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Design on Wind Turbine Performance to Support Sustainable Development: A Systematic Literature Review

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Abstract: To achieve the Sustainable Development Goals (SDGs), wind energy optimization is crucial, but it is often ineffective in environments with low wind speeds and high turbulence. This systematic literature review (SLR) examines the impact of wind turbine design modifications on improving aerodynamic performance. This study analyzes peer-reviewed articles from the Scopus database published between 2018 and 2025 using the PRISMA protocol. The selection process focused on physical design interventions, analysis techniques, and quantitative performance parameters. The results show that blade geometry modifications dominate the literature, with research covering conventional optimization approaches as well as emerging strategies such as biomimicry, blade tip engineering, and additive manufacturing materials. Methodologically, Computational Fluid Dynamics (CFD) simulations are predominantly used over purely experimental methods. Overall, the design modifications reviewed showed improvements in power coefficient (Cp) and initial torque characteristics. This study concludes that physical designs tailored to local wind conditions are crucial for maximizing wind energy potential in areas with limited resources.

Keywords: Wind Turbine, Design Optimization, Aerodynamic Performance, Systematic Literature Review, Renewable Energy

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Introduction

Wind energy is a key contributor to achieving Sustainable Development Goal 7 due to its renewable and low-emission characteristics. However, the practical performance of wind turbines is strongly limited by aerodynamic inefficiencies, particularly those related to blade design and flow behaviour. Aerodynamic optimisation is therefore essential to maximise power extraction, reduce energy losses, and improve turbine performance under varying wind conditions.

Especially on a decentralized scale, wind turbines have emerged as a strategic solution to fill the clean energy gap in urban environments (Campos Rubio et al., 2025). Despite these technological advances, significant aerodynamic challenges arise when wind turbines are deployed in such environments characterized by low wind speeds and high turbulence intensities (Waterhouse et al., 2025). Under these conditions, the energy conversion efficiency often falls significantly below the theoretical Betz limit (59.3%) due to complex aerodynamic losses (Jaszczur et al., 2024). These losses are primarily driven by flow separation phenomena at low Reynolds numbers (Rogowski et al., 2025) and the formation of strong tip vortices that induce drag (Huque et al., 2024). Therefore, improving the power coefficient (C_p) and start-up capability becomes a critical research focus to ensure the sustainability of energy supply in marginal wind areas (Khedr & Castellani, 2025).

Current literature addresses these aerodynamic challenges through a diverse spectrum of design interventions. While macro-geometric optimizations, such as blade twist and taper distribution, remain fundamental for maximizing the lift-to-drag ratio (Waterhouse et al., 2025; Jaszczur et al., 2024), there is a marked shift toward more advanced flow manipulation techniques. Biomimetic approaches, for instance, have successfully adopted complex features such as humpback whale tubercles and dragonfly wing configurations to delay stall and enhance torque stability (Alzgool et al., 2025; Khedr & Castellani, 2025). Complementing these approaches, micro-flow engineering is increasingly applied to mitigate tip vortices using passive control devices, ranging from zigzag tapes to hollow-tip designs (Rogowski et al., 2025; Yang et al., 2025). Furthermore, advances in additive manufacturing have expanded the feasibility of implementing such complex geometries, with polymer-based materials like PLA demonstrating suitability for micro-scale wind turbine applications (Suresh et al., 2024).

The current literature remains limited and lacks a comprehensive synthesis of the causal relationships between Design modifications (such as geometry, biomimicry, flow control, and materials) and quantitative performance parameters, despite rapid progress. Furthermore, an understanding of shifting methodological trends is necessary as the use of Computational Fluid Dynamics (CFD) is increasing compared to conventional testing (Huque et al., 2024; Rusli et al., 2025). By conducting a Systematic Literature Review (SLR) of scientific articles from 2018 to 2025, this study aims to fill this gap:

a. RQ1: What physical Design factors are modified in recent wind turbine research?
b. RQ2: What analysis methods are most commonly used to evaluate wind turbine performance?
c. RQ3: How does the magnitude of aerodynamic performance improvement, particularly in terms of the power coefficient and start-up torque, compare across different physical design modification strategies?

