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Recent Advances in Low-Speed Wind Turbines: A Critical Review

Dhiaa J. Shalal[1] Omer K. Ahmed[2] Shahab A. Abdulla[3]

[1]Kirkuk Technical Engineering College/ Northern Technical University
[2]College Polytechnic Hawija /Northern Technical University, Hawija, 36007, Iraq
[3]University of Southern Queensland, Australia

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Corresponding Author:
Dhiaa J. Shalal

Email:
Dhiaajumah94@gmail.com

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ABSTRACT

This review examines recent advancements in low-speed wind turbines, focusing on their design and suitability for regions with limited wind resources, such as Iraq. These turbines are crucial for enabling power generation under minimal wind speeds. Based on a comprehensive survey of relevant peer-reviewed studies, the review identifies innovations including bio-inspired blades achieving up to 13% efficiency at 4 m/s, wind boosters and diffuser nozzles increasing efficiency by up to 41%, and aerodynamic optimizations enhancing power coefficients by up to 38% while reducing blade mass by 50%. The study synthesizes findings on horizontal- and vertical-axis turbines, highlighting design strategies, tip speed ratio optimization, hybrid solar integration, and AI-based control to enhance performance and stability. Key challenges remain, including high initial costs, low public awareness, and limited policy support in developing regions. This review offers a structured, comparative analysis of low-speed turbine designs, bridging global innovations with regional implementation needs and providing practical recommendations for improving energy sustainability in low-wind areas.

Introduction

To meet climate goals, over 70% of global electricity must come from renewables by 2050, with wind energy playing a central role. Optimizing turbine design for efficiency, stability, and performance under variable wind conditions is thus a key technical challenge [1]. This crisis has raised living costs and weakened economies while worsening environmental decline and political unrest. Yet, the introduction lacks citations to prior reviews on low-speed wind turbines, which are essential for contextualizing this study within existing research. Overcoming these challenges requires efficient renewable integration, robust infrastructure, energy diversification, and global policy alignment. Technologies such as wind, solar, hydro, and bioenergy offer viable alternatives to reduce fossil fuel reliance [2].

Wind energy offers a clean, low-cost post-installation solution to reduce fossil fuel use. Its adaptability to remote, low-wind regions makes it vital for long-term energy sustainability [3],[4].Recent studies emphasize optimizing turbines for low-speed winds, especially in the Global South. Research on sub-4 m/s performance highlights the need for tailored blade designs, lower cut-in speeds, and improved torque—key for remote, off-grid applications [5].

Wind energy, used since ancient Persia for mechanical work, evolved into electricity generation in the 19th century. By 2022, global capacity exceeded 950 GW—led by China, the U.S., and Europe—through onshore and offshore expansion. Despite issues like intermittency and land impact, wind remains a key low-emission energy source [6][7][8].While recent studies address tip speed optimization and regional suitability, gaps remain in linking aerodynamic advances with real-world low-wind constraints—especially in underexplored regions like the Middle East. This review highlights wind turbines as clean technologies that convert wind energy less efficiently than conventional, higher-speed turbines, and this can affect the economic return on investment.

Initial costs: High manufacturing and installation costs can be a barrier, especially in emerging markets or rural areas where budgets are limited.

Technological requirements: Low-speed wind turbines need advanced technology to design and operate, requiring additional investment in research and development.

Awareness and social acceptance: The proliferation of these turbines may face a lack of awareness and understanding about the benefits of renewable energy, leading to the reluctance of the local community to accept them.

Legislation and government support: The absence of policies and legislation supporting renewable energy, such as fiscal incentives or tax breaks, can hinder investment in this type of turbine.

Installation and maintenance challenges: Weak wind environments can be a challenge in turbine installation and maintenance, requiring additional resources.

These challenges have also been highlighted in recent studies, which reported similar limitations in the implementation of wind energy systems across various regions in Africa. For all these challenges, it has become necessary to prepare review studies for the performance of this type of turbine and clarify its advantages with a review of the most important obstacles and future developments. This review uniquely provides a focused, comparative analysis of low-speed turbine designs for underexplored regions like Iraq. It systematically addresses challenges of low wind, highlights bio-inspired and hybrid solutions, and classifies innovations by turbine type. Its originality lies in regional context, synthesis of optimization techniques, and actionable research recommendations. This review systematically evaluates horizontal- and vertical-axis wind turbines under low-speed conditions, integrating diverse peer-reviewed studies. It compares their performance, challenges, and innovations, highlighting research gaps and regional implications for low-resource areas like Iraq. The focus is on design strategies, technical and economic challenges, and solutions to enhance turbine efficiency and adoption. This work responds to the global energy crisis by emphasizing sustainable alternatives amid fossil fuel depletion, rising demand, and climate change.

1. The Methodology

This study systematically reviews previous research on low-speed wind power The reviewed literature was selected through a systematic search across major scientific databases such as Scopus, Web of Science, and Science Direct. The inclusion criteria focused on peer-reviewed articles published within the last ten years that addressed design, modeling, or performance evaluation of low-speed wind turbines. The screening process involved title and abstract review, followed by full-text analysis to ensure relevance to low-speed operation, regional applicability, and technological innovation. Section 3 covers design strategies and performance modeling. Section 4 addresses studies on horizontal-axis wind turbines (HAWTs), while Section 5 focuses on vertical-axis wind turbines (VAWTs). Section 6 synthesizes key findings and provides recommendations. While prior results are summarized in tabular form, this work further interprets and integrates these findings to highlight their implications for advancing wind energy research and addressing practical knowledge gaps.

