International Journal of Environmental, Social and Economic Sustainability
www.ijeses.org

H. Benbouhenni Vol. 1, No. 2, June, 2026 Research Artical
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Multi-Rotor Wind Turbines and Their Impact on Sustainability: A Comprehensive Review

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Received: 07.05.2026 Accepted:05.06.2026

Abstract- The global transition toward low-carbon energy systems has intensified interest in advanced wind energy technologies capable of improving efficiency, reducing environmental impacts, and lowering the levelized cost of electricity (LCOE). Among emerging concepts, multi-rotor wind turbines (MRWTs) have gained attention as a promising alternative to conventional single-rotor wind turbines (SRWTs). MRWT systems employ several smaller rotors mounted on a common support structure instead of one large rotor. This review paper examines the technological evolution, engineering principles, environmental implications, economic viability, and social sustainability dimensions of MRWTs. The article synthesizes recent academic literature on aerodynamic performance, material efficiency, wake interactions, lifecycle impacts, maintenance requirements, and integration into future renewable energy systems. Particular emphasis is placed on sustainability assessment across environmental, social, and economic pillars. The review demonstrates that MRWTs offer substantial potential advantages, including reduced blade manufacturing constraints, lower transportation costs, improved scalability, enhanced recyclability, and potential reductions in material usage. However, challenges remain in rotor interaction control, aeroelastic stability, acoustic emissions, structural reliability, and commercial deployment readiness. The paper concludes by identifying critical research gaps and proposing strategic pathways for advancing MRWT technology within sustainable energy transitions.

Keywords: Multi-rotor wind turbines, levelized cost of energy, sustainability, wind energy systems, environmental impact, renewable energy, lifecycle assessment, offshore wind.

1. Introduction

The increasing urgency of climate change mitigation and energy security has accelerated the deployment of renewable energy (RE) technologies worldwide. Wind energy (WE) has emerged as one of the fastest-growing renewable electricity sources due to its low operational emissions and expanding technological maturity. Conventional horizontal-axis single-rotor wind turbines (SRWTs) have undergone dramatic scaling over the past three decades, with rotor diameters exceeding 220 meters in modern offshore installations. However, continued upscaling has introduced substantial engineering, logistical, environmental, and economic challenges [1].

The pursuit of larger rotor diameters is primarily motivated by the relationship between swept area and power generation. Since power extraction increases proportionally with rotor swept area, manufacturers have consistently increased blade lengths to maximize energy capture. Yet this scaling trend encounters practical limitations related to transportation, blade manufacturing, material fatigue,

Cite this article as: H. Benbouhenni, " Multi-Rotor Wind Turbines and Their Impact on Sustainability: A Comprehensive Review", International Journal of Environmental, Social and Economic Sustainability, (IJESES), Vol.1, No. 2, pp. 119-137, June, 2026.

installation complexity, and maintenance. Blades exceeding 100 meters create logistical complications during transport and require increasingly sophisticated composite materials and fabrication processes [2].

Multi-rotor wind turbine (MRWT) technology has emerged as a potential solution to these constraints. Rather than relying on a single large rotor, MRWTs distribute energy capture across multiple smaller rotors mounted on a shared support structure. This approach may reduce structural loads, improve manufacturing efficiency, enhance transportability, and potentially lower overall lifecycle environmental impacts. Researchers have suggested that MRWTs can provide advantageous scaling characteristics while addressing several limitations associated with large SRWT systems [3]. Recent research on MRWT systems has demonstrated significant progress in improving energy efficiency, structural performance, control robustness, and offshore deployment capabilities. The studies summarized in Table 1 highlight various innovative approaches, including advanced yaw control strategies, aeroelastic analyses, floating offshore configurations, robotic maintenance systems, and intelligent nonlinear control techniques such as sliding mode, backstepping, and fractional-order controllers. These works emphasize the potential advantages of MRWT systems, including higher power density, better land utilization, improved fault tolerance, modular design flexibility, and enhanced aerodynamic performance compared with conventional SRWTs. However, several technical challenges remain unresolved, such as aerodynamic interactions between rotors, structural vibration, controller complexity, computational burden, power ripple mitigation, and the high cost of implementation and maintenance. Furthermore, many studies are limited by simulation-based validation or simplified assumptions, indicating the need for more experimental investigations and large-scale practical applications. Overall, the existing literature confirms that MRWT technology is a promising direction for future RE systems, while also revealing important research gaps related to optimization, reliability, and real-world integration.

Table 1. Summary of recent research on MRWT systems: challenges, innovations, advantages, and limitations

Reference	Work / Topic	Work Constraints & Challenges	Novelty of the Work	Advantages	Disadvantages
[4]	Investigation into the Yaw Control of a Twin-Rotor 10 MW Wind Turbine (WT)	Complex yaw coordination between two rotors, aerodynamic interaction, large-scale structural loading, controller stability under turbulent wind	Introduced yaw-control investigation for a 10 MW twin-rotor turbine configuration	Improved yaw efficiency, reduced wake interaction, better energy capture potential	High control complexity, difficult real-time implementation, increased maintenance
[5]	Numerical Framework for the Coupled Analysis of Floating Offshore Multi-Wind Turbines	Coupled aero-hydro-servo-elastic modeling, floating platform instability, computational burden	Developed integrated numerical framework for floating offshore MRWT systems	Better offshore dynamic prediction, supports floating wind optimization	Very high computational cost, difficult validation with experiments
[6]	Design of a Multi-Robot System for WT Maintenance	Robot coordination, harsh offshore conditions, communication reliability	Proposed cooperative robotic maintenance system for WTs	Reduced human risk, improved inspection automation	High implementation cost, dependency on sensors and AI reliability
[7]	Aeroelastic Analysis of a Coplanar Twin-Rotor WT	Aeroelastic coupling effects, blade interaction, vibration prediction	Investigated aeroelastic behavior of coplanar twin-rotor WTs	Better understanding of structural dynamics, enhanced design reliability	Complex simulations, limited experimental validation
[8]	Coherence Effects on the Power and Tower Loads of a 7 × 2 MW MRWT System	Wind coherence modeling, load synchronization, tower fatigue estimation	Studied coherence effects on power and structural loads in large MRT systems	Improved load estimation accuracy, better tower design guidance	Results sensitive to turbulence assumptions
[9]	A Space-Efficient MRWT System for Decentralized Power	Space limitation, decentralized deployment, efficiency optimization	Proposed compact MRT system for decentralized generation	Efficient land utilization, suitable for urban/rural distributed power	Lower individual rotor efficiency, scaling limitations
[10]	Experimental Assessment of a Dual Super-Twisting Control Technique of Variable-Speed MRWT Systems	Nonlinear control tuning, experimental validation, chattering reduction	Applied dual super-twisting sliding mode control experimentally	Strong robustness, fast dynamic response	Controller design complexity, high computational demand
[11]	Experimental Validation of Feedback PI Controllers for Multi-	PI parameter tuning, sensitivity to disturbances	Experimental validation of PI control in MRT systems	Simple implementation, low computational cost	Lower robustness compared to advanced nonlinear controllers