The primary focus of this review is to provide a comprehensive analysis as a basis for the development of next-generation wind turbines. By dissecting the relationship between Design parameters and performance metrics, this study's findings are expected to assist designers in selecting the appropriate optimization strategy.

Methods

This study uses the SLR method to identify, filter, and synthesize studies discussing the influence of wind turbine Design on its performance. This approach was chosen because it provides a structured, transparent, and replicable review.

Research Design

This study uses the SLR method and follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. This method was chosen because it enables a systematic, transparent, and replicable review.

Data Sources and Databases

The literature search was conducted using the Scopus database. This platform was selected as the primary source due to its broad, curated coverage of peer-reviewed literature and its strong representation in the fields of fluid mechanics and renewable energy. Scopus indexes high-impact journals from major publishers, including Elsevier, IEEE, Springer, and Taylor & Francis, thereby ensuring that the retrieved articles reflect current state-of-the-art research while maintaining rigorous quality control and metadata consistency. Additionally, Scopus applies stringent selection criteria and provides extensive temporal coverage, ensuring comprehensive retrieval of both seminal works and recent advances in the field. To support a transparent and replicable review process, a single comprehensive database was used to minimize duplicate records, streamline data extraction, and ensure methodological consistency throughout the systematic review.

Literature Search Strategy

The search began by entering a query representing the main research issue. The initial query used was:
TITLE-ABS-KEY ("wind turbine design" AND performance)
This search process yielded n=479. To obtain more relevant and recent articles, the search is filtered using the following constraints:

TITLE-ABS-KEY ("wind turbine design" AND performance)
AND PUBYEAR > 2017 AND PUBYEAR < 2026
AND (LIMIT-TO (DOCTYPE, "ar"))
AND (LIMIT-TO (LANGUAGE, "English"))
AND (LIMIT-TO (OA, "all"))

The purpose of this filter is to:

1. Retrieve peer-reviewed journal articles published between 2018 and 2025.
2. Ensuring that the articles are published in peer-reviewed journals (doctype: article).
3. Avoiding language barriers (English).
4. Ensuring full access to article content (Open Access).

After this filtering process, there were 86 articles that met the criteria.

Inclusion and Exclusion Criteria

To ensure the relevance and quality of the data, the article selection process was conducted according to strict inclusion and exclusion criteria, summarized in Table 1. Irrelevant articles, narrative reviews, or articles that do not present performance data are excluded from the analysis.

The initial screening process was conducted by reading the abstracts and paying attention to the inclusion and exclusion criteria, resulting in n=48. Next, the articles were downloaded for full reading. During this process, 8 articles could not be downloaded, resulting in n=40 articles. The second screening was conducted by reading the articles in full, resulting in n=39 data sets ready for synthesis. The entire process is shown in Figure 1.

Table 1. Inclusion and Exclusion Criteria

Criteria	Inclusion (Accepted)	Exclusion (Rejected)
Document Type	Journal articles (research articles).	Review Article (without new data), Books, Theses, and Technical Reports.
Language	English.	Languages other than English.
Publication Year	2018 – 2025.	Before 2018.
Discussion Topics	Focus on physical design modifications (blade geometry, rotor, materials) and aerodynamic analysis.	Focus on grid management, energy policy, purely electrical aspects, or water turbines.
Data Availability	Presenting quantitative performance data (e.g., Cp graphs, velocity contours, comparison tables).	Qualitative articles or those without clear data validation.

