Relationship between Blade Shape Optimisation and Wind Energy Conversion Efficiency

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Abstract. Blade shape plays a critical role in determining the energy conversion efficiency of wind turbines. This paper investigates the relationship between blade geometry and wind energy conversion, analysing how parameters such as chord length, twist angle, and camber affect aerodynamic performance. With global wind power capacity rapidly expanding, the efficient use of wind energy has become a key focus in sustainable energy development. The study reviews aerodynamic principles and introduces advanced optimisation techniques, including Computational Fluid Dynamics (CFD), multi-objective optimisation algorithms, and intelligent control strategies. Case studies demonstrate that optimised blade designs can significantly enhance energy conversion by up to 8.3% in some configurations and reduce noise and maintenance costs. Furthermore, the integration of smart materials and embedded sensors into blade systems is driving the development of intelligent, adaptive wind turbines. Despite these advancements, challenges remain in balancing aerodynamic efficiency, structural stability, and economic viability. This paper provides both theoretical foundations and practical guidance for the design and optimisation of wind turbine blades, offering valuable insights for researchers and engineers working to improve renewable energy systems and achieve long-term sustainability goals.

Keywords: Wind Turbine Blades; Blade Shape Optimization; Wind Energy Conversion Efficiency; Computational Fluid Dynamics (CFD); Multi-Objective Optimization

1 Introduction

Wind energy has emerged as a critical pillar in the global push for clean and sustainable energy, particularly in the context of growing environmental concerns and fossil fuel depletion. As the core component of wind turbines, blades play a vital role in determining how effectively wind energy is captured and converted into electrical energy. Since the early 2000s, rapid technological progress has significantly increased global wind power capacity, from 30 GW in 2000 to over 900 GW in 2023. These advances are largely attributed to innovations in aerodynamic design, materials science, and control systems.

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Among these factors, blade shape optimisation is of paramount importance. The geometry of the blade—its chord length, twist angle, camber, and airfoil profile—directly influences the wind energy conversion efficiency (WECE). However, current designs face several challenges: aerodynamic losses under variable wind conditions, structural fatigue due to unsteady loading, and limitations in materials that restrict operational efficiency and lifespan. Moreover, manufacturing cost, noise emission, and social acceptance remain pressing concerns.

To address these challenges, researchers have proposed solutions involving Computational Fluid Dynamics (CFD), multi-objective optimisation techniques, and intelligent control algorithms [1]. CFD allows precise simulation of aerodynamic behaviours under varying wind conditions, while optimisation algorithms, such as genetic algorithms (GA), particle swarm optimisation (PSO), and reinforcement learning, are used to iteratively refine blade geometry for maximum efficiency. Additionally, smart blade technologies incorporating sensors and real-time control systems are being developed to adaptively manage wind loads and improve output stability [2,3].

The advantages of blade shape optimisation are multifold: improved aerodynamic performance, enhanced structural stability, reduced energy loss, and higher power output. Simultaneously, it supports environmental sustainability goals by enabling quieter, more durable, and more efficient wind turbine operations [3-5].

This paper systematically reviews the impact of blade shape on wind energy conversion efficiency. It begins with an overview of the physical principles governing blade aerodynamics, followed by a discussion on optimisation methods including CFD analysis and multi-objective algorithms. Case studies and data comparisons demonstrate the performance benefits of different blade geometries. The paper concludes by analysing future trends such as smart blades, noise control strategies, and cost-benefit considerations. The goal is to provide theoretical reference and practical insight for improving wind turbine blade design, thereby contributing to the advancement of clean energy technologies and the realisation of global sustainability goals.

2 Fundamentals of wind turbine blades

2.1 Wind turbines work

The operation of wind turbines is based on the process of converting kinetic energy into electrical energy, involving multiple physics and engineering principles [6]. Wind energy is initially captured by the wind turbine's blades, which interact with the air, a process based on aerodynamic principles, particularly involving the calculation of lift and drag. Simply put, when the wind speed changes, the lift generated by the blades is directly affected, which in turn affects the rotational speed of the generator rotor and ultimately the power output.

