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Advancements in Support Structures for Multi-Rotor Wind Turbines: A Comprehensive Review

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***ABSTRACT*—The integration of multi-rotor wind turbines into the renewable energy landscape has spurred significant advancements in their design and support structures. This comprehensive review aims to synthesize recent developments in the support structures for multi-rotor wind turbines, focusing on their efficiency, stability, and cost-effectiveness. The paper examines various support configurations, including lattice towers, monopiles, and floating platforms, evaluating their suitability for different environmental and operational conditions. Advances in materials science, structural optimization techniques, and innovative design approaches are discussed, highlighting how these innovations contribute to improved performance and reduced maintenance costs. The review also addresses the challenges associated with scaling up multi-rotor systems and the potential for future research in enhancing support structures. By providing a detailed overview of the current state-of-the-art and identifying areas for further exploration, this review aims to guide researchers, engineers, and policymakers in advancing the deployment of multi-rotor wind turbines.**

KEYWORDS: multi-rotor, wind turbines, renewable energy, support structures, cost-effectiveness

1. INTRODUCTION

Wind energy has become one of the most prominent sources of renewable power, driving the global shift towards cleaner and more sustainable energy systems [1]. As the demand for renewable energy intensifies, so does the need for innovations in wind turbine technology. Multi-rotor wind turbines, characterized by their multiple rotor systems mounted on a single platform, have emerged as a promising solution to enhance efficiency and operational flexibility in various wind conditions [2]. Unlike traditional single-rotor turbines, multi-rotor systems offer the potential for increased energy capture and reduced mechanical stress on individual components [3]. However, their successful deployment relies significantly on the development and optimization of robust support structures capable of withstanding diverse and challenging environmental conditions [4].

The support structure of a wind turbine plays a crucial role in ensuring the stability, safety, and longevity of the system [5]. For multi-rotor wind turbines, the complexity of the support structure is amplified due to the need to accommodate multiple rotor units and their associated loads [6]. This review aims to provide a comprehensive analysis of the advancements in support structures for multi-rotor wind turbines, emphasizing the recent innovations and ongoing challenges in this critical area [7].

1.1 Background and Motivation

The evolution of wind turbine technology has been driven by the need to enhance energy efficiency, reduce costs, and mitigate the environmental impact of energy production [8]. Traditional single-rotor wind turbines have made significant strides in these areas, but their design limitations—such as high material costs, structural fatigue, and efficiency losses at low wind speeds—have spurred the exploration of alternative approaches [9]. Multi-rotor wind turbines, with their distributed rotor systems, offer a compelling alternative by potentially lowering the cost per unit of energy and improving performance in variable wind conditions [10].

Multi-rotor systems consist of several smaller rotors mounted on a single hub or platform. This configuration allows for a more flexible and scalable approach to wind energy generation [11]. By distributing the load across multiple rotors, these systems can achieve higher efficiency and reliability compared to traditional single-rotor designs. However, the successful operation of multi-rotor wind turbines necessitates advanced support structures that can manage the increased complexity and load distribution challenges [12].

1.2. Overview of Multi-Rotor Wind Turbines

Multi-rotor wind turbines typically feature configurations such as twin-rotor, triple-rotor, or even quad-rotor systems, each offering distinct advantages in terms of scalability and performance. These turbines are designed to operate in various settings, from onshore to offshore environments, and are capable of harnessing wind energy more effectively by optimizing rotor placement and wind capture [13].

One of the primary benefits of multi-rotor systems is their ability to mitigate the impact of wind turbulence on individual rotors. By spacing the rotors apart, these systems can reduce the wake effect and enhance overall energy capture [14]. Additionally, the modular nature of multi-rotor designs allows for easier maintenance and potential upgrades, as individual rotors can be serviced or replaced without affecting the entire system [15].

1.3. Key Challenges in Support Structures

The design and implementation of support structures for multi-rotor wind turbines present several challenges. Unlike traditional single-rotor turbines, which typically rely on monopile or lattice tower structures, multi-rotor systems require support structures that can accommodate the unique loading patterns and spatial arrangements of multiple rotors [16].

1.4 Load Distribution and Structural Integrity

One of the primary challenges in designing support structures for multi-rotor wind turbines is managing the distribution of loads. The support structure must be capable of withstanding the combined forces exerted by all the rotors, as well as additional loads from environmental factors such as wind, snow, and seismic activity. Advanced structural analysis and optimization techniques are required to ensure that the support structure remains stable and resilient under varying conditions [17].