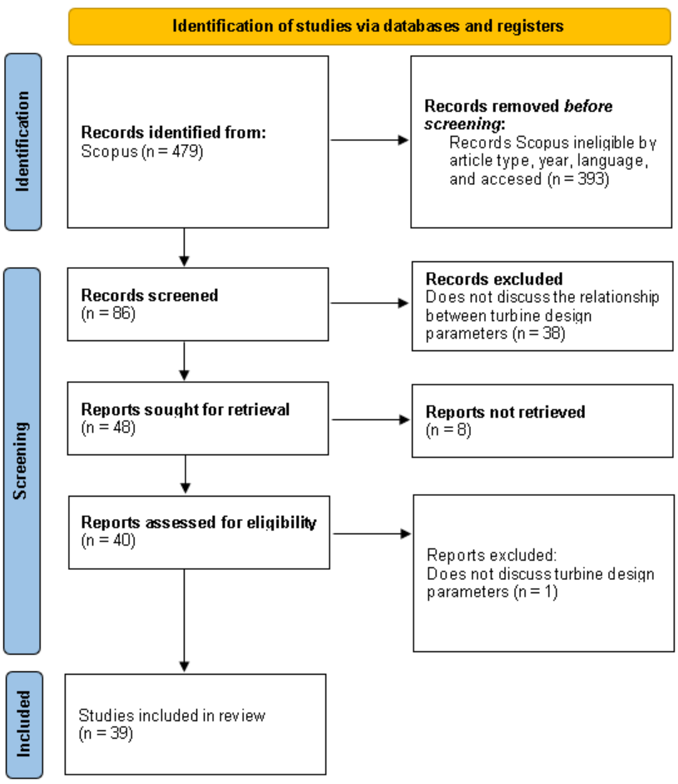

Figure 1. PRISMA flow diagram of the study selection process

Data Extraction and Codebook

The data extraction process was carried out systematically using a structured spreadsheet to mitigate bias and ensure consistent information across articles. The extracted data included bibliographic metadata (author, year, title), turbine technical characteristics, simulation/experiment parameters, and quantitative performance metrics.

To answer the research questions (RQ1, RQ2, and RQ3) in a structured manner, a classification scheme or codebook was developed. This codebook serves as a taxonomy for grouping the various Design innovations into logical parent categories. Based on an initial thematic analysis of the literature, articles were classified according to four main dimensions: (A) Turbine Type, (B) Design Modification Focus, (C) Analysis Method, and (D) Performance Parameters. Details of the codes and their operational definitions are presented in Table 2.

The application of this codebook enables precise literature mapping. For example, research by Huque et al. (2024) that modified blade tips using fluid-interactive simulations was classified under the codes [TURB-HAWT, DES-TIP, MET-FSI, PERF-STR]. Meanwhile, the biomimicry study by Khedr & Castellani (2025) that mimics dragonfly wings is categorized as [TURB-HAWT, DES-BIO, MET-HYB, PERF- TRQ]. The distribution of papers according to these codes serves as the basis for the synthesis analysis in the following subchapter.

Table 2. Codebook for Wind Turbine Literature Classification

Main Categories	Classification Code	Operational Definition & Inclusion Criteria
Turbine Type	TURB-HAWT	Horizontal Axis Wind Turbine (HAWT), covering utility scale (NREL Phase VI) and micro.
	TURB-VAWT	Vertical Axis Wind Turbine, including Savonius (drag based), Darrieus (lift-based), and H-Rotor types.
	TURB-HYB	Turbines with unconventional configurations, such as cross axis turbines or Savonius Darrieus hybrids.
Design Focus (RQ1)	DES-GEO	Optimization of blade macro geometry, including chord distribution, twist angle, taper, and selection of specialized airfoils (e.g., Wortmann).
	DES-BIO	Biomimetic design inspired by nature, such as whale tubercles or dragonfly wings.
	DES-TIP	Micro-modifications at the blade tip for vortex mitigation, including winglets, pointed tips, or hollow tips.
	DES-FLOW	Active/passive flow control devices, such as zigzag tape, flow concentrators (ODFC), or deflectors.
	DES-MAT	Material and manufacturing investigation, particularly the use of polymer materials (PLA/ABS) in 3D printed turbines.
Analysis Methods (RQ2)	MET-CFD	Numerical simulation using Computational Fluid Dynamics (RANS turbulence model, URANS, k-ω SST).
	MET-EXP	Physical experimental testing, both in wind tunnels and full-scale field testing.
	MET-FSI	Fluid-Structure Interaction (FSI) simulation for aerodynamic load analysis and deformation.
Performance Parameters (RQ3)	PERF-POW	Increase in Power Coefficient (Cp) or electrical power output (Watts).
	PERF-TRQ	Start-up Torque Characteristics or Torque Coefficient (Cm), crucial for low-speed wind.
	PERF-STR	Structural integrity, including stress analysis (Von Mises), blade deformation, and vibration.

