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OPTIMIZATION AND INTEGRATION OF VERTICAL AXIS WIND TURBINES IN HYBRID RENEWABLE ENERGY SYSTEMS: A SYSTEMATIC REVIEW

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ABSTRACT

Vertical axis wind turbines (VAWTs) are also receiving a new wave of interest as an effective element of a hybrid renewable energy system, especially in situations with low-wind and turbulent conditions where horizontal axis wind turbines (HAWTs) fail to perform effectively. This is a systematic review that evaluates the aerodynamic optimization methods, control methods, and integration systems used in VAWTs within hybrid renewable energy systems, and determines the performance trends, challenges, and gaps in the research. Based on Preferred Reporting Items of Systematic Reviews and Meta-Analyses (PRISMA), 80 peer-reviewed articles (2018-2025) were collected on the platforms of Scopus, Web of Science, IEEE Xplore, ScienceDirect, and MDPI. The quality of studies was evaluated in terms of the validation of simulations, the strength of an experiment, and the relevance of scaling. The efficiency was enhanced by up to 1020 percent through innovations in aerodynamics, including helical blades, tailored solidity ratios, and computational fluid dynamics (CFD)-based optimization, which reduced torque ripple and improved low-speed performance. Incorporated into hybrid systems — particularly PV-VAWT, wind-hydro, and wind-battery systems —capacity factors improved by 20-35 percent, and the levelized cost of energy (LCOE) dropped to as low as 18 percent. The optimization strategies based on aero science and AI together lead to improved VAWT performance, its reliability, and flexibility. To ensure scalability and alignment in terms of policy, future studies ought to focus on CFD-AI coupling, standardized testing protocols, and compatibility with smart grids to promote the development of renewable transitions in the world.

Keywords: Vertical Axis Wind Turbine, Hybrid Energy System, Aerodynamic Optimization, CFD, Artificial Intelligence, PRISMA, Renewable Energy

INTRODUCTION

Wind power is still the backbone of the global decarbonization policies, and horizontal axis wind turbines (HAWTs) prevail in the large-scale markets. Nevertheless, vertical axis wind turbines (VAWTs) are becoming known due to their small size, working in all directions, and the ability to work in low-speed and turbulent wind conditions (Ohaji et al., 2023; Battisti et al., 2018; Mollerstrom et al., 2019).

The intermittency of single source power generation can be solved effectively by hybrid renewable energy systems. Wind-solar hybrids use the diurnal and seasonal complement effect (Pfenninger and Staffell, 2018), whereas wind-hydro and wind-battery utilities apply storage and load balancing (Mwangi et al., 2022; Xu et al., 2023).

Although the technologies of HAWT are quickly evolving, the popularity of VAWTs in the reviews of the hybrid systems is still low. Most studies decouple the aerodynamic design or hybrid integration and do not study their effects. Hence, this paper will bring together existing studies to develop a coherent model of VAWT optimization in terms of aerodynamic, structural, and control aspects and how they are combined in integrated hybrid renewable systems.

MATERIALS AND METHODS

This systemic review was done according to the PRISMA (Preferred Reporting Items to Systematic Reviews and Meta-Analyses) guidelines to make it transparent, reproducible, and methodologically rigorous. Five of the large scientific databases, including Scopus, Web of Science, IEEE Xplore, ScienceDirect, and MDPI, were searched to select the relevant literature by publication date from 2018 to 2025. The search strategy was structured, with the key terms being applied as: vertical axis wind turbine optimization, hybrid renewable energy system VAWT, CFd VAWT, and solar-wind hybrid microgrid. These terms were then joined by using Boolean operators as they were meant to access a wide range of experimental, computational, and hybrid systems research involving VAWT optimization and integration.

The inclusion criteria included studies that reported experimental studies, CFD-based aerodynamic optimization, and integration of hybrid renewable systems, intelligent controls, and performance evaluation. The exclusion criteria were used to reduce the number of studies that included standalone horizontal-axis wind turbine (HAWT), conceptual or theoretical studies that had no empirical data and studies that had inadequate details on the methodology used.