	Rotor Wind Energy Conversion Systems				
[12]	Fractional-Order Synergetic Control of the Asynchronous Generator-Based Variable-Speed MRWT Systems	Fractional-order parameter tuning, stability analysis	Introduced fractional-order synergetic control for MRT systems	Improved robustness and dynamic performance	Difficult practical implementation, mathematical complexity
[13]	Multi-rotor wind turbines: A review of modern research efforts and challenges	Integrating diverse MRT studies, identifying research gaps	Comprehensive review of modern MRT developments and challenges	Broad overview, identifies future directions	Limited original experimental contribution
[14]	Design Study of Multi-Rotor and Multi-Generator WT with Lattice Tower—A Mechatronic Approach	Integration of generators, lattice tower dynamics, mechatronic optimization	Combined mechatronic design with MRT and lattice tower concepts	Reduced tower mass, modularity benefits	Increased structural complexity
[15]	Solving the problem of power ripples for a MRWT system using fractional-order third-order sliding mode algorithms	Ripple minimization, advanced nonlinear control implementation	Used fractional-order third-order sliding mode control (SMC) to reduce power ripples	Enhanced power quality and robustness	Complex controller tuning and implementation
[16]	Comparative Analysis of Conventional and MRWTs	Fair comparison metrics, scaling analysis	Comparative performance evaluation of single and MRWT systems	Clear comparison framework, highlights MRT potential	Limited practical validation
[17]	Development of a multi rotor floating offshore system based on vertical axis WTs (VAWTs)	Floating stability, VAWT interaction, offshore deployment	Combined floating offshore concept with multi-rotor VAWTs	Potential reduction in offshore installation costs	Immature technology, uncertain long-term reliability
[18]	Multirotor Systems Using Three Shrouded WTs for Power Output Increase	Shroud design optimization, aerodynamic losses	Proposed shrouded multi-rotor configuration	Increased power output, improved airflow concentration	Additional structural weight and cost
[19]	Performance and Economic Analysis of MRWT	Economic modeling uncertainty, lifecycle cost estimation	Combined technical and economic analysis of MRT systems	Demonstrated economic feasibility potential	Economic assumptions may vary by region
[20]	Aerodynamic Performance and Structural Design of 5 MW MRWT System	Structural optimization, aerodynamic interaction analysis	Studied aerodynamic and structural design for 5 MW MRT	Improved understanding of large-scale MRT design	Complex structural requirements
[21]	Analysis Model of a Small Scale Counter-Rotating Dual Rotor WT with Double Rotational Generator Armature	Counter-rotation synchronization, generator complexity	Developed analytical model for counter-rotating dual rotor WT	Better low-speed energy extraction	Higher mechanical complexity
[22]	Second Order Sliding Mode Control of a Dual-Rotor WT System by Employing a Matrix Converter	Matrix converter control, SMC chattering	Applied second-order SMC to dual-rotor WT	High robustness against disturbances	Difficult hardware implementation
[23]	Using neural network super-twisting sliding mode to improve power control of a dual-rotor WT system	Neural network training, fault-mode stability	Combined neural networks with super-twisting SMC	Improved fault tolerance and adaptive control	Requires extensive training data
[24]	Application of Backstepping Control With Nonsingular Terminal Sliding	Stability proof, nonlinear controller integration	Hybrid backstepping and terminal sliding mode approach	Fast convergence and strong robustness	High design and implementation complexity

	Mode Surface Technique				
[25]	Using Fractional-order Technique and Non-linear Surface to Improve the Performance of the Backstepping Control of MRWT Systems	Fractional-order modeling difficulty, nonlinear tuning	Enhanced backstepping control using fractional-order methods	Better dynamic and transient response	Computationally intensive
[26]	Improved vector control of a counter-rotating WT system using adaptive backstepping sliding mode	Adaptive parameter estimation, counter-rotating dynamics	Adaptive backstepping sliding mode for vector control	Improved robustness and tracking performance	Controller structure is mathematically complex

On the other hand, MRWTs have attracted increasing attention as a promising alternative to conventional SRWTs, particularly for large-scale and offshore energy applications. Their main advantage lies in the potential to achieve higher power density by distributing aerodynamic loads across multiple smaller rotors instead of relying on a single large rotor. This configuration can reduce structural weight requirements, simplify transportation and installation, and improve scalability for very large capacity systems. In addition, MRWTs offer greater design flexibility and redundancy, since the failure of one rotor does not necessarily lead to a complete system shutdown. From a research perspective, MRWTs open new opportunities in advanced control systems, wake interaction optimization, and modular energy harvesting strategies.

Despite these advantages, MRWTs also introduce new challenges such as complex aerodynamic interactions between rotors, increased control system complexity, and higher coordination requirements. However, ongoing developments in nonlinear control techniques, floating offshore platforms, and intelligent monitoring systems are progressively addressing these issues. Overall, MRWT technology presents a strong future direction for WE development, with the potential to outperform traditional single-rotor designs in specific high-capacity, space-constrained, and offshore environments.

Despite growing research interest, MRWT technology remains at a relatively early stage of development compared with mature SRWT systems. Existing studies primarily focus on aerodynamic interactions, structural optimization, and preliminary economic assessments. Comprehensive evaluations of sustainability impacts remain limited. Accordingly, this review synthesizes current knowledge regarding MRWTs through the lens of environmental, social, and economic sustainability.

The objectives of this review are to:

- Examine the technological foundations of MRWT systems;
- Evaluate environmental sustainability implications;
- Assess economic performance and lifecycle costs;
- Explore social acceptance and policy considerations;
- Identify research gaps and future opportunities.

2. Evolution of WT Technology

2.1 Conventional Single-Rotor Wind Turbines

Modern WTs are predominantly horizontal-axis systems featuring three blades attached to a central nacelle. Continuous increases in rotor diameter have improved energy capture efficiency and reduced electricity costs. Offshore turbines now commonly exceed capacities of 12–15 MW. However, scaling introduces nonlinear increases in structural loads and material requirements [27].

Figure 1 illustrates the external configuration of a conventional SRWT, currently the most widely used technology for both onshore and offshore power generation. This type of turbine typically consists of a large, horizontally oriented rotor mounted atop a tall tower, facing the wind. The streamlined rotor usually comprises three blades connected to a central shaft, which converts the kinetic energy of the wind into rotational mechanical energy. The streamlined casing behind the rotor houses the main mechanical and electrical components responsible for power generation and control operations.

Figure 2 presents the principal components of the SRWT system. The main parts include the rotor blades, hub, low-speed shaft, gearbox, high-speed shaft, generator, brake system, nacelle, yaw mechanism, pitch control system, and tower. The rotor blades capture WE and transfer rotational motion through the shafts to the gearbox and generator. The yaw system aligns the WT with wind direction, while the pitch

system regulates blade angles to optimize power extraction and protect the WT under high wind conditions. The tower provides structural support and elevates the rotor to higher altitudes where wind speeds are generally stronger and more stable. Together, these components ensure efficient conversion of WE into electrical power.