Results and Discussion

Physical Design Factors Modified in Wind Turbine Studies

Compared to other Design components, most studies have concentrated on modifications to turbomachinery blades, including wind turbine blades, as shown in Figure 2. This dominance is demonstrated by the fact that blade position is the most important aerodynamic component in the wind energy conversion process, particularly in terms of the power coefficient (Cp).

The blades directly control flow interaction, lift distribution, and tip vortex formation. Therefore, changes in blade geometry, whether through blade tip engineering, twist, taper, or airfoil optimization, have the most significant and most measurable impact on power efficiency. Hence, this is the main subject of this study. Aerodynamic principles of blades are cross-applicable, as demonstrated by the strong relationship between turbomachinery and wind turbine research. Research results are often transferred from one field to another.

On the other hand, the distribution in Figure 2 shows not only the frequency of research but also the scientific priority given to improving aerodynamic efficiency through blade Design. This is because designs such as Savonius rotors, deflectors, and open-close blade mechanisms are typically intended to increase initial torque in low-wind conditions rather than to maximize Cp.

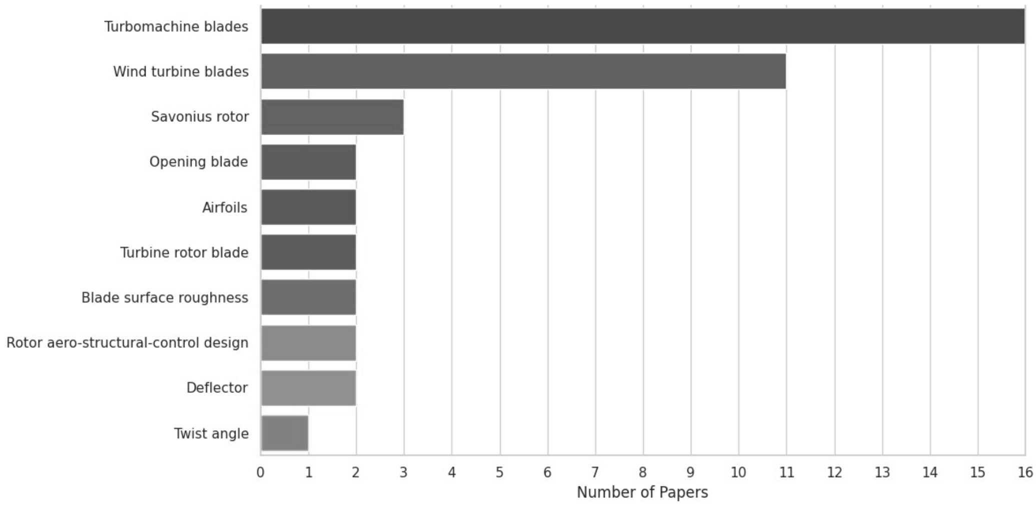

Figure 2. Physical Design Factors Modified in Wind Turbine Studies

To clarify the hierarchical structure of design modifications identified in RQ1, Figure 5 presents a taxonomic classification of wind turbine design modification strategies derived from the systematic review. Macro-geometry optimization emerges as the dominant category (n = 28), encompassing blade twist and taper, airfoil selection, and chord distribution, underscoring the central role of blade geometry in enhancing aerodynamic performance.

Additional categories include material and manufacturing innovations (n = 6), such as PLA-based 3D-printed blades and composite structures, as well as flow control devices (n = 4), including deflectors, zigzag tape, and flow concentrators. Blade tip engineering (n = 3) and biomimetic approaches (n = 2) appear as more specialized but emerging research areas.

This classification provides a structured framework for examining the interrelationship between design focus (RQ1), analytical methods (RQ2), and reported aerodynamic performance parameters (RQ3) in the subsequent sections.

Trends in Analysis Methods Used

Building on the design distribution shown in Figure 2 and the taxonomic structure presented in Figure 3, the analytical methods employed to investigate these design modification strategies are summarized in Figure 4.

