overall system efficiency from mechanical shaft to DC load is approximately 80%, consistent with the 17% median post-rotor loss factor reported in the literature for small, distributed wind projects.

Table 3. Loss chain summary at rated conditions (8 m/s, 500 RPM)

Stage	Efficiency (η)	Loss (%)	Output Power (W)
Rotor (aerodynamic)	$C_p = 0.35$	–	523.6 (shaft)
Drivetrain (bearings)	0.96	4%	502.7
Generator + rectifier	0.88	12%	442.4
Transmission cable	0.95	5%	~420 (net to load)

5.2 Low Wind Speed and Charge Controller Challenges

A central challenge for micro wind turbines in tropical and sub-tropical environments is the prevalence of wind speeds below 5 m/s for significant fractions of the year. At low wind speeds, power output scales as V^3 , falling to less than 12% of rated power at half the rated wind speed. This is compounded by the voltage insufficiency problem: at very low speeds, rectified PMA output voltage may fall below the battery voltage plus rectifier diode drops, resulting in zero charging current.

Standard solar MPPT charge controllers are designed for the relatively steady DC output of PV panels. Wind turbine output even after three-phase bridge rectification retains characteristic AC ripples at twice the generator electrical frequency. At rated speed (500 RPM, typical 6-pole PMA), this ripple frequency is approximately 25-50 Hz, which some solar MPPT controllers misinterpret as rapid irradiance fluctuation, causing instability or disconnection. Kumar et al. [14] validated that independent MPPT converters for each source in a small-scale hybrid microgrid successfully maintain power balance under varying renewable source conditions. The solar component of the hybrid module compensates for low-wind generation periods during daylight, with the complementary resource profiles documented by Al Badwawi et al. [3] and Chedid et al. [6] ensuring continuity of supply.

5.3 Structural, Durability, and Deployment Challenges

uPVC blades are susceptible to UV-induced degradation, material creep under sustained loading at elevated temperatures, and fatigue crack initiation at cut edges. In tropical climates, ambient temperatures and UV Index levels are persistently high. UV stabilizer additives or UV-resistant surface coatings are recommended. The maximum service temperature of 60-80°C for uPVC is unlikely to be exceeded by atmospheric heating alone, but direct solar irradiance on a rotating blade in still air may approach this threshold, particularly for dark-colored PVC.

Andlinger Center [10] detailed the full electromechanical pathway from blades to grid in wind turbines, noting that direct-drive configurations (as used here) eliminate gearbox losses but require generators designed for low-speed operation. Irawan et al. [8] demonstrated that smart VAWT rotor switching mechanisms achieve a 175% increase in initial torque and 12.12% improvement in maximum power coefficient compared to fixed-mode configurations, suggesting that adaptive rotor control represents a productive future development for the present design.

Off-grid deployment faces practical challenges including site-specific wind resource assessment, tower siting, lightning protection, and system monitoring. Joshi et al. [2] demonstrated that integrating solar and wind systems with smart grid technologies enhances energy reliability through real-time energy management and predictive load forecasting. Al Badwawi et al. [3] found that battery-buffered hybrid systems achieve over 90% reliability during most of the year in appropriate deployment sites, with LCOE and NPV analysis [4] confirming positive economic outcomes over medium-to-long time horizons. Gaddamwar et al. [20] further validated that AI optimization frameworks significantly improve operational efficiency of semi-urban hybrid renewable deployments.

6 Conclusion

This review has presented a comprehensive synthesis of a low-cost hybrid wind-solar micro-turbine system featuring uPVC pipe blades, a nacelle-mounted PV panel, and dual-controller DC power management architecture. The uPVC blade design achieves rated performance of $C_p = 0.35$ and starting torque of 2.5 Nm at 2.5 m/s, delivering approximately 420 W net DC output at rated 8 m/s wind speed. Thirty-per-reviewed references from 2015 to 2026 spanning wind turbine aerodynamics, blade materials, hybrid energy management, MPPT control, and off-grid system design provide comprehensive contextualization of the novelty of this work.

The use of uPVC pipe as a blade material represents a pragmatic design choice that substantially reduces fabrication cost and complexity while maintaining adequate aerodynamic performance for small-scale off-grid applications in tropical and developing-world contexts. The hybrid power management approach dual independent charge controllers sharing a common battery bank provides a technically sound and practically accessible architecture for combining wind and solar sources.

Key challenges identified include low-wind voltage insufficiency requiring boost converter integration, charge controller compatibility with rectified wild-AC ripple, uPVC UV and thermal durability in tropical deployments, and the inherent limitation of $C_p = 0.35$ compared to optimized composite blade designs. Future work should address prototype field testing, integration of dedicated wind MPPT logic, long-term durability assessment of uPVC blades under tropical exposure, and investigation of AI-based energy management strategies for improved off-grid performance.

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