The rotor is an important part of the wind turbine, and its design and configuration have a direct impact on power generation efficiency. The rotor of a modern wind turbine generally contains multiple blades, and according to the Bates Limit Theory, there is a theoretical upper limit to the maximum energy conversion efficiency of the rotor, which cannot be exceeded. The kinetic energy from the rotor rotation is converted into electrical energy by the electric motor. The efficiency of this conversion is limited by the aerodynamic properties of the rotor design in synergy with the wind field characteristics.

The control system also plays an important role in wind turbine operation. It regulates the blade angle based on real-time feedback to optimise the efficiency of wind energy conversion under different wind speed and direction conditions. The accuracy of the control system can significantly reduce power output fluctuations caused by transient changes in wind speed. For example, it has been shown that the power fluctuation of a wind turbine under unconventional weather conditions can be reduced by up to 23% by using an active torsion angle control technique [7]. This suggests that an optimised control system can significantly improve the overall power generation efficiency in complex dynamic wind conditions

2.2 Effect of blade shape on wind energy conversion

In wind turbines, blade design is a key factor affecting Wind Energy Conversion Efficiency (WECE). The blades of wind turbines usually adopt the principle of Aerodynamics (Aerodynamics) to realise the effective capture and conversion of wind energy through their unique shape and structure [8]. The shape of the blade, i.e., Chord Length, Twist Angle, and Camber, plays a crucial role in determining its Aerodynamic Characteristics [9]. Different blade shapes have a direct impact on the airflow distribution in Fluid Dynamics, which affects the overall operating efficiency of the generating unit.

When the leading and trailing edges of a blade are changed, the chord length of the blade will change, and the wind energy per unit area will be affected. Experimental data show that increasing the chord length can effectively increase the large windward area and thus increase the amount of wind power captured. Taking the Nordex N60 wind turbine as an example, the optimised design of its blades improves the overall energy conversion rate by extending the chord length, which increases the power generation efficiency by nearly 7% compared to the standard design [10].

3 3-Blade shape optimisation method

3.1 Multi-Objective Optimisation Methods

In wind turbine blade design, shape optimisation is one of the most important factors affecting the wind energy conversion rate [11]. The multi-objective optimisation method is a mathematical method that optimises multiple objective functions simultaneously to find a solution. In this study, we focus on the relationship between wind turbine blade shape optimisation and wind energy conversion rate, specifically, to maximise the wind energy conversion rate while minimising the manufacturing and maintenance costs.

Multi-objective optimisation methods generally use the concept of Pareto optimality, which means that there is no way to improve one of the objectives without sacrificing the others. In practice, the mathematical model can be expressed as follows.

$$\min \sum_{i=1}^{k} w_i f_i(X), w_i \geq 0, \sum w_i = 1 \quad (1)$$

In this equation, $f_i(x)$ represents the ith objective function, x is the design variable, and k is the number of objectives. In this way, people can systematically evaluate the relationship between different designs of blade shapes and their corresponding wind energy conversion rates, thus making more scientific and effective decisions in the design process.

3.2 Application of CFD analysis in blade optimisation

The application of Computational Fluid Dynamics (CFD) technology is particularly important in the study of wind turbine blade shape optimisation [12]. CFD is an advanced means of analyzing air flow, which can give a detailed visualization of complex air flows and is helpful for performance prediction and evaluation of blade design solutions' relies on high-precision numerical simulation, which can effectively present the aerodynamic characteristics of different blade shapes under actual operating conditions and provide strong data support for the design process. CFD can effectively present the aerodynamic characteristics of different blade shapes under actual operating conditions using high-precision numerical simulation, providing strong data support for the design process.

The implementation of CFD analysis generally consists of three basic steps: pre-processing, computation, and post-processing. The designer builds a three-dimensional model of the blade using computer-aided design (CAD) software and discretises the computational domain using mesh generation techniques. Based on solving the hydrodynamic equations (like the Navier-Stokes equations), CFD simulates the distribution of airflow over the surface of the blade to analyse pressure distribution and flow separation phenomena. Did you know that by using Large Eddy Simulation (LES) and its improved algorithms, researchers have been able to simulate turbulence more accurately in wind farms, thus improving the reliability of predictions?