Figure 4 shows the dominance of Computational Fluid Dynamics (CFD), especially in recent publications. This trend is directly related to the complexity of design modifications identified in RQ1, particularly for blades with unconventional geometries and micro-aerodynamic features. Complex aerodynamic phenomena, such as three-dimensional flow behavior, local flow separation, and inter-blade wake interactions, cannot be adequately captured using simplified experimental setups or analytical models. In this context, CFD enables detailed evaluation of aerodynamic forces and flow fields, supporting accurate estimation of both the power coefficient (Cp) and start-up torque. Although several studies adopt hybrid approaches by incorporating experimental validation, this does not alter the dominant role of CFD as the primary analysis tool in contemporary wind turbine design research.

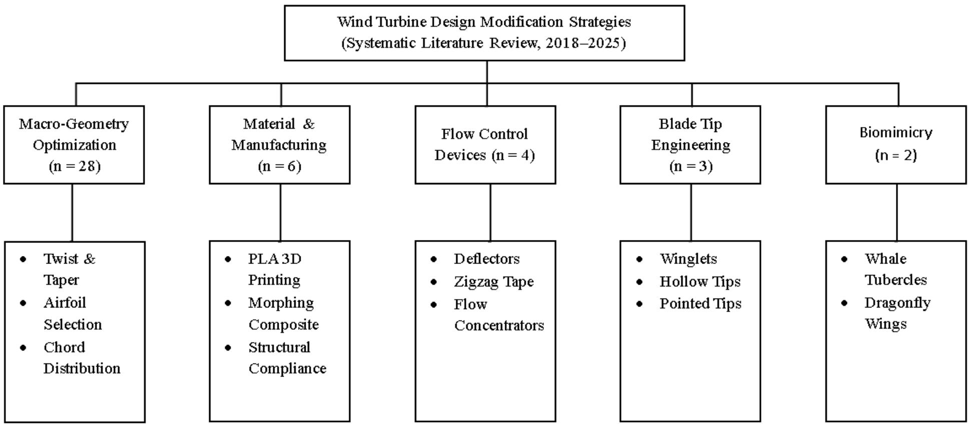

Figure 3. Hierarchical classification of wind turbine design modification strategies identified in the systematic review. The numbers in parentheses indicate the frequency of studies discussing each category (N = 39 articles). Categories are aligned with the design focus codes defined in the codebook (Table 2).

Impact of Design Modifications on Performance Parameters

Building on the dominant design strategies identified and classified in Figures 2 and 3, as well as the prevalent analysis methods summarized in Figure 4, Figure 5 examines how these design modification approaches translate into measurable improvements in aerodynamic performance.

Figure 5 illustrates that the power coefficient (Cp) is the most frequently reported performance parameter in the reviewed studies, reflecting its role as the primary indicator of wind energy conversion efficiency. This emphasis is consistent with the dominance of blade-focused design modifications identified in RQ1, as Cp directly captures the aerodynamic effectiveness of rotor geometry. In contrast, improvements in start-up torque are reported less frequently. They are primarily associated with vertical-axis wind turbines or drag-based configurations, where self-starting capability is prioritized over maximum efficiency. Notably, several studies demonstrate that simultaneous improvements in Cp and start-up torque can be achieved through integrated blade design strategies, suggesting that a strict trade-off between these parameters does not inherently constrain them but depends on the specific nature of the applied design modifications.