The primary challenges associated with oversized SRWTs include:

- Blade transportation limitations;
- Manufacturing complexity;
- Increased tower and foundation loads;
- Material consumption;
- Fatigue stresses;
- End-of-life disposal concerns.

As WTs grow larger, these challenges intensify and may eventually offset gains in energy production and cost reductions.

Figure 1. SRWT.

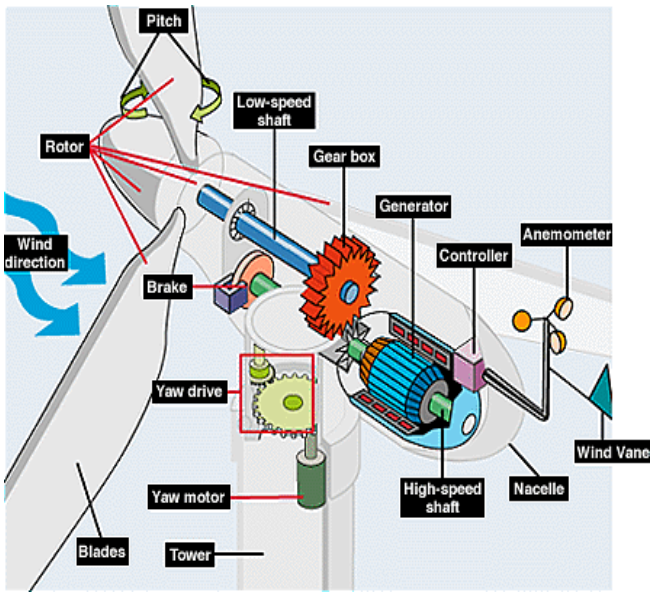

Figure 2. SRWT components [28].

The cost of energy generated by conventional SRWTs is strongly influenced by the dimensions of the WT, particularly the rotor diameter and tower height. Increasing the rotor size generally allows the WT to capture more WE due to the larger swept area, which can improve annual energy production and reduce the levelized cost of energy (LCOE). For this reason, modern WT development has historically focused on scaling up turbine dimensions to achieve higher power outputs and improved economic performance. However, as WT size continues to increase, several technical and economic challenges emerge, including higher blade mass, increased structural loads, transportation and installation difficulties, and more demanding maintenance requirements. These factors can significantly increase manufacturing and operational costs, partially offsetting the economic benefits of larger turbines. Consequently, although large SRWTs can achieve lower energy costs under favorable conditions, excessive scaling may eventually lead to diminishing economic returns and greater engineering complexity. Table 2 represents the cost of electricity produced for different turbine size ranges in a wind system based on SRWTs [28].

The results presented in Table 2 demonstrate a clear relationship between WT size and the cost of electricity generation. Small-scale wind turbines in the range of 1 to 20 kW exhibit the highest electricity production costs, ranging from $0.20 to 0.40/kWh, mainly due to lower energy output and reduced economies of scale. As WT capacity increases, the cost of generated electricity decreases significantly. Medium-scale turbines between 20 and 200 kW produce electricity at a lower cost of approximately $0.12 to 0.20/kWh, while larger systems in the range of 200 to 1500 kW further reduce costs to about $0.08 to 0.15/kWh. The lowest electricity generation costs are observed for large utility-scale

WTs with capacities between 1.0 and 3.0 MW, where the cost ranges from $0.07 to 0.12/kWh. These results indicate that increasing WT size generally improves economic efficiency due to higher energy capture capability, better operational efficiency, and reduced cost per unit of generated power. However, very large WT systems may also introduce additional structural, transportation, and maintenance challenges that must be considered in practical applications.

Table 2. Cost of electricity produced for different WT size ranges [28]

Turbine Size	Cost of Electricity Produced per kilowatt-hour (kWh)
1 to 20 kW	$0.20 to 0.40/kWh
20 to 200 kW	$0.12 to 0.20/kWh
200 to 1500 kW	$0.08 to 0.15/kWh
1.0 to 3.0 MW (1 to 5 turbines)	$0.07 to 0.12/kWh

Table 3 represents the WE density categories for SRWTs [28]. The results presented in the table demonstrate the strong relationship between WE density, wind speed, and measurement height. As the WE class increases from Class 1 to Class 7, both wind speed and WE density rise significantly, indicating improved WE potential. Lower wind classes, such as Classes 1 and 2, are characterized by relatively low wind speeds and power densities, making them more suitable for small-scale or low-power WE applications. In contrast, higher classes, particularly Classes 5 to 7, exhibit substantially greater wind speeds and power densities, which are highly favorable for large-scale commercial WE generation and offshore wind farms.

The table also shows that WE density increases with elevation height. At 10 m, the WE density ranges from 100 W/m² for Class 1 to 1000 W/m² for Class 7, whereas at 50 m it increases from 200 W/m² to 2000 W/m². Similarly, wind speed rises consistently with height due to reduced surface friction and turbulence effects. This confirms that taller WT towers can access stronger and more stable wind resources, thereby increasing energy production efficiency and reducing the cost of generated electricity.

Overall, the results highlight the importance of site selection, tower height optimization, and wind resource assessment in the design and deployment of efficient WE systems. High WE density regions are particularly attractive for utility-scale wind farms and advanced technologies such as MRWT systems, which can maximize energy extraction under strong and stable wind conditions.

Wind power density has a direct and significant relationship with the dimensions of SRWTs and the amount of electrical energy they can generate. Wind power density represents the available wind energy per unit area and depends mainly on wind speed, which increases with height above ground level. Therefore, larger SRWTs with greater tower heights can access stronger and more stable wind resources, resulting in higher WE density and improved energy production. In addition, increasing the rotor diameter enlarges the swept area of the turbine, allowing the blades to capture a greater amount of kinetic WE. Since the extracted WE is proportional to the swept area and approximately proportional to the cube of wind speed, even small increases in rotor size and tower height can substantially increase power output.

For this reason, modern SRWT development has focused on increasing turbine dimensions to maximize annual energy production and reduce the levelized cost of electricity. However, larger turbine dimensions also lead to increased blade mass, higher structural loads, transportation difficulties, and more complex installation and maintenance operations. Consequently, although higher wind power density and larger turbine dimensions generally improve energy generation efficiency, they also introduce important engineering and economic challenges that must be carefully optimized in large-scale WE systems.

Table 3. Classes of wind power density[28]

WE Class	WE Density at 10 m (33ft)	Wind Speed	WE Density at 30 m (98 ft)	Wind Speed	WE Density at 50 m (164 ft)	Wind Speed
	W/ m²	m/s (ft)	W/m²	m/s (ft)	W/ m²	m/s (ft)
1	100	4.4 (9.8)	160	5.1 (11.4)	200	5.6 (12.5)
2	150	5.1 (11.5)	240	5.9 (13.2)	300	6.4 (14.3)
3	200	5.6 (12.5)	320	6.5 (14.6)	400	7.0 (15.7)
4	250	6.0 (13.4)	400	7.0 (15.7)	500	7.5 (16.8)

5	300	6.4 (14.3)	480	7.4 (16.6)	600	8.0 (17.9)
6	400	7.0 (15.7)	640	8.2 (18.3)	800	8.8 (19.7)
7	1000	9.4 (21.1)	1600	11.0 (24.7)	2000	11.9 (26.6)

2.2 Emergence of Multi-Rotor Wind Turbines

MRWT concepts date back several decades but have recently regained attention due to advances in materials science, control systems, and distributed power electronics. Early designs proposed arrays of small turbines mounted on lattice structures. Contemporary MRWT systems typically consist of multiple coordinated rotors operating collectively to achieve power outputs comparable to a single large WT [29].