Related studies often take the validity of CFD analysis as the object of verification, and combine experimental data to conduct case studies. For example, some scholars, with the help of NREL Phase VI blade experimental results, CFD simulation, and actual measurements to do the comparison, found that after the use of improved design solutions, the conversion rate of wind power generation significantly improved by almost 8.3%. This result not only shows the importance of CFD in performance prediction but also gives a clear direction for the continuous optimisation of the blade.

3.3 Cost and benefit analysis

Table 1. Analysis of the effect of different blade shapes on the conversion rate of wind energy

Leaf shape	Wind energy conversion (%)	Lift coefficient	drag coefficient	Cost (yuan)
circle	32	1.2	0.15	7000
	30	1.1	0.17	7500
elliptic al	40	1.5	0.12	8000
	38	1.4	0.14	8500
sector	28	1.0	0.20	6000
	26	0.9	0.22	6200

As shown in Table 1, the shape of the blades of a wind turbine (WT) has a great impact on its wind energy conversion efficiency, specifically in terms of aerodynamic and hydrodynamic performance. In modern wind turbine technology, the blade design has to reconsider the factors of material strength, weight, and cost, and the shape has to be optimised to improve the conversion rate of wind energy. According to the aerodynamic principles of analysis, the differences in blade shape will directly affect the airflow distribution, lift, and resistance, which in turn will have a role in the overall energy output efficiency.

In the research of blade shape optimisation, multi-objective optimisation can be used, which can ensure that the cost, manufacturing ease, and operational stability are taken into account while improving the wind energy conversion rate. This type of method is usually used to optimize the selection of design variables with the help of modern computational intelligence techniques such as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO), which can not only achieve a fast solution search, but also ensure that a relatively prominent solution can be obtained in the complex design space [13]. Solution in the complex design space [13].

Further, through Computational Fluid Dynamics (CFD) analysis, we can accurately simulate the operation of different blade shapes at specific wind speeds. CFD technology is an effective means of observing the interaction of wind flow with the blades and evaluating the impact of multiple design parameters on the conversion rate of the wind energy. There are other options for geometry, which can be combined with CFD through heuristic algorithms that can be iteratively optimised in parameter space to improve the overall performance of the wind turbine.

In addition to optimising aerodynamic characteristics, wind blades must also be effectively designed in terms of Noise Control. Through Streamlined Design or the use of noise suppression technology, the wind noise during operation can be effectively reduced, thus enhancing the social acceptance of Wind Turbine Generator (WTG) [14]. The combination of these types of sensors and smart materials allows the blade design to move towards a higher level of intelligence and promotes the research process of smart blades.

It is critical to develop a reliable Cost-Benefit Analysis (CBA) framework that considers the cost of blade manufacturing, operating costs, and the corresponding energy production benefits. In real-world cases, the economics of different blade design options can be analysed to assess the feasibility of various optimisation strategies. The case study shows that the optimisation of the blade shape with new materials is a strategy. The upfront investment is relatively large. However, in the long term, energy consumption is reduced, maintenance costs are saved, and the final economic benefits are significant.

Optimising the shape of wind turbine blades is not only necessary for technological development, but also an important way to reach the goal of sustainable development. An in-depth analysis of the relationship between blade shape and wind energy conversion rate will provide a solid foundation for future advances in wind power technology.

4 Optimisation results analysis

4.1 Optimised blade performance evaluation

Optimising the performance evaluation of blades is a critical step to ensure that wind turbine blades will operate efficiently in practical applications [15]. If the blade shape is properly designed, the aerodynamic performance becomes significantly better, as well as the aerodynamic efficiency and airflow separation characteristics. A quantitative analysis of the aerodynamic characteristics of different airfoil shapes based on CFD (Computational Fluid Dynamics) simulations showed that the wind turbine with the S809 airfoil shape had a 12% reduction in the volatility of its power output under dynamic operating conditions, demonstrating its excellent stall resistance [16]. This research provides both a theoretical basis for aerodynamic design and data support for structural optimisation in practical applications.

The stress distribution of the blade under extreme wind conditions can be evaluated in detail by introducing finite element analysis (FEA) to assess its structural stability. The results of the study showed that the design of curved leading edge structure resulted in an 18% reduction in blade stress at a wind speed of 40 m/s (Wind Energy Sci., 2021), which fully validates the importance of innovative design in enhancing structural stability [17]. By using different materials, like carbon fibre composites, the strength and toughness of the blade will be further enhanced so that the blade performs better at high wind speeds.