2. design strategies and performance modeling:

Jian Ding et al.[21] examined wind turbine integration into multi-story buildings as an urban renewable solution. Despite limited local data, they highlighted innovations such as sandwich panels, enclosed blades, and noise and vibration reduction to enhance low-speed efficiency. Ma et al. [22] enhanced low-speed turbine shaft bearing monitoring using acoustic emission and spectral features combined with physics-informed learning models. Their method accurately detected faults at ultra-low speeds, improving turbine health monitoring. Yilmaz [23] investigated tip speed ratio (TSR) effects on small wind turbine efficiency using blade element theory.

Tests on rotors (0.9–3 m diameter, 2–12 blades) showed optimal power near TSR 4. Turbines with multiple blades and TSR < 3 started easier and ran more efficiently at low wind speeds, underscoring TSR tuning for energy optimization. Yossri et al.[24] studied bio-inspired blade designs for small turbines, modeling aerodynamics from birds and insects. computational fluid dynamics CFD results showed the golden eagle-inspired blade achieved 13% efficiency at 4 m/s with a 50 cm rotor. Some flow disturbances improved performance, indicating real-world resilience. Gray et al. [25] evaluated nine airfoils, including the new G4510, for low-wind turbine aerodynamics using Q-BLADE and X-Foil. G4510 outperformed NACA 2412, 4412, and into electricity [9-11].

Unlike general reviews, this study offers a structured technical assessment of HAWTs and VAWTs for low-speed winds, with a regional focus on Iraq and similar low-resource areas. Wind turbines are mainly classified by axis orientation into Horizontal (HAWTs) and Vertical (VAWTs) types [12],[13]. Several studies have compared HAWTs and VAWTs under low wind conditions, highlighting this classification's relevance. While most research targets high-speed winds, low-speed regions hold significant wind energy potential, which can be tapped using innovations like long-blade or vertical-axis turbines designed for low wind conditions [14].

A stronger link to practical use is needed. In low-wind regions like Iraq, optimized turbines are crucial for efficient operation. This addresses the key challenge of exploiting wind energy for decentralized, rural, and off-grid power solutions. An important gap remains in the integration of detailed regional analyses from other low-wind areas, particularly South Asia For instance, the study by Ali et al. [15] conducted a regional study in Pakistan using empirical and predictive models to assess wind potential at low-speed sites. Their work compares HAWTs and VAWTs under real conditions and proposes optimization strategies, offering valuable insights relevant to similar climates in South Asia. Recent studies [16] and [17] provide key insights into regional climate modeling and wind data reliability, aiding the optimization of turbines for varying low-speed wind conditions. Including such findings would strengthen this review by contextualizing Iraq's wind profile and improving turbine deployment strategies [18]. Higher-altitude turbines, wind-solar hybrids, and autonomous blade control enhance performance, while energy storage (e.g., batteries) ensures stable power amid variability [19].

Advances in low-speed wind turbines have boosted sustainable wind energy adoption and reduced environmental harm. Despite fossil fuel abundance, their emissions exacerbate climate change, underscoring the need for cleaner renewables [20]. Low-speed wind turbines operate efficiently at 2–3 m/s, ideal for weak-wind areas. They use long, lightweight blades and adjustable angles to reduce starting torque and optimize airflow, offering sustainable power for rural and low-wind regions while reducing fossil fuel dependence. Recent reviews mostly target high-wind regions or lack detailed HAWT-VAWT comparisons for low-speed contexts. Few synthesize advances in aerodynamics, materials, and controls for weak-wind areas like Iraq. This paper fills that gap by providing a structured review of innovations in turbine design and deployment under low wind, offering valuable insights for researchers and policymakers in resource-limited settings.

Moreover, the emphasis on Iraq and comparable low-wind regions is grounded in the pressing need for localized renewable energy strategies in areas lacking stable infrastructure, consistent energy access, and strong policy frameworks. By addressing these contextual limitations, this review aims to inform region-specific deployment and support targeted policy and economic planning. Wind turbines operating at low wind speeds have faced several obstacles to their deployment, including:

Low efficiency: Although these turbines are designed to operate in weak wind conditions, they are usually 6409 by 52.2%, 21.92%, and 3.24% in lift-to-drag ratio at various Reynolds numbers, enhancing efficiency in weak winds .X.liet et al. [26] addressed blade design challenges in low-wind, high-turbulence areas via a streamlined profile optimization method. Their integrated framework combined advanced modeling and auto-optimization to improve lift, lift-to-drag ratio, and reduce sensitivity to roughness and turbulence, enhancing performance. Adeyeye et al. [27] designed a low-speed turbine inspired by a Ferris wheel for Africa, addressing high-speed and cost issues. Tested with an 800-kW motor across towns, it operated effectively at 6.74 m/s versus 12 m/s for conventional turbines, offering a cost-efficient renewable solution. Nada & Al-shahrani [28] enhanced small wind turbine blade design for low wind speeds using flexible multibody dynamics, as shown in Fig. (1) and Fig. (2). A dynamic model using floating frame formulation (FFR) integrated blade flexibility with aerodynamics. Aero foil optimization enhanced efficiency, reduced noise and mass. Reverse-tapered blades improved performance in low winds.