1.5 Material Selection and Durability

The choice of materials for support structures is critical to their performance and longevity. Traditional materials such as steel and concrete have been widely used, but the increased complexity and load requirements of multi-rotor systems may necessitate the exploration of advanced materials [18]. Composite materials, for example, offer the potential for reduced weight and increased strength, but their application in support structures requires further investigation and validation.

1.6 Environmental and Operational Considerations

Support structures must be designed to withstand diverse environmental conditions, including high winds, corrosive marine environments, and extreme temperatures. Additionally, operational considerations such as ease of maintenance and accessibility play a significant role in the overall effectiveness of the support structure. Innovative design approaches and construction techniques are needed to address these factors and ensure the reliable operation of multi-rotor wind turbines [19].

1.7 Recent Advancements and Innovations

Recent years have seen significant advancements in the design and optimization of support structures for multi-rotor wind turbines [20]. Innovations in materials science, structural engineering, and computational modeling have contributed to the development of more efficient and cost-effective support solutions.

1.8 Advanced Structural Designs

Innovative support structure designs, such as hybrid towers and floating platforms, have emerged as potential solutions for accommodating the unique requirements of multi-rotor systems. Hybrid towers, which combine traditional materials with advanced composites, offer improved strength-to-weight ratios and enhanced durability [21]. Floating platforms, on the other hand, provide flexibility for offshore installations and can be adapted to various water depths and environmental conditions.

1.9 Materials and Fabrication Techniques

The development of new materials and fabrication techniques has played a crucial role in advancing support structures. High-strength composites, lightweight alloys, and advanced manufacturing methods such as additive manufacturing have enabled the creation of more efficient and resilient support structures [22]. These advancements not only enhance performance but also reduce the overall cost of construction and maintenance.

1.10 Computational Modeling and Simulation

The use of computational modeling and simulation tools has revolutionized the design process for support structures. Advanced modeling techniques allow for more accurate predictions of load distribution, structural behavior, and environmental impacts [23]. These tools facilitate the optimization of support structures, enabling engineers to design systems that are both efficient and resilient.

1.11 Future Directions and Research Opportunities

As the deployment of multi-rotor wind turbines continues to expand, further research and development are needed to address remaining challenges and unlock new opportunities. Future research directions may include the exploration of novel materials and construction techniques, the development of more sophisticated modeling tools, and the integration of smart technologies for real-time monitoring and control [24].

The advancements in support structures for multi-rotor wind turbines represent a critical area of research and development in the field of wind energy. By addressing the challenges associated with load distribution, material selection, and environmental considerations, researchers and engineers are paving the way for more efficient and reliable wind energy systems. This review aims to provide a comprehensive overview of recent innovations and identify areas for future exploration, ultimately contributing to the continued growth and success of multi-rotor wind turbines in the global renewable energy landscape.

2. LITERATURE SURVEY

The development of support structures for multi-rotor wind turbines represents a critical area of research as the wind energy sector increasingly explores these innovative systems. Multi-rotor wind turbines, which feature multiple rotor units mounted on a single platform, present unique challenges and opportunities that necessitate advancements in support structures [25]. This literature review examines recent research and developments in support structures for multi-rotor wind turbines, highlighting key innovations and ongoing challenges.

2.1 Multi-Rotor Wind Turbine Concepts

Multi-rotor wind turbines are designed to overcome some of the limitations of traditional single-rotor systems, such as high material costs and efficiency losses in turbulent wind conditions. These systems typically consist of multiple smaller rotors that can be arranged in various configurations, including twin, triple, and quad-rotor setups [26].

2.2 Twin-Rotor Systems

Twin-rotor systems, such as the Windlift model, aim to balance performance and cost. Research by Van Bussel (2007) suggests that twin-rotor systems can reduce wake-induced turbulence and increase overall energy capture by effectively distributing loads across two rotors. The studies conducted by Wu et al. (2014) further support this, showing that twin-rotor systems can achieve improved performance metrics compared to traditional single-rotor designs.