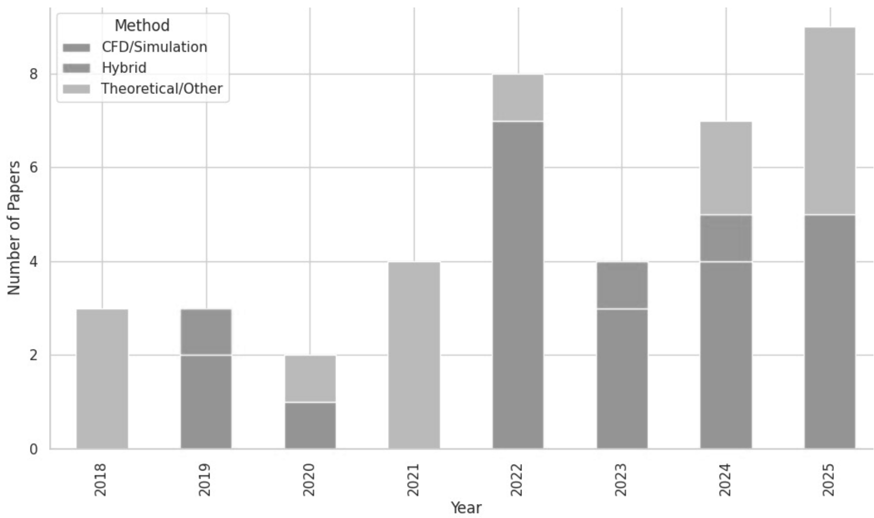

Figure 4. Trends in analysis methods used in wind turbine studies (experimental and CFD-based approaches).

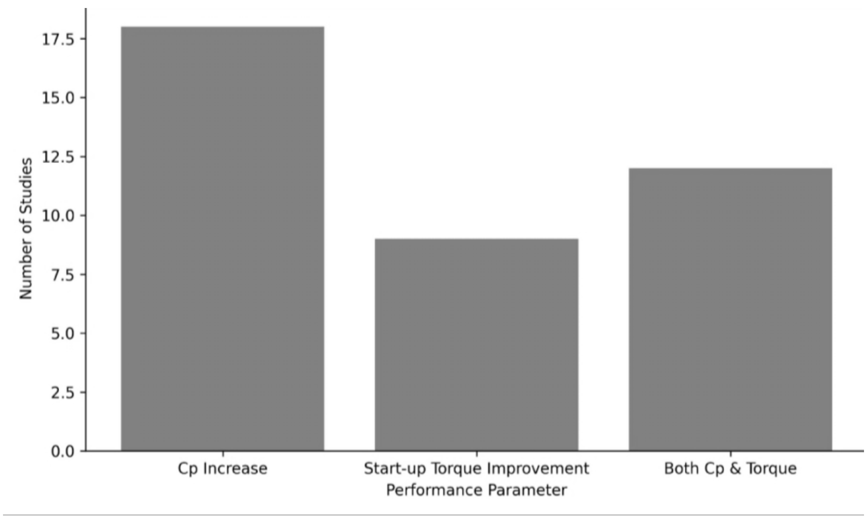

Figure 5. Comparative impact of design modifications on wind turbine performance parameters (power coefficient and start-up torque).

This section discusses the interpretation of key findings from RQ1, RQ2, and RQ3, relating them to relevant literature and the context of sustainable wind energy development.

Interpretation of Findings

Analysis methods and performance parameters were evaluated. The results of the study indicate that blade design modifications dominate the literature related to wind turbines and turbomachinery. This dominance not only reflects research trends but also represents a preference with a strong scientific basis. Blades are the main aerodynamic components that directly control flow interaction, lift force distribution, and tip vortex formation. Therefore, changes in blade geometry, including blade tip optimization, twist angle, taper ratio, and airfoil profile, have the most significant and measurable impact on increasing power efficiency. Conversely, configurations such as Savonius rotors and deflectors, although effective in low wind conditions, receive relatively less attention because their main objective is to increase initial torque rather than optimize the power coefficient (C_p).

Connecting the findings of RQ1 to RQ2, a clear pattern emerges: the more complex the design modifications, the greater the reliance on numerical simulation. The dominance of Computational Fluid Dynamics (CFD) in recent publications, especially for blades with unconventional geometries and micro-aerodynamic features, demonstrates that CFD offers greater flexibility and cost efficiency than experiments for analyzing complex three-dimensional flow phenomena, such as local separation and inter-blade wake interactions. Although some studies use a hybrid approach with experimental validation, this does not alter CFD's position as the primary analysis tool in modern wind turbine design research.