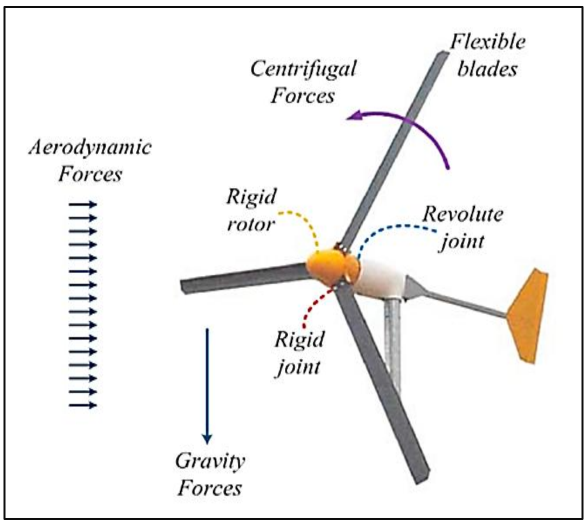

Figure (1): Schematic of a small-sized wind turbine modeled as a multi-body dynamic [28]

Talavera & Shu. [29] studied Reynolds number effects on turbine performance using single and two-turbine setups with laminar and active-grid-generated turbulent flow. Measurements with 2D-PIV showed turbulence impacts power coefficient by affecting blade flow separation and aids flow recovery in arrays, effectively simulating real conditions despite Reynolds number differences.

Santhakumar et al. [30] developed a cost-effective Savones turbine to evaluate performance on four-lane highways during monsoons. Operational at 3.5 m/s with initial torque recorded, tests showed rotation speed varied by location and wind direction, with a 64% increase at road center, emphasizing wind direction's role in optimization.

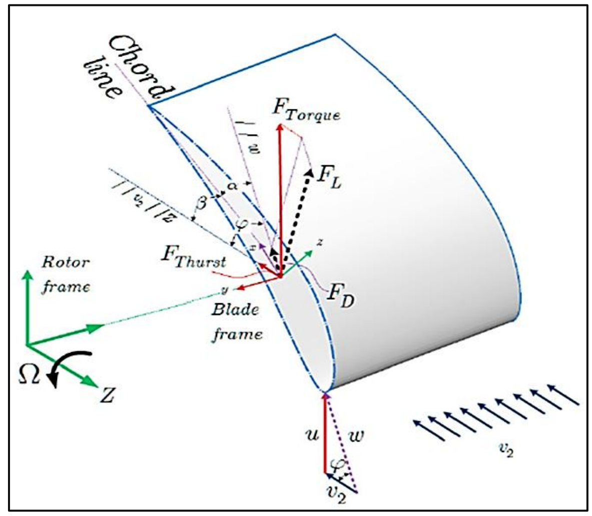

Figure (2): Distribution of aerodynamic forces acting on a wind turbine blade cross-section [28]

Akour et al. [31] designed small wind turbine blades for low-wind regions like the Arabian Peninsula and UAE, as shown in Fig. (3). Using wind data from two UAE sites, they optimized blade design at 5 m/s with BW3, WA18, and SG6043 aero foils via Blade Element Momentum theory. Blade analysis favored BW3, and a 3D-printed prototype validated the design under real conditions. Yang et al. [32] adapted blade designs from high-wind to low-wind regions, keeping chord length and Aileron series. They proposed an optimization method integrating aerodynamic and structural parameters via aerodynamic integration theory, as shown in Fig. (4). Blade Element Momentum BEM and finite element analyses confirmed improved efficiency and durability under high loads.

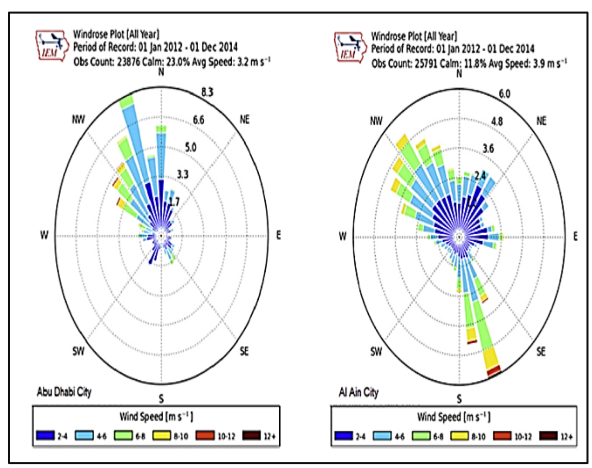

Figure (3): Wind rose diagrams for Abu Dhabi and Al Ain, illustrating prevailing wind directions and frequencies [31]

Vaz &Wood.[33] assessed turbine performance at low tip speed ratios, where tail eddies dominate. They combined vortex and momentum theories to compute thrust and torque, applying Rankine, Vatistas, and Delery models to correct infinite velocities in the Joukovsky model. The Betz-Goldstein model proved most effective, preventing vortex collapse while staying within Betz-Joukovsky limits.Mathew et al.[34] matched low-speed turbines with suitable wind regimes to boost efficiency. Using various mathematical models validated by real data, they analyzed turbine performance across locations. The study emphasized optimizing design and siting to maximize wind resource use.