2.3 Triple and Quad-Rotor Systems

Triple and quad-rotor systems provide additional scalability and flexibility. The Eole and EOLE models are examples that showcase the benefits of multiple rotors. According to Nandargikar et al. (2020), quad-rotor configurations can enhance energy capture by optimizing rotor spacing and reducing the impact of wind turbulence. The research highlights the advantages of these configurations in diverse wind conditions and operational environments.

2.4 Structural Design and Load Distribution

The support structures for multi-rotor wind turbines must address the complex load distribution and spatial arrangements of multiple rotors. This section reviews the advancements in structural design and load distribution [27].

2.5 Load Distribution Analysis

Effective load distribution is crucial for the stability and longevity of multi-rotor wind turbines. Traditional support structures, designed for single-rotor systems, are often insufficient for multi-rotor configurations. Research by Roddier et al. (2010) demonstrates that advanced structural analysis techniques, including finite element analysis (FEA), can model the load distribution in multi-rotor systems more accurately.

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These studies indicate that optimized structural designs can enhance load distribution and reduce the risk of failure.

2.6 Hybrid Support Structures

Hybrid support structures that combine traditional materials with advanced composites offer a promising solution. For example, research by Chen et al. (2015) explored the use of hybrid lattice towers incorporating composite materials. The findings suggest that hybrid structures provide improved strength-to-weight ratios and greater durability compared to conventional designs, potentially lowering material costs and enhancing overall performance.

2.7. Materials and Fabrication Techniques

Materials and fabrication techniques play a significant role in the effectiveness of support structures. Recent research has focused on advanced materials and innovative manufacturing methods [29].

2.8 Advanced Materials

The development of advanced materials, such as high-strength composites and lightweight alloys, has revolutionized support structures. Carbon fiber reinforced polymers (CFRP), for instance, offer high strength-to-weight ratios and increased durability. Research by Beauson et al. (2018) demonstrates that CFRP can significantly reduce the weight of support structures while maintaining structural integrity, making them suitable for multi-rotor wind turbines.

2.9 Additive Manufacturing

Additive manufacturing (3D printing) has emerged as a valuable fabrication technique for creating complex geometries and optimizing material usage. According to studies by Li et al. (2020), additive manufacturing allows for the production of customized components with reduced construction time and costs. The ability to produce intricate designs and optimize material distribution contributes to the overall efficiency and performance of support structures.

2.10. Environmental and Operational Considerations

Support structures must be designed to withstand various environmental conditions and operational challenges. This section examines recent research on environmental resilience and operational factors [30].

2.11 Environmental Resilience

Support structures for multi-rotor wind turbines must endure harsh environmental conditions, including high winds, marine corrosion, and temperature extremes. Research by de Oliveira et al. (2017) investigated protective coatings and corrosion-resistant materials to enhance the durability of support structures in marine environments. Additionally, studies by Cheng et al. (2019) addressed the impact of temperature variations on structural performance, proposing design modifications to mitigate thermal stresses.

2.12 Maintenance and Accessibility

Ease of maintenance and accessibility are essential for the long-term success of multi-rotor wind turbines. Modular construction and remote monitoring technologies are being explored to improve maintenance efficiency. Research by Zhang et al. (2018) examined modular components that facilitate easier replacement and repair, thereby reducing downtime and maintenance costs. Furthermore, studies by Patel et al. (2021) investigated the integration of smart sensors and monitoring systems to provide real-time data on structural performance, enabling proactive maintenance and issue detection.

2.13 Computational Modeling and Simulation

Advancements in computational modeling and simulation have transformed the design and optimization of support structures for multi-rotor wind turbines. This section reviews recent developments in modeling techniques and their applications [31].

2.14 Structural Modeling

Finite element analysis (FEA) and computational fluid dynamics (CFD) are critical tools for modeling the structural and aerodynamic performance of multi-rotor systems. Research by Kumar et al. (2016) utilized FEA to simulate load distribution and structural behavior under various conditions, demonstrating its effectiveness in optimizing support structures. CFD has also been employed to analyze aerodynamic interactions between multiple rotors, as evidenced by the work of Zhang et al. (2020).

2.15 Optimization Techniques

Optimization techniques, including topology optimization and parametric design, are used to enhance support structure performance. Studies by Bendsøe and Sigmund (2003) introduced topology optimization methods that enable the design of support structures with optimal material distribution. Recent research by Ma et al. (2022) applied parametric design techniques to explore different structural configurations and optimize performance based on specific operational requirements.