Regarding the relationship between methodology (RQ2) and performance results (RQ3), the findings show that the power coefficient (Cp), as a direct indicator of rotor aerodynamic efficiency, is the most frequently reported performance parameter. This aligns with the dominance of blade optimization in RQ1, as Cp directly reflects the rotor's aerodynamic efficiency. Conversely, reports of increased starting torque are fewer. They are generally found in studies of vertical-axis turbines or drag-based designs, which naturally prioritize self-starting capability over maximum efficiency. Interestingly, several studies show that increased Cp and starting torque can be achieved simultaneously through innovative, integrated blade designs, suggesting that the two parameters are not always in trade-off.

Overall, this study's results confirm that blades serve as the main link between primary design changes and performance improvements. The focus on improving renewable energy efficiency through blade optimization is relevant to Sustainable Development Goals, particularly in providing clean and affordable energy (SDG 7).

Implications

The results of the study indicate that, to achieve higher efficiency, wind turbine design must prioritize blade optimization through CFD analysis. In addition, wind turbine concepts and designs can be used as contextual teaching materials to improve energy literacy and understanding of sustainable development.

Conclusion

Based on a comprehensive literature review, it can be concluded that blade design modification is a significant topic in wind turbine studies; CFD is the most popular analysis method, and the most relevant performance parameter is the power coefficient (Cp). As indicated by the correlation between design focus, analysis methods, and performance indicators, blade optimization plays an important role in improving wind turbine efficiency and supporting the development of sustainable renewable energy.

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Appendix

No	Author	Turbin Type	Design Focus	Analysis Method	Parameter
1	(Stringer et al., 2018)	VAWT	DES-GEO (Airfoil 360°)	MET-CFD (Model Numerik)	PERF-TRQ (Thrust Potential)
2	(Wang et al., 2018)	HAWT	DES-GEO (Blade Optimization)	MET-CFD (Optimization Algorithm)	PERF-POW, PERF-STR
3	(Wu et al., 2018)	HAWT	DES-GEO (Integrated Design)	Other (Economic Optimization)	PERF-POW (AEP)
4	(Guo et al., 2019)	HAWT	DES-GEO (Airfoil S809)	MET-CFD (Discrete Phase Model)	PERF-POW (Lift/Drag Coeff)
5	(Elshazly et al., 2019)	HYB (Energy Ball)	DES-FLOW (Venturi Effect)	MET-EXP, MET-CFD	PERF-POW (Cp), PERF-TRQ
6	(Lipian et al., 2020)	HAWT	DES-GEO (Blade)	MET-FSI, MET-CFD	PERF-POW, PERF-STR
7	(Kelele et al., 2020)	HAWT (Single Blade)	DES-GEO (Catchment/Single Blade)	MET-CFD (BEM/Numerical)	PERF-POW (Aerodynamic Power)
8	(Cavens et al., 2021)	HAWT	DES-MAT (Compliant Structure), DES-GEO (Morphing)	MET-FSI (Aeroelastic Simulation)	PERF-STR (Load Alleviation), PERF-POW
9	(Didane et al., 2021)	VAWT	DES-GEO (Dual-rotor Counter-rotating)	MET-EXP (Experimental)	PERF-POW (Cp), PERF-TRQ
10	(Bourhim et al., 2021)	HAWT	(Sizing/Optimization)	Other (Techno-Economic Model)	PERF-POW (Energy), PERF-ECO (Cost)
11	(Prince et al., 2021)	VAWT	DES-GEO (Variable Pitch/Geometry)	MET-EXP (Wind Tunnel)	PERF-POW (Cp)
12	(Siddiqui et al., 2022)	HAWT	DES-GEO (Geometric Modeling)	MET-CFD (Parametric Analysis)	PERF-POW
13	(Adeyeye et al., 2022)	HYB (Ferris Wheel)	DES-GEO (Novel Design)	Other (Feasibility/Theoretic)	PERF-POW (Energy Production)
14	(Mohamed, Alqurashi, & Thévenin, 2022)	VAWT	DES-GEO (Blade Shape Optimization)	MET-CFD (Numerical Optimization)	PERF-POW (Cp)
15	(Mohamed, Alqurashi, Ramadan, et al., 2022)	VAWT	DES-GEO (Blade Enhancement), DES-FLOW (Deflector)	MET-CFD	PERF-POW (Cp), PERF-TRQ
16	(Ghiasi et al., 2022)	VAWT	PERF-POW (Cp), PERF-TRQ	MET-CFD (Analytical/BEM)	PERF-POW (Performance at Low Re)
17	(Gao et al., 2022)	HYB (Drag-Lift)	DES-GEO (Hybrid), DES-MAT (Adaptive Mechanism)	MET-CFD	PERF-POW (Aerodynamic Performance)
18	(Kianbakht et al., 2022)	HAWT	DES-MAT (Morphing/Ultralight), DES-GEO	MET-FSI (Aero-structural), Other	PERF-POW, PERF-STR (Mass/Load)