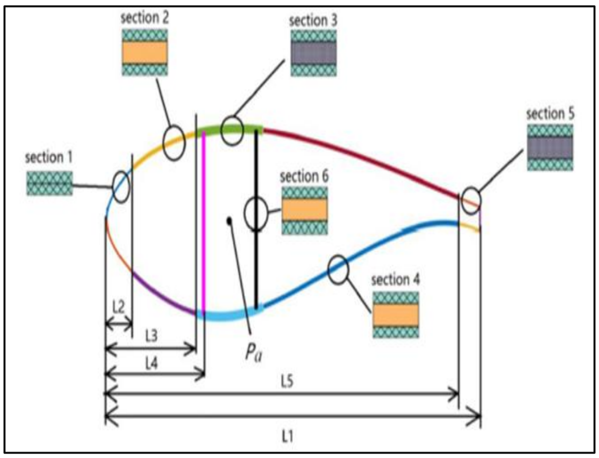

Figure (4): Typical structural configuration and parameters of a wind turbine blade section[32]

Thumthae. [35] designed a 300 kW HAWT using BEM-based software to optimize blade shape and speed. CFD validation confirmed 50.5% efficiency at a tip speed ratio of 7.5. The turbine adjusted RPM (16–36) to maintain output between 4–9 m/s, and limited efficiency above 10 m/s to cap power at 300 kW. Barnes et al.[36] compared blade efficiency for low- and high-wind sites, as shown in Fig.(5). Blades optimized for high winds underperformed in low-speed areas. Structural analysis showed that enhancing rigidity improved low-wind blade efficiency while reducing weight and cost. Using fiber-reinforced composites and 3D printing can cut weight, boost strength, and reduce costs, improving turbine viability in low-wind areas.

Monroy Aceves et al. [37] used FEA and a selection algorithm to design lightweight composite blades with unidirectional reinforcement. The method cut blade weight by nearly 50%, showing its adaptability. Wright & Wood.[38] tested 2 m, three-blade turbines and compared results with blade element analysis. Torque was mainly generated at blade tips, with rotor acceleration well predicted. Results showed that start and stop speeds differ, challenging the use of a cut-in speed.

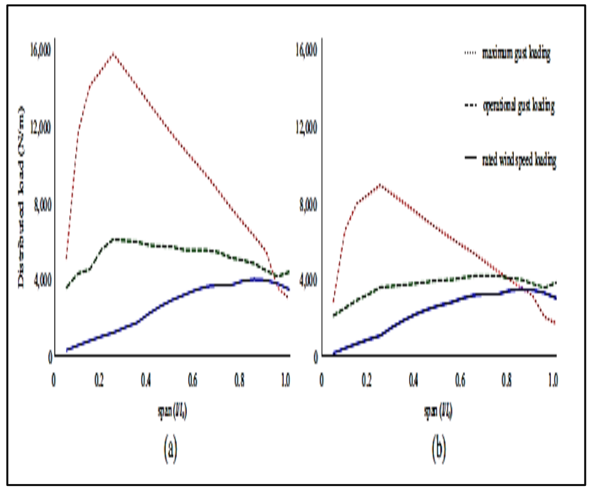

Figure (5): Comparison of aerodynamic loads on turbine blades at (a) high and (b) low wind speeds [36]

Hadi Ali [39] assessed two- and three-bladed Savonius turbines using aluminum models (200 mm height/diameter, AR = 1) with 100 mm semi-cylindrical blades. The two-bladed model had better efficiency due to lower wind resistance and reverse torque.B. Zhang et al.[40] proposed a method combining wind and storage systems to stabilize frequency and reduce torsional stress on low-speed shafts. Their approach lowered LSS loads by 20.94% and frequency variation by 50%, surpassing fuzzy logic methods.Akpan et al.[41] evaluated wind turbine feasibility in Nigeria's low-wind regions using a decade of data from 12 cities.

They studied population, remote sensing, and turbine setups at 50 and 400 m heights. Results confirmed turbines can operate efficiently at ~2 m/s, with Obudu as the best site due to high energy potential. Tebibel[42] studied clean hydrogen production from wind-powered water electrolysis in small decentralized systems. They proposed a multi-objective system (WHPS) with dynamic energy and hydrogen management (PHMS), including turbine, electrolyzer, battery, converters, and storage. Optimized PHMS reduced hydrogen shortage, cost ($33.70/kg), energy disposal, and cut CO_2 emissions by 87.75 tons/year.

H.Wang et al.[43] developed an operational strategy for low-speed turbines using real-time wind prediction with wave analysis, neural networks, and xmeans clustering. Seven indicators helped classify wind patterns and tailor operations. This method improved energy output, reduced relay switching, power fluctuations, and enhanced wind energy use and EV charging efficiency.