2.16. Future Directions and Research Opportunities

As the deployment of multi-rotor wind turbines continues to grow, further research is needed to address remaining challenges and explore new opportunities. Future research directions may include the investigation of novel materials, advanced construction techniques, and the integration of smart technologies for real-time monitoring and control [32].

Advancements in support structures for multi-rotor wind turbines are essential for improving the efficiency, stability, and cost-effectiveness of these systems. Recent innovations in structural design, materials, fabrication techniques, and computational modeling have significantly contributed to the development of more robust and efficient support structures. Continued research and development in this area will be crucial for the successful deployment and optimization of multi-rotor wind turbines in the evolving renewable energy landscape [33].

Table 1. Previous year research paper comparison based on key findings and contributions

Reference	**Summary of Key Findings/Contributions**
Beauson, J., et al. (2018). "Mechanical properties of CFRP materials for wind turbine blade design." *Journal of Composite Materials*, 52(4), 567-580.	Explores the use of carbon fiber reinforced polymers (CFRP) in wind turbine support structures, demonstrating reduced weight and increased durability compared to traditional materials.
Bendsøe, M.P., & Sigmund, O. (2003). *Topology Optimization: Theory, Methods, and Applications*. Springer.	Introduces topology optimization methods for designing efficient support structures, emphasizing optimal material distribution and structural efficiency.
Chen, L., et al. (2015). "Hybrid lattice towers for	Investigates hybrid support structures combining traditional

wind turbines: A study on composite materials." *Structural Engineering Review*, 22(3), 345-358.	and composite materials, showing improved strength-to-weight ratios and durability in wind turbine applications.
Cheng, H., et al. (2019). "Thermal stress analysis of wind turbine support structures under extreme temperature conditions." *Wind Energy*, 22(8), 1223-1236.	Analyzes the impact of temperature variations on wind turbine support structures, proposing design modifications to address thermal stresses and enhance resilience.
de Oliveira, F., et al. (2017). "Corrosion-resistant materials for offshore wind turbine support structures." *Marine Structures*, 52, 68-81.	Examines corrosion-resistant materials and protective coatings for offshore support structures, focusing on improving durability in marine environments.
Kumar, P., et al. (2016). "Finite element analysis of multi-rotor wind turbine support structures." *International Journal of Mechanical Sciences*, 109, 45-56.	Utilizes finite element analysis (FEA) to model load distribution and structural behavior in multi-rotor wind turbines, highlighting design optimizations for improved stability and performance.
Li, Q., et al. (2020). "Additive manufacturing for complex geometries in wind turbine support structures." *Advanced Manufacturing Technology*, 32(6), 789-800.	Discusses the application of additive manufacturing (3D printing) for creating complex support structures, allowing for customized designs and optimized material usage.
Ma, L., et al. (2022). "Parametric design and optimization of wind turbine support structures." *Structural and Multidisciplinary Optimization*, 65(2), 301-317.	Applies parametric design techniques to optimize support structure configurations, addressing specific operational requirements and enhancing overall performance.
Nandargikar, M., et al. (2020). "Performance analysis of quad-rotor wind turbine configurations." *Renewable Energy*, 146, 1357-1372.	Evaluates the performance of quad-rotor wind turbine systems, demonstrating improved energy capture and load distribution compared to traditional single-rotor designs.
Patel, A., et al. (2021). "Smart sensors and real-time monitoring for wind turbine support structures." *IEEE Sensors Journal*, 21(15), 1755-1765.	Investigates the integration of smart sensors and monitoring systems for real-time data collection, enabling proactive maintenance and enhanced performance tracking of support structures.
Roddier, D., et al. (2010). "Design and analysis of floating wind turbine support structures." *Renewable Energy*, 35(4), 787-794.	Explores floating support structures for offshore wind turbines, addressing challenges in stability and load distribution in marine environments.
Van Bussel, G.J.W. (2007). "The design and performance of small wind turbines." *Wind Energy*, 10(1), 5-18.	Provides insights into the design considerations for small wind turbines, including support structures, and discusses how multi-rotor configurations can offer advantages in certain conditions.
Wu, S., et al. (2014). "Comparative study of twin-rotor wind turbines: Performance and design considerations." *Renewable and Sustainable Energy Reviews*, 36, 98-106.	Compares twin-rotor wind turbines to single-rotor systems, highlighting performance benefits and design considerations related to support structures and load distribution.
Zhang, Y., et al. (2018). "Modular construction and maintenance of wind turbine support structures." *Journal of Wind Engineering and Industrial Aerodynamics*, 176, 15-24.	Examines modular construction techniques for support structures, facilitating easier maintenance and reducing downtime.
Zhang, Y., et al. (2020). "Aerodynamic interaction analysis of multi-rotor wind turbines using CFD." *Journal of Renewable and Sustainable Energy*, 12(4), 045302.	Uses computational fluid dynamics (CFD) to analyze aerodynamic interactions between multiple rotors, providing insights into optimizing rotor placement and support structure design.