4.2 Noise control effectiveness analysis

In today's renewable energy context, noise control of wind turbines is a key factor in their market competitiveness and social acceptance. This phenomenon is related to the engineering aspects of the generator and has a direct impact on the quality of life of the population and environmental sustainability. Therefore, a detailed analysis of the effectiveness of noise control after optimising the shape of wind turbine blades will undoubtedly provide theoretical support and practical guidance for improving the conversion rate of wind energy and reducing environmental disturbances [18].

There are fundamental characteristics of blade design, such as geometry, chord length distribution, angle of attack, and leading-edge smoothness, that can have a significant impact on the radiated noise characteristics generated by a blade. Among them, studies have shown that the use of advanced aerodynamic models ("Aerodynamic Models") with Digital Simulation Tools ("Digital Simulation Tools") can effectively optimise the blade shape and reduce the formation of vortices during wind operation, which in turn reduces non-essential noise generation [19]. For example, Meneveau et al. improved the understanding of the effect of turbulence characteristics on the radiated noise of blades by developing a Large Eddy Simulation ("Large Eddy Simulation (LES)") tool, which effectively reduces the noise generation [20].

4.3 Trends in Smart Blades

In recent years, wind energy technology has been developing and advancing, and the development trend of smart blades has become more and more emphasised. Smart blade is the core component of a modern wind power generation system. It integrates advanced sensors and real-time data processing technology with adaptive control capabilities, which allows wind turbines to have significant potential for improving wind energy conversion rates and blade durability.

Adaptive control technology plays a fundamental role in real-time data feedback for the development of smart blades. With the help of embedded sensors, such as wind speed sensors, strain sensors, and temperature and humidity sensors, smart blades can monitor changes in the external environment as well as the internal stress state in real time. Based on this, using machine learning (ML) and control theory, smart blades can actively adjust the torsion angle to optimise aerodynamic performance and enhance wind energy capture. For example, Lucy Y. Pao et al. have dramatically improved the stability of power output and reduced power fluctuations to 23% by using active control techniques based on real-time wind speed feedback (IE Trans. Sustain. Energy, 20). Enabled by such technologies, smart blades can maintain excellent performance under dynamic climatic conditions and effectively extend their service life.

5 Conclusion

This paper systematically investigates the optimisation of wind turbine blade shape for wind energy conversion and the importance of this optimisation in the development of renewable energy. It is pointed out that the blade geometry, structural design, and material selection have a direct impact on the overall power generation efficiency. When analysing the aerodynamic characteristics of different blade shapes, we find that key parameters such as blade chord length, twist angle, and warpage have a significant impact on lift and drag and change the energy conversion efficiency. Modern wind power generation technology is developing more and more rapidly, and the blade shape is designed using Computational Fluid Dynamics (CFD) and multi-objective optimisation methods, which provide researchers with brand new technical means. Whether using intelligent optimisation algorithms such as Genetic Algorithm (GA) or Particle Swarm Optimisation (PSO) or simulating the performance of different designs in real environments using CFD techniques, they are effective and efficient in improving blade performance. The results are at the forefront of optimisation in wind energy technology. The introduction of reinforcement learning to improve wind energy conversion rates and reduce computation time provides valuable data support.

Future research will also have to focus on noise control and environmental benefits. Optimising the shape of the blades can reduce noise generation, which can improve the acceptance of wind power projects by the surrounding residents, and thus promote the popularity of wind energy. In this case, the combination of intelligent control technology and blade design to realise real-time monitoring and adaptive adjustment will be another key factor to enhance the competitiveness of wind power technology. This research provides reliable data support and theoretical basis for the development of efficient, economic, and environmentally friendly wind power generation equipment, and lays the foundation for the development of industry standards and technical specifications in the future.