Sotoudeh et al. [44] assessed the INVOLOX turbine on Sistan plain via simulations and tests. Raising height from 10 to 40 m increased output by 87.5% but noise by 39.3%. A new two-story design improved energy by 44% without extra maintenance costs. Galarza-urigoitia et al.[45] addressed low-speed shaft failures posing safety and cost issues.

They developed an autonomous ultrasonic system that extends shaft life by 50%+ versus manual checks. It uses electronics, detection software, and transducers to identify cracks early and warn near end-of-life. Field tests confirmed its superior flaw detection.

X Zhang et al.[46] noted that China's strong wind sites are limited and distant, making low-wind areas (3–7 m/s) more viable due to technological progress. Low wind and high turbulence complicate MPPT control. They proposed an improved MPPT using a dynamic torque gain reduction (DTG) algorithm to optimize power capture. Simulations showed better energy output than conventional methods in low-wind conditions.

Farozan et al.[47] confirmed the Savonius turbine's suitability for low-wind areas due to self-starting and alignment. Wind tunnel tests examined aspect ratio, stage number, and torsion angle effects on start-up speed and power factor. Increasing stages or torsion angle, or lowering aspect ratio, reduced start-up speed. A 90° torsion turbine started at 2.5 m/s with power factor 0.184, producing 1.6–5.1 times more power despite lower efficiency. This highlights start-up speed's importance in low winds.

Swisher et al.[48] assessed a 3.4 MW low-speed turbine (208 m rotor, 127.5 m hub) in Northern and Central Europe. Despite costs rising 45% above conventional 142 m rotor turbines, it remained economically viable. The design lowers electrical transmission investments and can generate more than double the revenue of traditional models, improving feasibility in wind-reliant regions like Denmark.

Kandukuri et al. [49] emphasized case-based maintenance for optimal wind farm performance amid growing renewable energy use. They reviewed monitoring methods for low-speed bearings and planetary gears, assessing accuracy, reliability, and practicality. The study concludes with insights on future challenges and trends in wind farm health management. The study introduced a turbine design creating complex eddies to reduce outlet pressure, boosting power output by 240%, proving effective for low-speed wind.

Pourrajabian et al. [50] examined three horizontal turbines (0.5, 0.75, 1 kW), optimizing blade chord and twist using a genetic algorithm that included startup time and output capacity. Results showed improving root chord and torsion is key for low-wind performance.

Akour et al. [31] designed small wind turbine blades optimized for low average wind speeds in regions like the Arabian Peninsula, Jordan, and UAE. Using BW3, A18, and SG6043 airfoils and BEM theory, they optimized blade geometry at 5 m/s. QBlade simulations showed BW3 blades had the best performance.

A prototype tested under real conditions confirmed the design's cost-effectiveness and higher energy output. Wichser & Klink[51]. focused on wind energy development in southwestern Minnesota, evaluating low-speed turbines in underinvested areas. Turbines with lower start/stop speeds and larger rotors increased capacity by 15–30%, especially in low-wind (Category 2) summer regions. Annual wind power varied regionally with weather conditions.

Ani et al. [52] assessed energy output and cost of small commercial turbines in low-wind conditions. Many turbines produced only half the expected electricity. Turbines over 3 meters diameter showed better cost-effectiveness and higher annual energy yield per area. A summary of conclusions from previously published design and troubleshooting studies is provided and tabulated in Table 2.

Recent advances in AI and neural networks enable real-time control of blade pitch and rotor speed, enhancing energy output and load stability in low-wind conditions. Biomimetic blade designs, inspired by bird flight, reduce noise and delay flow separation, improving lift at low Reynolds numbers. Combined with CFD and multi-objective genetic algorithms, these innovations boost turbine efficiency. AI control and bio-inspired designs are increasingly applied in practical turbines, especially in resource-limited regions**.**

Table 1: Comparative Performance of Low-Speed Wind Turbine Design Innovations

Design Approach	Description / Key Features	Efficiency Improvement / Power Coefficient (Cp)	Blade Mass Reduction	References
Bio-inspired blades	Blades modeled after birds and insects (e.g., golden eagle)	Up to 13% at 4 m/s	~50 cm rotor; lightweight design	[24]
Wind boosters / diffuser nozzles	Devices directing airflow to increase velocity and torque	Up to 41% increase in efficiency	N/A	[55], [56], [66]
Aerodynamic optimization	Airfoil shape tuning, tip modifications, plasma actuators	Up to 38% higher Cp	Reduced structural weight via advanced materials	[57], [61]
Hybrid designs (bio + aero)	Combines biomimetic shaping with aerodynamic enhancements	Up to 38% higher Cp	50% lighter blades	[24], [28]

In order to accurately analyze and design wind turbines operating under low wind speed conditions, it is essential to understand the fundamental mathematical relationships that govern wind energy capture. The following equation expresses the total kinetic power available in the wind:

$$P_{wind} = \frac{1}{2}\rho A V^3 \quad (1)$$

Where Pawing is the power available in the wind (W), ρ is the air density (typically 1.225 kg/m³ at sea level), A is the swept area of the rotor (m²), and V is the wind speed (m/s). This relationship highlights the cubic dependence of wind power on wind speed, which is particularly significant in low-wind-speed environments.