Researchers argue that MRWTs benefit from favorable scaling effects because smaller rotors experience lower bending moments and reduced structural stresses. Smaller blades can also be manufactured using existing infrastructure and transported using conventional logistics systems [30].

3. Technical Characteristics of Multi-Rotor Wind Turbines

3.1 System Architecture

Multi-Rotor WTs are characterized by an external configuration that consists of several smaller rotors mounted on a common support structure instead of using a single large rotor as in conventional WTs (See Figure 3). The overall structure may include multiple nacelles, rotor hubs, generators, and support frames integrated on a single tower or lattice structure. The principal mechanical components of MRWT systems include multiple rotor blades, hubs, shafts, generators, support arms, yaw mechanisms, pitch control systems, and a central structural platform. Unlike conventional SRWTs, which rely on one very large rotor and nacelle assembly, MRWTs distribute aerodynamic and structural loads across several smaller units.

Compared with SRWTs, MRWT systems generally have smaller individual rotor diameters and lighter blade components, which simplifies transportation, manufacturing, and installation processes. In terms of dimensions, the total swept area of MRWTs can be equivalent to or larger than that of conventional WTs while avoiding the excessive blade lengths required in very large SRWTs. Economically, MRWTs may reduce certain costs related to logistics, maintenance, and material usage through modular construction; however, they may also require additional investment due to the larger number of generators, control units, and structural connections. From a mechanical perspective, MRWTs contain more distributed components and interconnected subsystems than SRWTs, leading to increased structural and aerodynamic complexity. Furthermore, the control system of MRWTs is generally more sophisticated because it must coordinate multiple rotors simultaneously while minimizing aerodynamic interactions and load fluctuations. Despite these challenges, MRWT technology offers promising advantages in scalability, redundancy, maintenance flexibility, and offshore deployment potential compared with traditional SRWT systems.

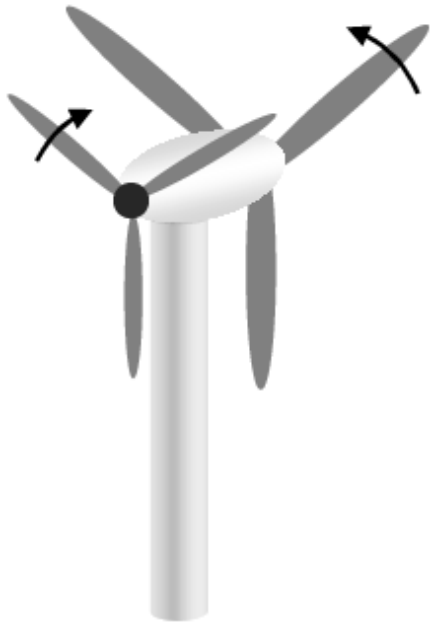

Figure 3. MRWT.

3.2 Aerodynamic Principles

The aerodynamic operation of MRWTs differs fundamentally from SRWTs because rotor interactions create complex wake effects. Rotor spacing, orientation, and synchronization significantly influence performance. Studies indicate that wake interactions may accelerate wake recovery and improve downstream WT efficiency under certain conditions [31].

Potential aerodynamic advantages include:

- Faster wake recovery;
- Reduced turbulence intensity;
- Improved farm-level efficiency;

- Enhanced control flexibility.

However, poorly optimized rotor arrangements may increase turbulence and reduce net power output.

3.3 Structural Considerations

MRWT structures distribute loads across multiple rotors rather than concentrating them on one hub. This distribution can reduce peak blade stresses and potentially extend component lifetimes. Nonetheless, support structures become more complex and may require sophisticated dynamic load management systems [32].

Critical structural issues include:

- Tower vibration;
- Rotor synchronization;
- Aeroelastic instability;
- Fatigue loading;
- Dynamic coupling effects.

Advanced control systems are therefore essential for reliable MRWT operation.

Multi-rotor WTs can be classified according to their WE density, which refers to the amount of electrical power generated per unit swept area or land area occupied. A possible classification is summarized in Table 4.

Table 4. Classification of MRWT systems based on WE density and typical applications

Class	Power Density Range	Characteristics	Typical Applications
Low Power Density MRWTs	< 200 W/m²	Small rotor systems with lower energy capture efficiency; generally used for small-scale or decentralized applications	Rural electrification, microgrids, residential systems
Medium Power Density MRWTs	200–400 W/m²	Balanced performance between energy production and structural complexity; moderate rotor interaction effects	Commercial wind farms, distributed generation
High Power Density MRWTs	> 400 W/m²	Optimized aerodynamic layouts with enhanced energy extraction and compact land utilization	Offshore wind farms, utility-scale renewable energy systems

In MRWT systems, power density is influenced by several factors, including rotor spacing, aerodynamic interaction, wake effects, tower configuration, and control strategies. Compared with conventional SRWTs, MRWTs may achieve higher effective power density because multiple rotors can utilize the available wind field more efficiently while reducing structural scaling limitations associated with extremely large blades. This characteristic makes MRWT technology particularly attractive for offshore installations and regions where land availability or transportation constraints limit the deployment of very large conventional turbines.

4. Environmental Sustainability Impacts

4.1 Carbon Emissions and Lifecycle Assessment

WE generally exhibits substantially lower greenhouse gas emissions than fossil-fuel-based electricity generation. Lifecycle assessments (LCAs) indicate that WTs produce low carbon emissions over their operational lifetimes [33].

MRWTs may further reduce lifecycle emissions through:

- Lower material intensity;
- Reduced transportation emissions;
- Improved manufacturing efficiency;
- Easier maintenance access;
- Enhanced recyclability of smaller components.

Smaller blades may require less composite material and enable alternative recyclable materials that are difficult to implement in extremely large SRWT blades.

4.2 Material Use and Resource Efficiency

Large SRWT blades are typically manufactured using advanced composite materials such as fiberglass and carbon-fiber-reinforced polymers, which provide high strength-to-weight ratios but remain difficult to recycle using conventional methods. As a result, blade disposal has become an increasingly important sustainability challenge within the WE sector, particularly as the number of decommissioned

WTs continues to grow worldwide. Current end-of-life practices, such as landfilling or energy-intensive thermal processing, raise environmental concerns and highlight the need for more sustainable material management strategies.