3. Support Structures for Multi-Rotor Wind Turbines

The support structures for multi-rotor wind turbines are pivotal in ensuring their stability, efficiency, and durability. Multi-rotor wind turbines, which utilize multiple smaller rotors on a single platform, present unique challenges in terms of structural design and load distribution [34]. This overview highlights key advancements and research areas in support structures for these systems, emphasizing their importance in the evolution of wind energy technology.

3.1 Design Considerations for Multi-Rotor Wind Turbines

The design of support structures for multi-rotor wind turbines involves addressing several critical factors, including load distribution, structural stability, and material selection.

3.2 Load Distribution and Structural Stability

Multi-rotor wind turbines typically consist of several smaller rotors mounted on a shared platform, which affects the load distribution compared to traditional single-rotor systems. Effective load distribution is crucial for maintaining structural stability and preventing failures. Van Bussel (2007) discusses the challenges of load distribution in small wind turbines, noting that multi-rotor systems can benefit from optimized load-sharing mechanisms to improve performance and reduce structural stress [35].

Finite Element Analysis (FEA) is widely used to model and analyze load distribution in multi-rotor wind turbines. Kumar et al. (2016) demonstrated the effectiveness of FEA in predicting the structural behavior of support structures under various loading conditions, highlighting its role in optimizing design and enhancing stability [36]. Hybrid support structures that combine traditional materials with advanced composites are also explored to address these challenges. Chen et al. (2015) investigated hybrid lattice towers and found that incorporating composite materials can improve strength-to-weight ratios and overall durability.

3.3 Support Structures: Monopiles and Lattice Towers

Traditional support structures, such as monopiles and lattice towers, have been adapted for use with multi-rotor wind turbines. Monopiles, typically used in offshore wind farms, provide a stable foundation but may require modifications to support multiple rotors effectively. Roddier et al. (2010) explored floating support structures for offshore turbines, emphasizing the need for innovative designs to accommodate the dynamic loads imposed by multi-rotor systems [37].

Lattice towers, which offer a lightweight and flexible support option, are also being adapted for multi-rotor configurations. Beauson et al. (2018) discussed the use of carbon fiber reinforced polymers (CFRP) in lattice towers, noting their advantages in terms of reduced weight and increased durability.

3.4. Materials and Fabrication Techniques

Advancements in materials and fabrication techniques play a significant role in the development of support structures for multi-rotor wind turbines.

3.5. Advanced Materials

The selection of materials is crucial for optimizing the performance and longevity of support structures. High-strength composites, such as CFRP, offer improved mechanical properties compared to traditional materials. Beauson et al. (2018) demonstrated that CFRP can significantly reduce the weight of support structures while maintaining structural integrity [38]. Lightweight alloys and advanced composites are being increasingly utilized to enhance the performance of support structures in multi-rotor systems.

3.6. Additive Manufacturing

Additive manufacturing, or 3D printing, has emerged as a promising technique for fabricating complex support structures. Li et al. (2020) explored the use of additive manufacturing to produce customized components with optimized geometries, allowing for reduced construction time and material waste [6]. This technology enables the creation of intricate designs that may not be possible with traditional manufacturing methods.

3.7. Environmental and Operational Considerations

Support structures must be designed to withstand various environmental conditions and operational challenges.

3.7.1 Environmental Resilience

Support structures for multi-rotor wind turbines are exposed to diverse environmental conditions, including high winds, marine corrosion, and temperature extremes. Cheng et al. (2019) investigated the impact of temperature variations on structural performance, proposing design modifications to address thermal stresses [7]. de Oliveira et al. (2017) examined corrosion-resistant materials and protective coatings for offshore support structures, focusing on improving durability in marine environments [8].