The actual power that the wind turbine can extract is a fraction of the total wind power, governed by the power coefficient. C_p, as given by:

$$P_{turbine} = \frac{1}{2} C_p \rho A V^3 \quad (2)$$

The power coefficient C_p represents the efficiency of the turbine in converting wind energy to mechanical energy and is theoretically limited by Betz's law to a maximum of 0.593.

Another important parameter in wind turbine design is the tip speed ratio (TSR), defined as:

$$\lambda = \frac{R.\omega}{V} \quad (3)$$

Where λ is the tip speed ratio, R is the rotor radius (m), ω is the angular velocity (rad/s), and V is the wind speed (m/s). Optimal TSR values vary depending on turbine type and are crucial in maximizing efficiency under low wind conditions. For drag-based vertical-axis turbines, the aerodynamic drag force can be estimated using:

$$F = \frac{1}{2}\rho A C_d V^2 \quad (4)$$

Where F is the drag force (N), and C_d is the drag coefficient. This formulation is particularly relevant for Savonius-type turbines commonly used in low-speed scenarios due to their simplicity and self-starting capability. Finally, the overall efficiency of the system can be calculated as:

$$\eta = \frac{P_{output}}{P_{wind}} \times 100\% \quad (5)$$

This expression allows the evaluation of total energy conversion efficiency, taking into account aerodynamic, mechanical, and electrical losses. These equations form the basis for modeling, simulation, and performance evaluation of small-scale wind turbines optimized for low wind speeds.

3. Horizontal-axis turbines:

Bourhis et al. [53] developed a compact horizontal-axis turbine (300 mm diameter) for better efficiency at low wind and tip speed ratios. Using Euler-based geometry, they designed stiff, multi-blade fans. Wind tunnel tests showed a peak power coefficient of 0.31 and higher torque at low ratios versus a standard three-blade turbine. The design cuts start-up speed from 7.9 m/s to 2.4 m/s and yields a stable downstream flow, allowing further optimization like adding a counter-rotating rotor. Suresh & Rajakumar[54] designed a 2-kW horizontal-axis turbine (1.8 m radius, tip speed ratio 6) for rural low-wind areas. Using QBlade, they analyzed ten aero foils, evaluating lift and lift-to-drag ratios at different attack angles. Results showed the SD7080 aero foil offered the best performance under low wind speeds, as shown in Fig. 9.

Pambudi et al.[55] studied how nozzle lenses of different diameters and blade counts affect HAWT performance using a NACA 4415 non-twisted aero foil, as illustrated in Fig. (6). Tests at 2.5–4.5 m/s showed lenses boost power output, with diameter strongly influencing rotor speed and TSR.

The three-blade setup delivered the most energy, confirming its efficiency when combined with nozzle lenses in low-wind conditions. Riyanto et al. [56] tested a horizontal-axis turbine with two diffuser types under low wind (1–5 m/s): one without an inlet cap (L/D = 0.25) and one with a cap (L/D = 0.39). The uncapped diffuser improved efficiency by 20.5%, while the capped one raised it by 41.1%, showing that diffusers notably enhance turbine performance in low-wind settings.

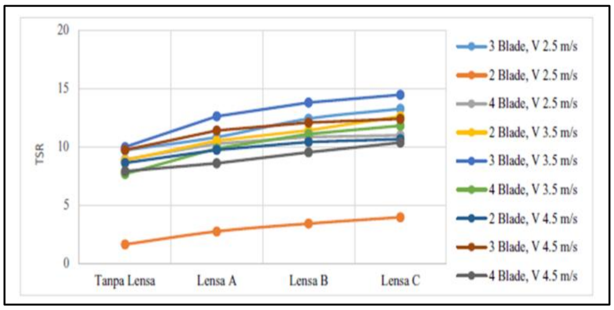

Figure (6): Impact of nozzle lens design on the power generation at various tip-speed ratios (TSR) [55]

4. Vertical-axis turbines.

Benmoussa & Pascoa. [57] explored efficiency gains in VAWTs, which face aerodynamic losses and variable stresses. Using CFD and a sliding lattice model with k-ω SST, they tested DBD plasma actuators on a cycloid VAWT with rotating and oscillating blades. Optimized plasma control raised the power coefficient by 8% over baseline and 38% over fixed-blade turbines, significantly improving performance. Sranpat et al. [58] used CFD simulations to study how design factors affect VAWT performance at low wind speeds. Virtual wind tunnel tests assessed blade count, material, and height-to-radius ratio. Turbine configuration and blade number strongly impacted performance, while material mainly affected speed. This approach aids design optimization before production. Ajayi et al. [59] studied vibrations from dynamic instability in wind turbine gearboxes, which lower energy efficiency. They analyzed shaft-gearbox interactions to enhance durability, using a subdivision method with finite element equations and boundary conditions. MATLAB simulations showed this approach accurately models gearbox dynamics and outperforms alternatives , as shown in Figures 7, 8, and 9. Z. Wang & Zhuang. [60] found that dynamic stall significantly reduces VAWT performance at low TSR (<4) and Re ($<10^5$), lowering lift, torque, and efficiency. To address this, they added sinusoidal ripples to blade leading edges to limit flow separation. Simulations showed improved power at low TSR and better energy capture at optimal TSR by delaying stall and increasing positive torque.Y. Li et al.[61] identified ice buildup on turbine blades as a major efficiency issue in cold, humid areas. They studied its impact on a vertical axis straight blade turbine (SB-VAWT) using wind tunnel tests in winter with the NACA 0018 aerofoil at low tip speed ratios.