In this context, MRWT systems may offer improved material sustainability due to their inherently modular design. Smaller blades used in MRWT configurations are generally easier to transport, process, and recycle compared with the very large blades used in SRWTs. In addition, the manufacturing of smaller components can potentially reduce production defects and material waste, contributing to more efficient resource utilization. The modular architecture also enables partial replacement of individual rotor units, which can significantly reduce total material demand over the WT lifetime.

Furthermore, the use of standardized components in MRWT systems can enhance opportunities for reuse, remanufacturing, and recycling, thereby supporting circular economy principles in WE infrastructure. The system-level modularity of MRWTs may also facilitate maintenance, repair, and refurbishment operations, reducing the need for complete WT replacement and extending overall operational lifespan. Consequently, MRWT technology represents a promising pathway toward improving the environmental sustainability and lifecycle efficiency of future WE systems.

4.3 Land Use and Ecological Impacts

Wind farms inevitably affect surrounding ecosystems through habitat alteration, noise generation, and bird and bat collisions. Public concerns often focus on visual intrusion and wildlife mortality.

MRWTs could influence ecological impacts in several ways:

- Positive Effects
- Smaller individual rotors may reduce wildlife collision severity;
- Distributed wakes may reduce atmospheric disturbance;
- Lower tower heights may decrease visual dominance.
- Negative Effects
- Increased rotor count may increase collision probability;

More moving components may create additional acoustic emissions;

- Structural complexity could enlarge maintenance footprints.
- Comprehensive ecological studies specific to MRWTs remain limited.

4.4 Noise Pollution

Aerodynamic and mechanical noise are recognized as significant social and environmental concerns in WE projects, as they can affect nearby communities, wildlife, and overall public acceptance of wind farms. In conventional SRWTs, noise is primarily generated by blade–air interaction, wake turbulence, mechanical components in the nacelle, and tower interaction effects. However, in MRWT systems, the presence of multiple interacting rotors introduces additional complexity to the acoustic behavior, potentially resulting in unique and less predictable noise signatures compared with traditional WT configurations. These interactions may lead to variations in tonal noise, broadband noise levels, and phase-dependent acoustic fluctuations, especially under changing wind conditions and rotor synchronization states.

Current literature indicates that empirical and field-based studies on MRWT noise generation remain limited, particularly at large-scale or operational conditions. Most existing analyses are based on numerical simulations or small-scale prototypes, which may not fully capture real-world acoustic behavior. Therefore, further investigation is required to understand the environmental and social implications of MRWT acoustic emissions.

Future research should focus on several key aspects, including low-frequency noise propagation and its long-range environmental impact, the effects of rotor synchronization and phase interaction on sound intensity, community noise perception and acceptability thresholds, and the specific characteristics of offshore acoustic impacts in marine environments. In addition, integrated studies combining aeroacoustic modeling, experimental measurements, and human perception analysis are essential to develop accurate noise prediction tools and to ensure compliance with future environmental regulations.

5. Economic Sustainability

5.1 Levelized Cost of Energy (LCOE)

Reducing LCOE remains a primary objective for RE technologies. MRWT proponents argue that distributed rotor systems may lower both capital expenditures (CapEx) and operational expenditures (OpEx).
Potential economic advantages include:

- Lower manufacturing costs;
- Reduced transport expenses;
- Easier installation;
- Modular maintenance;
- Improved reliability through redundancy.

However, empirical evidence supporting major LCOE reductions remains inconclusive due to limited commercial deployment.

5.2 Manufacturing and Supply Chain Benefits

MRWTs may help mitigate several supply-chain and logistics bottlenecks that are commonly associated with the manufacturing, transportation, and installation of very large SRWT blades. As WT sizes continue to increase, conventional systems often require specialized factories, oversized transport vehicles, reinforced road networks, and heavy-lift cranes, all of which significantly increase project complexity and capital investment. In contrast, MRWT systems rely on multiple smaller rotor units and components that can be produced using existing manufacturing facilities without the need for extensive industrial upgrades [33].

This modular approach offers several operational and economic advantages, including more efficient use of existing production infrastructure, simplified shipping and handling procedures, and reduced dependency on ultra-heavy lifting equipment during installation. The use of smaller components also lowers transportation risk, decreases the likelihood of damage during logistics operations, and enhances flexibility in assembly and maintenance processes. In addition, installation activities can be performed with lighter cranes and less specialized offshore vessels, which can significantly reduce project costs and improve deployment feasibility.

Furthermore, these characteristics make MRWT technology particularly attractive for developing economies or regions with limited heavy industrial infrastructure, where the deployment of large-scale SRWTs may be constrained by logistical and financial barriers. By lowering entry requirements for manufacturing and installation, MRWT systems may contribute to a more distributed and accessible global WE market, while also supporting faster expansion of RE capacity in emerging regions.

5.3 Maintenance and Reliability

Distributed rotor architectures in MRWT systems can significantly enhance operational resilience compared with conventional SRWTs. In such configurations, energy production is shared among multiple independent rotor units, meaning that the failure or shutdown of a single rotor does not necessarily result in a complete system outage. This inherent redundancy can reduce total downtime, improve energy availability, and increase overall system robustness, particularly in remote or offshore environments where maintenance access is limited. Moreover, modular replacement strategies allow damaged rotor units or subcomponents to be individually repaired or replaced without requiring full turbine disassembly, thereby simplifying maintenance procedures and reducing operational disruption.

However, despite these advantages, the increase in the number of mechanical and electrical components introduces additional challenges. A higher component count leads to more potential failure points, which may increase the probability of subsystem malfunctions over the turbine's lifetime. In addition, coordinating multiple rotors requires more advanced control strategies to manage aerodynamic interactions, load balancing, and power synchronization, thereby increasing overall control-system complexity. This also results in greater demands for real-time monitoring, condition assessment, and predictive maintenance systems to ensure safe and efficient operation.

Consequently, reliability optimization remains a key research priority for MRWT development. Future work should focus on improving fault-tolerant control algorithms, enhancing sensor integration, developing advanced diagnostic techniques, and optimizing system architecture to balance redundancy benefits with increased system complexity.

6. Social Sustainability Dimensions

6.1 Public Acceptance

Social acceptance strongly influences RE deployment success. WE projects frequently encounter opposition related to visual impacts, noise concerns, and environmental perceptions.

MRWTs may alter public perception due to:

- Different visual profiles;
- Lower structure heights;
- Perceived technological innovation.

owever, communities may also express concern regarding:

- Increased rotor density;
- Novel technology uncertainty;
- Maintenance traffic and infrastructure expansion.

Public engagement and transparent environmental assessment remain essential.

6.2 Employment and Economic Development

WE development contributes to employment in manufacturing, construction, operation, and maintenance sectors. MRWTs could expand economic opportunities through decentralized manufacturing and modular assembly processes.

Potential employment benefits include:

- Localized blade production;
- Expanded maintenance services;
- Distributed supply-chain participation;
- Increased technical training opportunities.

Such benefits may support regional economic diversification and green industrialization strategies.