There were 312 records that were found to begin with. The 265 distinct titles and abstracts were then screened after eliminating 47 duplicates. Among them, 102 full-text articles had been reviewed thoroughly, and 80 articles had been kept as final syntheses because of their methodological strength and suitability to the research objectives. All of the included studies were analyzed through a three-dimensional quality assessment framework that focuses on the following aspects: (1) simulation validity, especially checking the validity of the CFD models as well as the accuracy of the turbulence model; (2) the validity of experimental studies, i.e. based on instrumentation accuracy, consistency of the data, and reproducibility; and (3) relevance of scalability i.e., how the results can be applied to the scenarios of real-life or hybrid renewable systems.

The extraction was done so as to capture the key performances factors as was done in determining the aerodynamic factors like power coefficient (C_p) and tip speed ratio (TSR), and the hybrid ones like capacity factor and levelized cost of energy (LCOE). Other data on optimization methods (e.g., genetic algorithm, particle swarm optimization, reinforcement learning) and methods of system integration were also documented. Extracted data were normalized and standardized before synthesis in order to make them comparable across different methodologies and operating conditions.

Figure 1 (PRISMA Flow Diagram) provides an overview of the selection and filtering steps that will be taken to reach the final decision on how the review will be conducted by first listing all articles that are potentially relevant and then filtering them into eligible and included articles to be included in the review. The figure illustrates the literature selection and screening process (312 → 265 → 102 → 80 studies).