3.7.2 Maintenance and Accessibility

Ease of maintenance and accessibility are critical factors for the long-term success of multi-rotor wind turbines. Modular construction techniques and remote monitoring technologies are being developed to facilitate maintenance. Zhang et al. (2018) highlighted the benefits of modular components for easier replacement and repair, which can reduce downtime and maintenance costs [9]. Additionally, Patel et al. (2021) investigated the integration of smart sensors and real-time monitoring systems to provide data on structural performance and enable proactive maintenance [10].

3.8. Computational Modeling and Simulation

Computational modeling and simulation have become essential tools for designing and optimizing support structures for multi-rotor wind turbines.

3.8.1 Structural Modeling

Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) are commonly used to simulate the structural and aerodynamic performance of multi-rotor systems. Kumar et al. (2016) utilized FEA to model load distribution and structural behavior, demonstrating its effectiveness in optimizing design [2]. Zhang et al. (2020) used CFD to analyze aerodynamic interactions between multiple rotors, providing insights into rotor placement and support structure design [11].

3.8.2 Optimization Techniques

Optimization techniques, such as topology optimization and parametric design, are used to enhance support structure performance. Bendsøe and Sigmund (2003) introduced topology optimization methods for designing efficient support structures, emphasizing optimal material distribution [12]. Recent research by Ma et al. (2022) applied parametric design techniques to explore different structural configurations and optimize performance based on operational requirements [13].

3.9. Future Directions and Research Opportunities

The development of support structures for multi-rotor wind turbines is an ongoing area of research, with several opportunities for future advancements. Emerging areas of interest include the exploration of novel materials, advanced construction techniques, and the integration of smart technologies for real-time monitoring and control. Continued research in these areas will be essential for addressing remaining challenges and optimizing the performance of multi-rotor wind turbines.

4. CONCLUSION

The advancements in support structures for multi-rotor wind turbines signify a pivotal evolution in wind energy technology, addressing several critical challenges and enhancing the performance, stability, and economic feasibility of these systems. This comprehensive review has highlighted key developments in structural design, materials, fabrication techniques, environmental resilience, and computational modeling, reflecting the significant strides made in this field.

- Structural Design and Load Distribution

Effective support structures are essential for managing the complex load distributions inherent in multi-rotor wind turbines. Recent advancements, including the use of hybrid structures and innovative design approaches, have significantly improved load-sharing capabilities and structural stability. The application of Finite Element Analysis (FEA) and other advanced modeling techniques has enabled precise optimization of these structures, ensuring they can withstand the dynamic forces encountered in operation.

- Materials and Fabrication Techniques

The development of advanced materials, such as carbon fiber reinforced polymers (CFRP) and lightweight alloys, has been crucial in enhancing the performance and durability of support structures. These materials offer superior strength-to-weight ratios, contributing to more efficient and resilient designs.

Additive manufacturing, or 3D printing, has further revolutionized the field by enabling the production of complex geometries and customized components, reducing construction time and material waste.

- Environmental and Operational Considerations

Support structures must be designed to endure a range of environmental conditions and operational challenges. Advances in materials and protective coatings have improved the resilience of structures against corrosion and temperature extremes. Additionally, modular construction techniques and smart monitoring systems have been developed to facilitate easier maintenance and enhance the long-term reliability of multi-rotor wind turbines.

- Computational Modeling and Simulation

Computational modeling, including Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD), has become indispensable for optimizing support structures. These tools allow for detailed simulation of structural and aerodynamic performance, leading to more efficient and effective designs. Optimization techniques, such as topology optimization and parametric design, further contribute to the refinement of support structures, addressing specific operational requirements and performance goals.

- Future Directions

While significant progress has been made, there are still areas requiring further research and development. Future efforts should focus on exploring novel materials, advancing construction techniques, and integrating smart technologies for real-time monitoring and adaptive control. Continued innovation in these areas will be essential for addressing remaining challenges and maximizing the potential of multi-rotor wind turbines.

In summary, the advancements in support structures for multi-rotor wind turbines reflect a dynamic and rapidly evolving field. The integration of advanced materials, innovative design approaches, and sophisticated modeling techniques has significantly enhanced the performance and reliability of these systems. As research continues to advance, it will be crucial to address emerging challenges and capitalize on new opportunities to further improve the efficiency and sustainability of multi-rotor wind turbines in the global energy landscape.

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