6.3 Energy Equity and Accessibility

The modularity of MRWT systems can significantly improve the accessibility and feasibility of RE deployment in regions where infrastructure is insufficient to support the transportation and installation of extremely large SRWTs. In many developing countries, remote areas, and island communities, limitations such as narrow roads, weak bridges, limited port capacity, and lack of heavy-lift equipment often restrict the installation of large-scale WE systems. MRWTs, which rely on multiple smaller and more manageable components, can be transported using conventional logistics networks and assembled on-site with less specialized infrastructure and lower technical requirements.

This increased accessibility has several important implications. First, it can accelerate the deployment of RE systems by reducing logistical barriers and shortening project implementation timelines. Second, it can decrease dependence on imported fossil fuels by enabling local energy generation, thereby improving economic resilience and reducing exposure to volatile fuel prices. Third, MRWT systems can support rural electrification initiatives by providing scalable and adaptable power solutions for off-grid or weak-grid regions. Finally, by diversifying energy supply sources and enabling decentralized generation, these systems can enhance national and regional energy security.

In addition, MRWT technology may encourage local industrial participation through the use of standardized and smaller components that can be manufactured or assembled locally, fostering job creation and technology transfer. As a result, MRWTs represent a promising pathway for expanding equitable access to clean energy while supporting sustainable development goals in both emerging and underserved regions.

The cost of electricity produced by MRWT systems is expected to become increasingly competitive with that of conventional SRWTs, particularly for large-scale and offshore applications. MRWTs aim to reduce the LCOE by distributing power generation across multiple smaller rotors instead of relying on a single very large rotor. This configuration can lower manufacturing, transportation, and installation costs because smaller blades and modular components are easier to produce, transport, and maintain using existing infrastructure. In addition, MRWT systems may reduce structural loads on towers and floating platforms, potentially decreasing material consumption and maintenance expenses over the WT lifetime.

Compared with conventional SRWTs, which often require expensive heavy-lift equipment, specialized transportation systems, and large manufacturing facilities for oversized blades, MRWTs may offer improved economic flexibility and scalability. However, MRWT systems also introduce additional costs related to more complex control systems, multiple generators, increased component counts, and aerodynamic interaction management. As a result, their short-term costs may still be comparable to or slightly higher than those of mature SRWT technologies. Nevertheless, future technological advances in control strategies, modular manufacturing, predictive maintenance, and offshore engineering are expected to improve MRWT efficiency and reliability, thereby reducing operational costs over time.

From a long-term perspective, MRWTs have strong future potential, especially in offshore wind farms, deep-water floating platforms, and regions with transportation infrastructure limitations. Their modular architecture, redundancy capability, and compatibility with circular economy principles may contribute to lower lifecycle costs and improved sustainability. Consequently, with continued research, industrial optimization, and large-scale demonstration projects, MRWT systems could become a cost-effective and strategically important component of future RE systems.

7. Offshore Applications and Floating Multi-Rotor Systems

7.1 Offshore Wind Expansion

Offshore WE represents one of the fastest-growing sectors within the global RE landscape, driven by increasing demand for clean electricity and the availability of vast wind resources over open seas. Offshore environments generally provide stronger, more stable, and more consistent wind regimes compared with onshore locations, which significantly enhances energy production potential and capacity factors. However, these advantages are accompanied by substantial engineering, economic, and environmental challenges, including harsh marine conditions, corrosion, wave and current loading, complex installation procedures, and high operation and maintenance costs [33].

In this context, floating offshore wind systems have emerged as a highly promising solution, particularly for deep-water regions where fixed-bottom foundations are technically or economically infeasible. Floating platforms enable WTs to

be deployed in deeper waters with higher wind speeds and reduced visual and coastal impact. Nevertheless, these systems introduce additional challenges related to dynamic stability, mooring system design, power cable fatigue, and long-term structural reliability. Advanced control strategies, improved materials, and innovative structural designs are therefore essential to ensure safe and efficient operation. As technology continues to mature, offshore wind energy is expected to play a central role in large-scale RE expansion, especially when combined with next-generation turbine concepts such as multi-rotor configurations.

7.2 Advantages of Offshore MRWTs

MRWTs may offer several unique advantages for offshore applications compared to conventional SRWT systems. One of the most significant benefits is the reduction of transportation constraints, as smaller rotor blades and modular components are considerably easier to manufacture, handle, and transport to offshore sites than very large single blades, which often require specialized vessels and infrastructure. In addition, the distributed rotor configuration can contribute to lower concentrated structural loads on floating or fixed offshore platforms, potentially reducing foundation size, material requirements, and overall structural cost.

Another important advantage is improved system stability, as the distributed mass of multiple rotors may help balance aerodynamic forces and reduce dynamic pitching and rolling motions in floating offshore environments. This distributed architecture also enhances redundancy, since the partial failure of one rotor does not necessarily lead to complete system shutdown, which is particularly valuable in harsh and inaccessible marine conditions where maintenance operations are costly and weather-dependent. Furthermore, the modular nature of MRWT systems can simplify offshore installation, assembly, and maintenance logistics by enabling stepwise deployment and easier replacement of individual rotor units.

Overall, these characteristics suggest that MRWTs could improve operational reliability and reduce certain logistical and structural challenges associated with offshore WE systems, while also enabling more flexible design strategies for future large-scale offshore wind farms.

7.3 Environmental Concerns Offshore

Offshore deployment of MRWT systems may generate several environmental and ecological impacts that require comprehensive assessment and long-term monitoring. These impacts can affect marine ecosystems through seabed disturbance during foundation installation, habitat modification, and changes in local hydrodynamic conditions. In addition, underwater acoustics generated during construction, operation, and maintenance activities may influence marine mammals, fish populations, and other sensitive aquatic species. The presence of large offshore MRWT structures may also alter bird migration routes and increase collision risks for migratory birds and bats, particularly in ecologically sensitive coastal regions.

Furthermore, offshore wind installations can influence fisheries, shipping routes, and marine navigation activities by restricting access to certain sea areas or modifying maritime traffic patterns. The larger spatial footprint associated with some MRWT configurations may require additional marine planning and environmental management strategies to minimize conflicts with existing ocean activities.

Lifecycle assessment studies indicate that offshore wind systems generally possess higher embodied carbon emissions and environmental impacts compared with onshore systems due to the substantial marine infrastructure required, including floating platforms, subsea cables, specialized foundations, offshore substations, and heavy installation vessels. Additional energy consumption associated with offshore transportation, maintenance logistics, and corrosion protection systems also contributes to increased lifecycle emissions and operational complexity [33]. Nevertheless, despite these challenges, offshore MRWT systems remain highly attractive because of the stronger and more stable wind resources available offshore, which can significantly enhance long-term energy production and reduce greenhouse gas emissions during operational life. Therefore, future MRWT development should integrate advanced environmental assessment methodologies, sustainable offshore engineering practices, and ecological mitigation strategies to ensure environmentally responsible deployment.