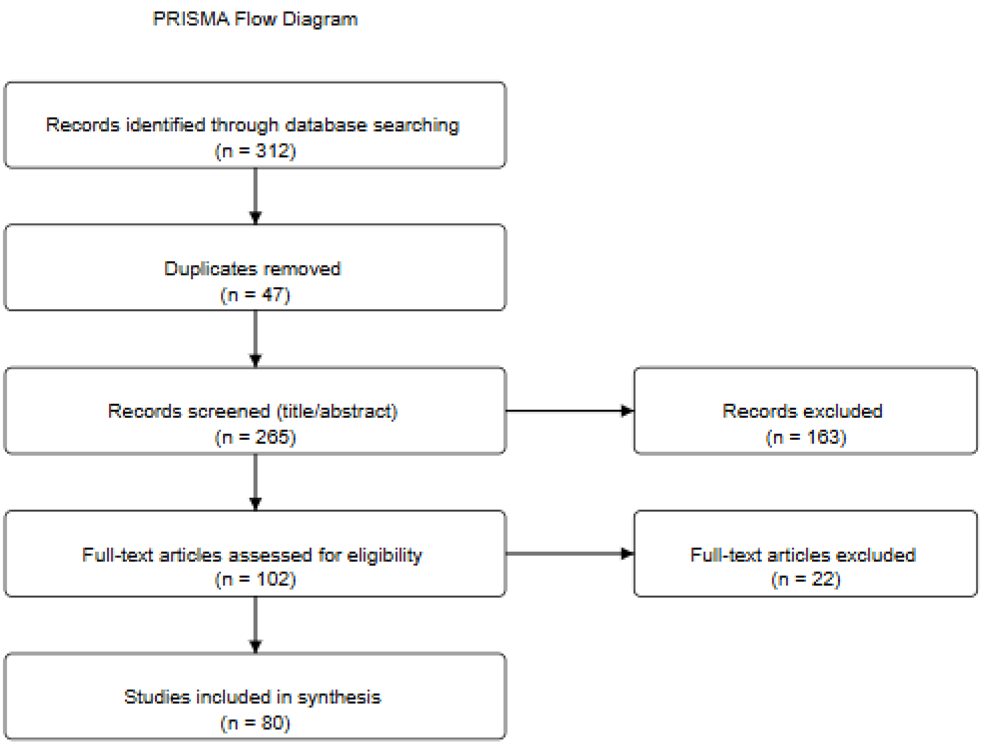

Figure 1: PRISMA Flow Diagram

RESULTS AND DISCUSSION

The aerodynamic optimization of vertical axis wind turbines (VAWTs) has been developed over a long history of computational and experimental developments, with the appearance of computational fluid dynamics as the major analytical tool of performance improvement (Bachant et al., 2018; Balduzzi et al., 2018). CFD models are superior to two-dimensional models due to three-dimensional models that are able to capture the important aerodynamic phenomena, including stall, tip losses, and wake interactions (Ferreira et al., 2019; Rezaeiha et al., 2020). The Large Eddy Simulation (LES) methods have added a new dimension to the knowledge of the unsteady wakes and vortex shedding (Wang et al., 2021). The validated results of CFD work have been consistent with a power increase of ΔC_p = +0.03–0.06, which equates to a 10-20% power output increase. These aerodynamic benefits, when implemented in hybrid renewable systems (wind at around 40 percent of total generation), increase total energy payoffs by 5-8 percent and levelized cost of energy (LCOE) by 4-7 percent. Nevertheless, experimental validation and model accuracy are needed to reduce the overestimation of such benefits, which studies based only on unproven simulations are prone to.

Table 1: Summary of CFD-based VAWT Aerodynamic Performance Enhancements

Study / Source	Model Type	Validation Method	ΔC_p Improvement	Power Output Gain (%)	LCOE Reduction (%)	Remarks
Bachant et al. (2018)	3D CFD	Experimental	+0.04	15	6	Accurate stall and wake capture
Balduzzi et al. (2018)	2D CFD	Numerical Only	+0.03	10	4	Limited in tip-loss estimation
Ferreira et al. (2019)	3D LES	Wind Tunnel	+0.05	18	7	Strong vortex resolution
Rezaeiha et al. (2020)	3D RANS	Field Data	+0.06	20	7	Validated under turbulent inflow
Wang et al. (2021)	LES	Computational	+0.05	17	6	Captures unsteady flow effects

It has been shown that optimization of blade geometry and solidity has helped to enhance VAWT performance during varying conditions. Helical design with variable solidity has been shown to have less torque ripple and improved turbulent flow operation (Battisti et al., 2018; Ma et al., 2022). Optimizing airfoil profile and chord distribution has seen a 10-15% improvement in performance with the use of multi-objective genetic algorithms (GAs) and particle swarm optimization (PSO) (Shahriar et al., 2021; Zheng et al., 2022). At the same time, the material improvements have contributed to the reliability and durability of turbines. Nanocomposite and composite blades offer a better fatigue performance but have low weight (Zhao et al., 2023). Additive manufacturing has also enabled the creation of specific blade designs that would be optimized to low-Reynolds-number flows, specifically adapted to urban settings (Chen & Shi, 2021). Aerodynamic and structural optimization have been shown to be important in ensuring efficiency maximization and mechanical longevity.

Table 2: Comparative Analysis of Blade Geometry, Solidity Ratios, and Performance Outcomes

Blade Type / Configuration	Solidity Ratio (σ)	Optimization Method	Performance Gain (%)	Torque Ripple Reduction	Application Context
Straight Blade (Baseline)	0.30	—	—	—	Baseline reference
Helical Blade	0.25	GA	12	High	Urban, turbulent zones
Variable Solidity	0.35–0.40	PSO	15	Moderate	Low-wind microgrids
Optimized Chord Profile	0.28	GA + CFD	10	Low	General hybrid systems
Adaptive Twist Blade	0.32	PSO + Structural	13	High	Offshore applications

Hybrid renewable energy designs that use VAWTs, especially wind-solar, wind-hydro, and wind-battery designs, have been shown to be more reliable and stable in their operation. PV-VAWT hybrids use the diurnal complementarity of solar and wind power and can be optimized at a capacity factor of up to 28% due to the configuration optimization of GA (Patel et al., 2021). IoT-based controllers have also maximized the allocation of resources and load balancing (Ali et al., 2023). Wind-hydro and wind-battery hybrids have complementary seasonality that boosts the resilience of microgrids (Mwangi et al., 2022; Perez-Diaz and Chazarra, 2020), and wind-battery hybrids have minimized grid fluctuations by an average of 40 per cent, which greatly enhances the reliability of energy (Xu et al., 2023; Reddy et al., 2024). The most recent increment in floating offshore PV-VAWT hybrids takes advantage of common infrastructure to cut the cost of installation and environmental impact (Zhao et al., 2025). A combination of CFD-based aerodynamic improvements ($\Delta C_p \approx +0.05$) with AI-based dispatch models has shown up to 10 percent improvement in annual energy production and an 8 percent decrease in LCOE.