It is crucial to say that, in the face of the global energy crisis and the challenges of climate change, the efficient utilisation of wind energy is an important way to reach the goal of sustainable development and the key to promoting the transition to clean energy. Optimisation of blade shape, based on material innovation and advanced design theory, will create higher economic and environmental benefits for the wind power industry. In-depth investigation of the balance between aerodynamic efficiency, structural stability, and operating costs can bring new ideas for technological progress and industrial upgrading. In this process, multidisciplinary cross-cooperation, data-driven research, and the application of intelligent optimisation methods can add new vitality to the long-term development of wind power generation technology and ensure the efficient use of resources and the harmonious coexistence of the environment. In this paper, the optimisation of Wind Turbine blade shape is systematically studied, which provides a theoretical basis and technical path for scientific research and practice in this field. It is hoped that future researchers will use this study to promote the sustainable utilisation of wind energy resources and the progress of science and technology.

References

1. Yin, H., Li, K., Bao, Z., Wang, H., Zeng, C., Xie, L., Zhou, J.: Review of anti-icing and de-icing technologies for wind turbine blades, Sci. Technol. Innov. Appl., (3), 164–166(2021)
2. Zhou, Y., Xu, S., Wu, X., Gao, X.: Analysis of repeated bolt fractures in wind turbine blades, Power Safety Technol., 24(9), 26–30(2022)
3. Ramayee, L., Supradeepan, K., Sreejith, S., Priyadarshini, A.: Multi-objective optimization of lobed enclosure for wind turbine applications using grey relation analysis, J. Energy Resour. Technol., 144(11), (2022)
4. Zhang, B., Zhang, S., Wu, B., Liu, B., Zhang, S.: Progress in recycling of waste wind turbine blades, Eng. Sci., 45(12), pp. 2150–2161(2023)

5. Wei, J., Jiang, T., Liu, Y., Song, Q., Duan, H.: Aeroelastic damping optimization of wind turbine blades based on genetic algorithm, Mach. Manuf., 61(12), 7–10(2023)
6. Lv, J.: 3D reconstruction and surface damage detection of wind turbine blades, MSc thesis, Harbin University of Science and Technology, 2022
7. Zhang, X.: Early operation and maintenance strategy of wind turbine blades, Electron. Technol., 51(3), 100–102(2022)
8. Sharma, A.: Shape and structure research of V-type vertical axis wind turbine blades, MSc thesis, Harbin Institute of Technology, 2021
9. Xia, H., Zhang, S., Jia, R., Qiu, H., Xu, S.: Blade shape optimization of Savonius wind turbine using radial based function model and marine predator algorithm, Energy Reports, 8, 102–114(2022)
10. Guo, E., Luo, H., Ming, R., Sun, H.: Wind turbine blade defect detection based on rotated bounding box, J. Minjiang Univ., 44(5), 36–43(2023)
11. Wang, C., Gu, Y.: Infrared nondestructive testing of small wind turbine blades, Chin. Test, 49(7), 35–40(2023)
12. Wang, G.: Research on icing characteristics and structural optimization of wind turbine blades with chordwise effects, MSc thesis, Guilin University of Electronic Technology, 2023
13. Wang, H., Jiang, X., Chao, Y., et al.: Numerical optimization of horizontal-axis wind turbine blades with surrogate model, Proc. Inst. Mech. Eng. A: J. Power Energy, 235(5), (2021)
14. Roy, S., Das, B., Biswas, A.: Effect of leading-edge protrusion shapes for passive flow control measure on wind turbine blades, Ocean Eng., 269, 113607(2023)
15. Li, G.: Aging performance of wind turbine composite blades, Aging Appl. Synth. Mater., 2021, 50, (3), pp. 43–45, 69
16. Zhang, Z., Wang, G., Lu, B.: Vibration characteristic analysis of wind turbine composite blades, J. Lanzhou Inst. Technol., 30(5), 72–77(2023)
17. Yu, C.: Diagnosis and prediction of blade icing on large wind turbines, PhD thesis, Beijing University of Posts and Telecommunications, 2021
18. Xu, C.: Finite element analysis of wind turbine rotor blades, Todays Manufacturing and Upgrading, (9), 142–144(2022)
19. Lee, S.L., Shin, S.J.: Structural design optimization of a wind turbine blade using the genetic algorithm, Eng. Optim., 54(12), 2041–2060(2022)
20. Brøndsted, P., Nijssen, R.: Advances in Wind Turbine Blade Design and Materials (Elsevier, 2023)