8. Lifecycle and Circular Economy Considerations

8.1 End-of-Life Challenges

Blade disposal has become one of the major sustainability challenges facing the modern WE industry, particularly due to the widespread use of composite materials such as fiberglass and carbon-fiber-reinforced polymers in WT blade manufacturing. These materials provide high mechanical strength and low weight; however, they remain difficult and costly to recycle using conventional industrial processes. As WTs reach the end of their operational lifetime, the accumulation of decommissioned blades creates increasing environmental and waste-management concerns. Current disposal methods, including landfilling and incineration, are

not fully consistent with long-term sustainability and circular economy objectives.

MRWT systems may provide important advantages for end-of-life management and material sustainability because they utilize multiple smaller blades instead of a few extremely large blades, as in conventional SRWTs. Smaller blades generally require less raw material, are easier to transport and process, and can simplify dismantling and recycling operations [32]. In addition, the modular architecture of MRWT systems facilitates partial refurbishment and selective component replacement, reducing the need for complete system disposal. This modularity may also support remanufacturing and reuse strategies within circular manufacturing frameworks.

Furthermore, smaller blade dimensions may enable the adoption of alternative recyclable materials and advanced recovery technologies that are more difficult to implement in very large blades. Future MRWT development should therefore emphasize eco-design strategies, recyclable composite materials, and sustainable end-of-life management approaches to minimize environmental impact and improve the overall lifecycle sustainability of WE systems.

8.2 Circular Economy Potential

The circular economy concept emphasizes sustainable resource utilization through strategies such as reducing material consumption, extending product lifespan, reusing components, repairing damaged systems, and improving recycling efficiency. MRWT systems exhibit strong potential to align with several important circular economy principles due to their modular and distributed architecture. Unlike conventional SRWTs, MRWTs consist of multiple smaller rotor units and interconnected subsystems that can facilitate modular component replacement, standardized manufacturing processes, easier maintenance operations, and simplified system upgrading.

The modular configuration of MRWTs may also improve repairability and refurbishment opportunities, since damaged or degraded rotor units can potentially be replaced individually without requiring the shutdown or replacement of the entire WT system. In addition, the use of smaller components may simplify transportation, dismantling, remanufacturing, and end-of-life recycling processes. These characteristics could contribute to reducing material waste, lowering maintenance costs, and extending the operational lifespan of WE systems.

Furthermore, future MRWT development should prioritize the integration of recyclable and environmentally friendly materials, particularly in blades, support structures, and electrical components. Design-for-disassembly strategies should also be incorporated during the early design stages to facilitate component separation, reuse, and recycling at the end of the WT lifecycle. Advanced monitoring systems, predictive maintenance techniques, and digital lifecycle management tools may further enhance the sustainability and circularity of MRWT technologies. Consequently, MRWT systems have the potential to support the transition toward more sustainable and resource-efficient WE infrastructures within future circular economy frameworks.

9. Policy and Regulatory Implications

9.1 Policy Support Mechanisms

Government incentives remain essential for emerging renewable technologies. MRWT commercialization may require:

- Research funding;
- Demonstration projects;
- Grid integration support;
- Offshore infrastructure investments.

Policies promoting sustainable manufacturing and recyclable materials may particularly benefit MRWT adoption.

9.2 Standardization and Certification

Existing WT certification frameworks and international design standards have been primarily developed for conventional SRWT systems. Consequently, the large-scale deployment of MRWT technologies will require the development of updated certification procedures and regulatory guidelines specifically adapted to their unique structural and operational characteristics. These new standards should address several critical aspects, including aerodynamic interactions between multiple rotors, distributed structural load management, fatigue and vibration assessment, coordinated control system reliability, electrical synchronization, and fault-tolerant operational strategies. In addition, dedicated safety protocols must be established to evaluate emergency shutdown procedures, rotor redundancy behavior, maintenance accessibility, and offshore operational risks. Noise assessment methodologies should also be revised, since the acoustic characteristics of MRWT systems may differ significantly from those of conventional turbines due to the presence of multiple interacting rotors. Furthermore, environmental impact assessment procedures should consider wake interactions, visual impact, and ecological effects specific to MRWT configurations. The establishment of internationally recognized standards and certification frameworks will play a crucial role in improving technology

reliability, facilitating industrial commercialization, increasing investor confidence, and accelerating the market acceptance of MRWT systems within future sustainable energy infrastructures.

10. Research Gaps and Future Directions

Current MRWT research remains fragmented across aerodynamics, structural mechanics, and sustainability assessment. Key knowledge gaps include:

10.1 Aerodynamic Optimization

Further experimental, numerical, and field-based investigations are required to comprehensively understand the complex aerodynamic and system-level behavior of MRWT configurations. One of the key aspects that needs deeper analysis is rotor spacing effects, as the distance between individual rotors significantly influences aerodynamic efficiency, load distribution, and structural stability. Closely spaced rotors may experience increased flow interference, while optimally spaced configurations could enhance overall energy capture and reduce detrimental interactions.

Another critical area is wake interaction phenomena, where the overlapping wakes generated by multiple rotors can lead to complex turbulence structures, reduced downstream performance, and increased fatigue loading. Understanding these interactions is essential for improving both single-WT performance and array-level efficiency. In addition, farm-level optimization strategies must be developed to determine optimal layout designs, control coordination methods, and power management approaches for large-scale MRWT wind farms, particularly in offshore environments.

Furthermore, detailed studies on turbulence behavior are necessary to accurately model unsteady wind conditions and their impact on MRWT systems. This includes the characterization of atmospheric turbulence effects, rotor-induced turbulence amplification, and their influence on structural loads and control stability. Advanced high-fidelity simulations, wind tunnel experiments, and full-scale field measurements will be essential to validate theoretical models and improve design reliability. Overall, addressing these research gaps is crucial for the successful commercialization and large-scale deployment of MRWT technologies.

10.2 Lifecycle Sustainability Assessment

Comprehensive life cycle assessment (LCA) studies comparing MRWTs and SRWTs remain limited in the current literature, particularly for large-scale and offshore applications. As MRWT technology is still in an emerging stage, most existing analyses are based on theoretical models or simplified assumptions, which do not fully capture real-world operational conditions, supply chain complexities, and long-term environmental effects. Therefore, more detailed and standardized LCA frameworks are required to accurately evaluate the overall sustainability performance of both technologies across their entire life cycle, from raw material extraction to end-of-life management.

Future research should specifically assess embodied carbon emissions associated with manufacturing, transportation, installation, and maintenance activities, taking into account the potential reduction in material usage and logistics requirements offered by MRWT modular designs. In addition, material circularity should be evaluated in terms of recyclability, reuse potential, remanufacturing opportunities, and the integration of sustainable composite materials. End-of-life scenarios also require deeper investigation, including dismantling processes, waste management strategies, blade recycling technologies, and potential landfill impacts, particularly for composite materials.

Moreover, ecosystem impacts must be systematically analyzed, including land use changes, marine and terrestrial habitat disturbances, wildlife interactions, and cumulative environmental effects at wind farm scale. Comparative assessments should also incorporate operational performance indicators such as energy yield, capacity factor, and system reliability to provide a holistic sustainability perspective. Ultimately, developing harmonized and comprehensive LCA methodologies will be essential to fairly compare MRWT and SRWT systems and to support evidence-based decision-making for future WE deployment.