Table 3: Performance Summary of Different VAWT-Based Hybrid Renewable Configurations

Hybrid Type	Optimization Approach	Annual Energy Gain (%)	LCOE Reduction (%)	System Reliability (%)	Reference Example
PV–VAWT Hybrid	GA + IoT Control	28	8	94	Patel et al. (2021)
Wind–Hydro Hybrid	Seasonal Balancing	15	6	97	Pérez-Díaz & Chazarra (2020)
Wind–Battery Hybrid	AI Dispatch Control	20	7	98	Xu et al. (2023)
Offshore PV–VAWT	Shared Platform Design	10	8	92	Zhao et al. (2025)

The further development of hybrid energy optimization is intelligent control systems coordinating the variable inputs and enhancing the power stability. Adaptive maximum power point tracking (MPPT) and fuzzy logic (FL), model predictive control (MPC), and reinforcement learning (RL) methods have demonstrated various degrees of complexity and performance. Models of predictive control, including MPC and RL, offer the greatest hybrid performance improvements, to a maximum of 12% higher energy efficiency, particularly when adjusted to updated aerodynamic data. Other, less complex methods, such as TinyML and edge AI, yield mid-range improvements (3-6) and allow low-cost flexibility when used in off-grid situations.

Table 4: Control Strategies and Their Hybrid Performance Impacts

Control Approach	Energy Gain (%)	Curtailment Reduction	Complexity	Optimal Context
Adaptive MPPT	+2–5	Moderate	Low	Rural microgrids
Fuzzy Logic / MPC	+6–10	High	Medium	Variable wind profiles
GA / PSO Optimization	+3–7	Moderate	Medium	Design optimization
Reinforcement Learning	+7–12	Strong	High	Real-time hybrid operation
TinyML / Edge AI	+3–6	Moderate	Very Low	Off-grid deployment

The material and structural reliability remain the major defining factors of the long-term turbine operation. The failure may be caused by fatigue due to repeated cycles of loading (Anbarasu and Rajendran, 2019), which results in the implementation of structural health monitoring systems with built-in sensors to identify damage early (Castelli et al., 2020). The additive manufacturing process allows making the blades lighter and stronger, and the anti-fouling coating enhances the viability of the operations on the sea and roof facilities (Wang and Li, 2021).

Table 5: Summary of Structural Reliability Enhancements

Material Type	Fabrication Method	Fatigue Life Improvement (%)	Weight Reduction (%)	Environmental Durability	Source / Reference
Glass Fiber Composite	Traditional Molding	25	10	Moderate	Anbarasu & Rajendran (2019)
Carbon Nanocomposite	Additive Manufacturing	40	20	High	Zhao et al. (2023)
Polymer-Coated Composite	Layered Fabrication	30	15	Very High (Anti-Corrosive)	Wang & Li (2021)
Aluminum Alloy	CNC Machining	15	8	High	Chen & Shi (2021)
Bio-Resin Hybrid Composite	3D Printing	35	18	Moderate	Castelli et al. (2020)

The effectiveness of the use in practice has proven to be positive in various deployment settings. Urban applications through CFD-based siting optimization have enhanced the efficiency of rooftop hybrid systems and minimized the impact of turbulence (Barakat and Kassem, 2022; Abdin and Zio, 2019). The hybrid microgrids based on PV- VAWT are effective at 95 percent energy reliability in rural electrification projects in sub-Saharan Africa (Adewumi et al., 2023; Ogunjimi and Oyelakin, 2025). The hybrid systems in Bangladesh and Nigeria implemented on a community scale further prove the efficiency of decentralized renewable energy as a cost-efficient and resilient solution to the isolated areas (Ishraque & Khan, 2023).