The ice distribution was recorded with a high-speed camera, and the accumulated ice mass was measured. Results showed that ice forms differently on rotating blades compared to stationary ones, increasing over time and with rotational speed, eventually spreading across the entire blade surface as shown in Fig. 8. Seifi Davari et al. [62] noted VAWTs are less used than HAWTs due to lower performance. They improved a Darrieus VAWT's self-starting by optimizing aero foil geometry. The NACA0015 aero foil's power coefficient rose 12.5% using MATLAB's DMST algorithm. Embossed and modified blades showed better starting, needing less force than straight blades due to enhanced airflow and less turbulence.

Elsakka et al.[63] improved VAWT performance at low wind speeds using response surface methods. They analyzed tip speed ratio, turbine density, and tilt angle via CFD models. A multi-objective genetic algorithm (MOGA) optimized the design. Enhanced blade tips notably boosted the power coefficient, especially at low dimensional ratios. Francis et al. [64] developed 11 new aero foils for VAWTs by interpolating four standard profiles. Using QBlade, they evaluated lift, drag, and torque at various angles. The optimized aero foil improved startup, reduced tip losses, and cut dynamic stall, producing 1, 11, and 13 kW at 2, 11, and 16 m/s. Flow analysis showed better pressure stability reducing stall. Oprasert's & Leephakpreeda[65] highlighted low VAWT output in urban low-wind areas. They introduced a wind booster—feather-like blade arrays directing airflow to increase velocity, rotation speed, and power. The design optimizes blade count, layout, and pitch to maximize power coefficient. This concept suits various turbine types and sizes .

Korprasertsak & Leephakpreeda. [66] studied wind boosters' effects on VAWT output in low-wind Thai regions using CFD (Fig. *7*). The booster's blade arrangement directs and speeds airflow, raising turbine angular velocity and mechanical energy. Results showed notable performance gains, especially at higher wind speeds. methods is needed. Key parameters—blade pitch, wind velocity, turbulence, pressure—should be detailed for better validation. It's vital to assess how well models match real conditions, supported by experiments. Advanced optimization like multi-objective genetic algorithms deserves more analysis versus basic methods, as they explore multiple criteria systematically. Adding a comparative table of optimization strategies and results would strengthen the review's depth and credibility.

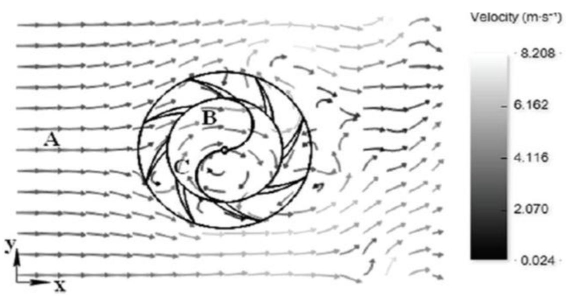

Figure (7): CFD simulation of wind flow through the wind booster[66]

Mohamed et al. [67] studied performance gains in vertical-axis turbines like Darrieus, less efficient than horizontal types. Using ANSYS Workbench and Gambit, they analyzed 25 aero foil designs and mesh techniques. Some novel designs improved efficiency by 10%. A zero-degree blade tilt angle gave the best performance.

Jagadish et al. [68] modeled and optimized a NACA 0012 H-Darrieus VAWT using MCRA and entropy methods. They ran 55 tests varying wind speed, turbine speed, blade speed, tip speed ratio, and wind-blocking. The best setup (trial 13) gave max torque (0.719 Nm) and power coefficient (0.237). Rotational speed, tip speed ratio, and wind speed most affected performance. Ullah et al. [69] studied passive flow control using leading-edge flanges to reduce dynamic stall in a vertical H-Darrieus turbine at low wind speeds. Using URANS with k-ω SST in ANSYS Fluent, they found optimal flange angles drop from 16° at 10 m/s to 12° at 5 m/s. This raised max lift by 32%, delayed stall by 3°, and improved efficiency by 15%,

To better interpret findings, comparing recent studies is key. Some highlight multi-blade and bio-inspired designs for low wind speeds, while others focus on improved airfoil shapes for efficiency. VAWT studies show that control strategies and blade tip modifications boost performance despite lower baseline efficiency. This review integrates these views, summarizing trends and challenges in the field. The review covers technologies like plasma actuators, wind boosters, and AI optimization but lacks structured quantitative validation. Reported gains include higher power coefficients from plasma actuation and efficiency from blade refinements. Aerodynamic devices boost angular velocity at low winds. AI methods improve prediction and load control. A comparative table summarizing performance and parameters would strengthen validation and guide future designs.