No	Author	Turbin Type	Design Focus	Analysis Method	Parameter
19	(Im & Kim, 2022)	VAWT	DES-GEO (Blade Design, Layout)	MET-CFD (Wake Analysis)	PERF-POW (Power Performance)
20	(Jiang et al., 2022)	HAWT	DES-MAT (Composite), DES-GEO (Retrofitting)	MET-CFD, MET-FSI	PERF-POW, PERF-STR (Fatigue)
21	(Zidane & Mahmood, 2023)	HAWT	DES-GEO (Blade Design)	MET-CFD (Q-Blade)	PERF-POW (Cp), PERF-TRQ (Ct)
22	(Shalby et al., 2023)	HAWT	DES-MAT (3D Print PLA), DES-GEO (5-Blade)	MET-CFD, MET-EXP	PERF-POW, PERF-TRQ
23	(Vincalek et al., 2023)	HAWT	DES-TIP (Ducted Winglet)	MET-CFD (FLITE3D)	PERF-POW (Drag Reduction)
24	(Stratila et al., 2024)	VAWT	DES-GEO (Helix Design)	MET-CFD (Theoretical)	PERF-POW (Power Curve)
25	(Suresh et al., 2024)	HAWT	DES-MAT (PLA 3D Print)	MET-EXP (Physical Test)	PERF-POW (Power Gen)
26	(Huque et al., 2024)	HAWT	DES-TIP (Pointed Tip)	MET-FSI, MET-CFD	PERF-STR, PERF-POW
27	(Zhang et al., 2024)	HYB	DES-GEO (Asynchronous)	MET-CFD	PERF-POW (Aero Perf)
28	(Jaszczur et al., 2024)	HAWT	DES-GEO (Optimization)	MET-CFD	PERF-POW (Efficiency)
29	(Korawan & Febritasari, 2024)	HYB	DES-GEO (Spiral Blade)	MET-EXP (Wind Tunnel)	PERF-POW, PERF-TRQ
30	(Mansour et al., 2024)	HAWT	DES-GEO (Parametric)	Other (Machine Learning)	PERF-POW (Prediction)
31	(Waterhouse et al., 2025)	HAWT	DES-GEO (Conceptual)	Other (Theoretical)	PERF-POW
32	(Yang et al., 2025)	HAWT	DES-TIP (Circular Hole)	MET-CFD	PERF-POW, PERF-TRQ
33	(Rogowski et al., 2025)	VAWT	DES-FLOW (Zigzag Tape)	MET-CFD, MET-EXP	PERF-STR, PERF-POW
34	(Khedr & Castellani, 2025)	HAWT	DES-BIO (Dragonfly)	MET-EXP, MET-CFD	PERF-TRQ, PERF-POW
35	(Rusli et al., 2025)	HYB	DES-FLOW (ODFC)	MET-CFD	PERF-POW (Cp)
36	(Alzgool et al., 2025)	HYB	DES-BIO (Whale Tubercles)	MET-CFD	PERF-POW, PERF-TRQ
37	(Campos Rubio et al., 2025)	VAWT	DES-GEO (Design Thinking)	Other (Design Process)	Design Concept / Urban Suitability
38	(Dutta et al., 2025)	VAWT	DES-GEO (Airfoil)	MET-CFD (Q-Blade)	PERF-POW (Cp), PERF-TRQ
39	(Demirdelen et al., 2019)	HAWT	(Prediction Model)	Other (Machine Learning)	PERF-POW (Energy Pred.)