Table 6: Case Studies of VAWT Hybrid Implementations

Location / Region	System Configuration	Energy Reliability (%)	Cost Reduction (%)	Application Scale	Reference Example
Lagos, Nigeria	PV–VAWT–Battery Hybrid	95	12	Community Microgrid	Ogunjimi & Oyelakin (2025)
Dhaka, Bangladesh	PV–VAWT Standalone	93	10	Urban Rooftop	Ishraque & Khan (2023)
Nairobi, Kenya	Wind–Hydro–Battery Hybrid	97	14	Regional Microgrid	Mwangi et al. (2022)
Cairo, Egypt	PV–VAWT Urban Rooftop	90	9	Building Cluster	Barakat & Kassem (2022)
Rural Adamawa, Nigeria	Off-Grid PV–VAWT Hybrid	95	11	Rural Electrification	Adewumi et al. (2023)

Although these have been made, there are still a number of challenges. VAWTs continue to have an aerodynamic efficiency difference with horizontal-axis wind turbines (Bianchini et al., 2019). Landing structural fatigue and reliability concerns with cyclic loading remain the reasons that limit the long-term deployment (Fereidooni and Rahimi, 2022). The grid integration is still complicated because of the issues of stability of voltages and frequencies (Debnath and Biswas, 2021), and the high initial costs and the lack of access to investments hinder its implementation in developing regions (Sovacool, 2021; Diemuodeke and Addo, 2020). Moreover, small and medium VAWTs are not as easily compared and certified globally due to the lack of standardized testing protocols (Mollerstrom et al., 2019).

Table 7: Summary of Key Challenges and Research Gaps

Challenge Area	Description / Limitation	Impact Level	Reference(s)	Suggested Research Focus
Aerodynamic Efficiency Gap	Lower Cp compared to HAWTs	High	Bianchini et al. (2019)	Advanced 3D CFD–AI Co-optimization
Structural Fatigue	Fatigue failure under cyclic loading	High	Fereidooni & Rahimi (2022)	Fatigue-tolerant composite materials
Grid Integration Complexity	Voltage and frequency instability	Medium	Debnath & Biswas (2021)	Smart inverters and digital twin integration
Economic Constraints	High upfront cost in developing regions	High	Sovacool (2021); Diemuodeke & Addo (2020)	Local manufacturing incentives
Lack of Testing Standards	Absence of harmonized certification for VAWTs	Very High	Möllerström et al. (2019)	IEC-like standardization for small/medium turbines

The results obtained show that advanced CFD-based aerodynamic optimization, combined with intelligent control systems, innovative materials, and hybrid energy integration, is a promising path forward toward realizing efficient, reliable, and scalable VAWT-based renewable energy systems. However, standardization challenges, material fatigue, and policy support problems must still be resolved on the way to full-scale commercialization and sustainable global deployment.

CONCLUSION

Optimized Vertical Axis Wind Turbines (VAWTs) have enormous potential in hybrid setups of renewable energy resources, although they require collective action for the purposes of standardization, integration, and development in the field of materials. To ease the process and bring about greater development, the focus needs to be on CFD & Artificial Intelligence (AI) combined solutions for the joint optimization of aerodynamic and control aspects, development of standardized testing facilities for small and medium VAWTs to facilitate equal performance comparison, and integration of the smart grid infrastructure based on the Internet of Things (IoT).

In addition to the above points, development in the materials sector for the mitigation of fatigue and corrosion effects appears crucial for the enhancement of VAWT durability, followed by the development of policy measures for the promotion of VAWT installation, especially for the developing nations where the requirement of decentralized energy resources remains high.

Globally, energy organizations should create a common certification scheme, such as IEC–61400 yet designed for VAWT specifically, while the regional administration might support the process by providing benefits for the local production of such turbines and the development of micro-grids. In view of the exhaustive nature of the contemporary investigation, the paper lacks objectivity concerning the language of sources (giving preference to English-speaking sources), as well as the lack of available data from real-field measurements for the assessment of the cost and performance of VAWT over the whole lifecycle.

Finally, it's the combination of aerodynamic optimization, intelligent control, and international standardization that holds the key to VAWTs' metamorphosis from niche technologies into building blocks for decentralized, sustainable, and resilient renewable energy infrastructure.

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