10.3 Acoustic and Ecological Studies

Further multidisciplinary research is required to fully assess the environmental and societal implications of WE systems, particularly emerging MRWT technologies. One important area of investigation is wildlife interactions, including the potential impacts on birds and bats through collision risks, habitat disturbance, and changes in migration patterns, especially in regions located along major ecological corridors. In addition, more detailed studies are needed on noise generation, including both aerodynamic and mechanical sources, as well as the propagation of low-frequency and infrasound components that may vary in MRWT configurations compared with conventional WTs.

Another critical aspect concerns potential human health impacts, particularly for populations living near wind farms. These include long-term exposure to noise, shadow flicker effects, and possible psychological responses related to visual and acoustic presence. Although current evidence generally supports the safety of WE systems, more high-resolution

epidemiological studies are necessary to better understand long-term effects under different operational conditions.

Furthermore, offshore ecosystem effects require in-depth analysis, including the influence of WT installations on marine habitats, seabed disturbance, underwater noise impacts on marine mammals and fish, and changes in local ecological dynamics. Cumulative impacts from large-scale offshore wind farms, especially those involving MRWT configurations, remain insufficiently understood. Therefore, integrated environmental assessment approaches combining ecological modeling, field observations, and long-term monitoring are essential to ensure sustainable and environmentally responsible WE development.

10.4 Commercial Demonstration

Large-scale pilot projects are essential to bridge the gap between theoretical studies, numerical simulations, and real-world deployment of WE systems, particularly for emerging MRWT technologies. Such demonstration projects are required to validate key economic assumptions, including CAPEX, operational expenditure (OPEX), LCOE, and long-term return on investment under realistic operating conditions. In addition, they are crucial for assessing reliability performance over extended periods, including component durability, failure rates, fatigue behavior, and system resilience under variable wind and harsh environmental conditions.

Pilot-scale implementations are also necessary to accurately determine maintenance requirements, such as inspection intervals, replacement strategies, logistics planning, and the effectiveness of condition monitoring and predictive maintenance systems. Furthermore, these projects play a critical role in evaluating grid integration feasibility, including power quality, voltage and frequency stability, control coordination with existing power systems, and compliance with grid codes, especially in offshore and weak-grid scenarios.

Beyond these technical aspects, large-scale pilot projects provide valuable data on environmental impact, operational safety, and public acceptance, which are often difficult to capture through simulations alone. Therefore, coordinated demonstration initiatives are indispensable for reducing technological uncertainty, improving design standards, and accelerating the commercial readiness and industrial adoption of advanced WE systems such as MRWTs.

11. Discussion

Multi-rotor WT technology represents a significant evolution in WE systems, offering a fundamentally different design philosophy compared to conventional SRWTs. Instead of relying on a single large rotor, MRWTs distribute aerodynamic energy capture across multiple smaller rotors mounted on a shared structure. This configuration has the potential to improve scalability and reduce several engineering constraints associated with very large rotor diameters, such as excessive blade mass, transportation difficulties, and structural loading on the tower.

From a sustainability and systems perspective, MRWTs may contribute to improved material utilization and reduced logistical impact due to the use of smaller, modular components that are easier to manufacture, transport, and assemble. This modularity also enhances maintainability, as individual rotor units can potentially be repaired or replaced without shutting down the entire system. Furthermore, MRWT designs may align more effectively with circular economy principles by enabling component reuse and simplified end-of-life disassembly strategies.

However, despite these advantages, several critical challenges limit current development and deployment. Aerodynamic interactions between closely spaced rotors can lead to complex wake effects, reduced efficiency, and increased unsteady loading, requiring advanced modeling and control strategies. In addition, structural integration of multiple rotors introduces new design constraints related to vibration, fatigue, and load distribution. The lack of extensive full-scale experimental deployments further limits confidence in long-term performance predictions and sustainability claims. Moreover, increasing the number of rotors may introduce additional environmental considerations, including noise distribution patterns and potential ecological impacts, which remain insufficiently studied.

Overall, MRWT systems should be considered as complementary rather than fully substitutive to SRWT technologies. Their most promising applications appear to be in offshore wind farms, floating platforms, and regions where transportation infrastructure limits the feasibility of ultra-large WT blades.

12. Conclusion

Multi-rotor WTs represent a promising direction for the advancement of WE technology, particularly in addressing several structural, logistical, and scalability limitations associated with conventional SRWTs. The reviewed literature demonstrates that MRWT systems can potentially enhance material efficiency, simplify transportation and installation processes, and provide improved modularity in both design and maintenance operations. These characteristics may also support broader sustainability goals, including reduced

lifecycle environmental impacts and better alignment with circular economy strategies.

In addition, MRWT configurations offer new opportunities for innovation in aerodynamic design, distributed power generation, and fault-tolerant system architectures. When combined with modern control techniques and intelligent monitoring systems, MRWTs may achieve improved operational flexibility and resilience under variable wind conditions.

Nevertheless, the technology is still in an early developmental and validation stage. Significant challenges remain in areas such as rotor-to-rotor aerodynamic interaction modeling, structural reliability under complex loading conditions, noise and environmental impact assessment, and large-scale economic feasibility. Current research is still limited by the scarcity of long-term field data and full-scale experimental implementations, which restricts the ability to fully confirm theoretical advantages.

Future development of MRWT systems will require interdisciplinary collaboration across aerodynamics, structural engineering, control systems, materials science, and environmental assessment. Advances in high-fidelity simulation tools, artificial intelligence-based control strategies, and offshore engineering technologies are expected to play a key role in overcoming existing limitations. With continued research and appropriate technological and policy support, MRWTs have the potential to become a valuable complement to existing WE technologies and contribute meaningfully to global sustainable energy transitions.

Nomenclature

WE	Wind energy
MRWT	Multi-rotor wind turbine
SRWT	Single-rotor wind turbine
WT	Wind turbine
OPEX	Operational expenditure
RE	Renewable energy
VAWT	Vertical Axis Wind Turbine
LCOE	Levelized cost of energy
LCA	Lifecycle assessments
LCOE	Levelized Cost of Energy
OPEX	Operational expenditures
CAPEX	Capital expenditures
SMC	Sliding mode control

Funding: Not applicable.

Data Availability: Data available on request from the authors. The datasets used and/or analysed during the current study available from the corresponding author on reasonable request. In the event of communication, the fist author (Habib Benbouhenni, E-mail: [h.benbouhenni@univ-chlef.dz](mail to: h.benbouhenni@univ-chlef.dz)) will respond to any inquiry or request**.**

Author Contributions:
Conceptualization, H.B.; methodology, H.B.; software, H.B.; validation, H.B.; formal analysis, H.B.; investigation, H.B.; resources, H.B.; data curation, H.B.; writing—original draft preparation, N.B.; writing—review and editing, H.B. ; visualization, H.B.; supervision, H.B.; project administration, H.B.; funding acquisition, H.B. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest: The authors declare no conflict of interest.

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