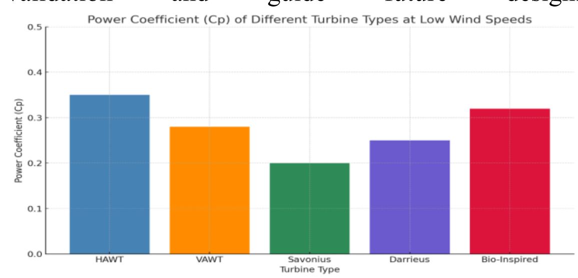

Figure (8): Power Coefficient (Cp) of Different Turbine Types at Low Wind Speeds Suggested [61]

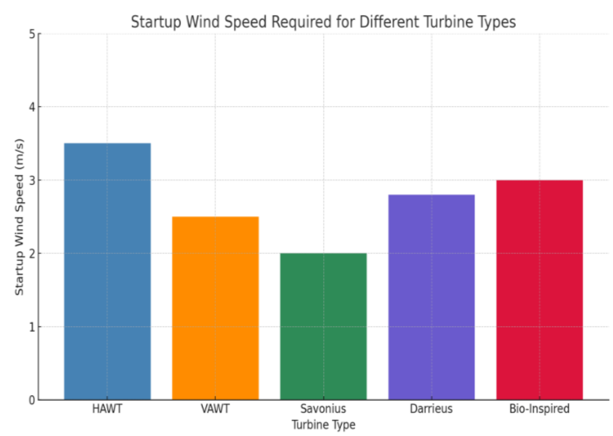

Figure (9): Startup Wind Speed Required for Different Turbine Types [54]

To enhance clarity and enable direct comparison between various low-speed wind turbine technologies, we have incorporated comparative tables and graphs. These visual aids summarize key design parameters, performance indicators, advantages, and limitations of both horizontal-axis and vertical-axis wind turbines, as discussed in the literature. The intention is to offer readers a concise and accessible overview that complements the narrative discussion and facilitates informed evaluation of different.

Table 2:. Comparative Features of HAWTs and VAWTs in Low Wind Speed Applications

Criterion	Horizontal-Axis Wind Turbines (HAWTs)	Vertical-Axis Wind Turbines (VAWTs)	Relevant References
Typical power coefficient	High under optimal alignment conditions0.15–0.35 depending on design (Savonius/Darrieus	Moderate to low; performance sensitive to turbulence 0.30–0.45 under optimized alignment	[53], [54], [56], [57], [61]
Performance in urban areas	Limited due to space and directional constraints	Better suited due to omnidirectional operation	[57], [65], [66]
Self-starting ability	Often poor; requires higher cut-in wind speed	Generally good, especially in Savonius-type and modified Darrieus designs	[26], [62], [67]
Installation complexity	Requires yaw mechanisms and tall towers	Simple design; can be installed close to the ground	[27], [60], [65]
Maintenance accessibility	Difficult due to tower height	Easier due to low mounting height	[66], [45], [59]
Suitability for hybrid use	Compatible with large solar arrays in open fields	Suitable for building-integrated wind-solar systems	[21], [28], [42]

As illustrated in Table 5, horizontal-axis wind turbines (HAWTs) generally exhibit higher aerodynamic efficiency in open and unobstructed environments. In contrast, vertical-axis wind turbines (VAWTs) demonstrate greater adaptability to low wind speed conditions, particularly in urban or spatially constrained settings. Several studies support the suitability of VAWTs for decentralized energy applications, citing advantages such as structural simplicity, lower installation requirements, and ease of maintenance.

Conclusions and recommendations:

From this review, we can conclude the following:

1. This review highlights recent advancements in low-speed wind turbine (LSWT) technologies, focusing on their suitability for regions with limited wind resources, such as Iraq, by analyzing innovative design and integration strategies.
2. The study covers various turbine designs, including horizontal-axis and vertical-axis models, with enhancements like aerodynamic optimization, bio-inspired blades, advanced materials, and hybrid solar integration.
3. Specialized configurations such as elongated blades, optimized tip speed ratios, and dynamic pitch control have proven effective in significantly increasing energy capture in low-wind environments.
4. Vertical-axis turbines, although traditionally less efficient, have improved through technologies like plasma actuators and wind boosters, making them more viable for urban and decentralized applications.
5. Integrating LSWTs with energy storage and AI-based control systems boosts their reliability and performance, especially under variable wind conditions, allowing for smarter and more adaptive energy solutions.
6. Despite technological progress, several challenges remain, including high initial costs, low public awareness, and weak policy support, which continue to limit widespread adoption in developing regions.
7. The review offers unique value by focusing on local applications, bridging global innovation with regional implementation needs, and providing practical insights for future research and deployment.
8. Future work should address unresolved issues, such as material durability, solar-wind hybrid systems, and advanced storage solutions, while establishing standardized testing and benchmarking for low-wind applications.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

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DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

Symbol	Description	Unit
A	Swept area of the wind turbine	m²
C_p	Power coefficient	–
ρ	Air density	kg/m³
V	Wind speed	m/s
P	Power output	W
Cd	Drag coefficient	-
λ	Tip speed ratio	–
ω	Angular velocity	rad/s
R	Rotor radius	m
F	Force	N

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