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Review

Wind-Assisted Propulsion Systems in the Carbon-Neutral Era: A Systematic Review of Multi-Modal Technologies

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Abstract: The global shipping industry faces substantial pressure to reduce greenhouse gas emissions to comply with the International Maritime Organization's stringent reduction policies. Consequently, wind-assisted propulsion systems (WAPs) have garnered extensive research interest due to their utilization of clean energy and the widespread availability of wind resources. However, previous reviews predominantly focused on literature published before 2020 or concentrated on single systems, lacking a systematic comparative analysis of multiple wind propulsion technologies. This review systematically examines WAPs, focusing on their development path, current status, and future trends. Our findings delineate three distinct developmental stages in WAPs research: aerodynamic fundamentals (2000–2015), performance optimization (2015–2020), and system integration (2021–present). Four main technologies dominate current research directions: rigid sails, Flettner rotors, kite systems, and hybrid configurations. With technological advancements, theoretical research has shifted from complex computational fluid dynamics toward systematic evaluations of the economic and environmental benefits of entire ship systems. Nevertheless, notable research gaps persist, including the absence of a comprehensive life cycle assessment framework, insufficient real-world operational data from commercial deployments, and inadequate maturity in control strategies for integrated systems. Ultimately, this review offers a comprehensive knowledge framework for researchers and practitioners, providing data-driven recommendations for technological advancement and carbon neutrality policy formulation.

Keywords: wind propulsion; green shipping; carbon neutrality; flettner rotor; rigid sail; kite system

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1. Introduction

Maritime shipping accounts for over 80% of global freight transportation in recent years because of its outstanding qualities: reliability, efficiency, and low cost. Some research recognized that increasing shipping demand conversely results in a significant environmental load. Data from international reports exhibited that about 2.9% of total global emissions were from shipping. This phenomenon emphasized the necessity for major international organizations to implement robust measures [1]. As a result, a phased plan was proposed to achieve net-zero greenhouse gas (GHG) emissions. These regulations offer guiding suggestions and indicators to decrease shipping emissions by half by 2050. These plans introduced the Carbon Intensity Indicator (CII) to monitor carbon emissions of every operator in 2023 and seek a 40% decrease by 2030 through effective methods [2, 3].

The strict emissions requirements impose a heavy burden on global shipping operators. In Europe, regional policies such as the inclusion of shipping in the European Union Emission Trading System (EU ETS) from 2024 and the implementation of Fuel EU Maritime in 2025 demand enterprises to apply reliable green shipping technologies. In

terms of market principles, carbon taxation and preferential green financing mechanisms promote enterprises to manage energy conservation and emissions reduction [4]. Driven by such demand, enterprises turn to pursue innovative technologies, thereby attracting researchers' interest.

With the development of environmental awareness, humans have proposed, explored, and applied various technologies for shipping emissions. Energy efficiency improvement is one of the most directed and effective approaches, including various aspects: hull form optimization, liquefied natural gas (LNG), wind-assisted propulsion systems (WAPs), and air lubrication systems (ALS). Table 1 shows a comprehensive comparison to exhibit their value: technology maturity, emissions reduction potential, and total investment. WAPs are also recognized as a convenient method for their compatibility with other measures. One study investigated an optimization combining WAPs and an optimal LNG solution, obtaining a 27% reduction in total GHG emissions. Considering its potential and relatively low cost, WAPs are attracting researchers' interest.

Table 1. Multimodal Comparison of Various Energy Efficiency Improvement Technologies

Technology	Hull Form Optimization	LNG	WAPs	ALP
Maturity a	TRL 9	TRL 7-8	TRL 6-8	TRL 5-6
Potential b	7-9%	5-20%	5-15%	10-15%
Investment	Minimum	Maximum	Slightly higher	Slightly lower

Technology Readiness Level (TRL) reflects maturity from history, application, difficulty, and other factors [5].

The technologies' abilities to reduce GHG emissions independently are comprehensively analyzed from several academic articles and applications.

The recognition of wind energy's potential is not new; in fact, its maritime application dates back millennia. Before the steam age, wind energy was widely used by humankind due to its wide distribution and easily accessible properties. Even by the mid-1920s, about a hundred sail cargo traders were still active on certain ocean-going routes, where they nearly matched steamers' speed [6]. Though sailing vessels were replaced by steamers because of the increasing economic effect by the second half of the 19th century, a brief revival during the 1970s oil crisis attracted increased attention. For instance, one study recorded a comprehensive comparison between various early WAPs, including wind turbines and kites, and investigated the coefficients of effective maximum forward driving force.

Since 2010, various WAPs technologies have been investigated and applied. At first, these studies focused on fuel reduction, which provides enhanced economic benefits. With the increasing requirements of carbon neutrality, WAPs show promising application prospects, thereby emerging as one of the mainstream perspectives to reduce GHG emissions. Early attempts mainly focused on traditional sails, while the E-ship 1 first applied the Flettner rotor in 2010, saving 15% of fuel and proving the feasibility of WAPs' design concept. In this period, other WAPs technologies also demonstrated good effects in reducing emissions. For instance, rigid sails applied in the Wind Challenger project showed a 30% reduction in carbon emissions. The International Maritime Organization (IMO) incorporated WAPs into the Energy Efficiency Existing Ship Index (EEXI) and highlighted their emission reduction benefits in 2024, offering clear guidance for WAPs' development. Recent years' computing power has seen a rapid increase [7, 8]. As a result, researchers proposed smart ship systems: applying various technologies via monitoring different routes, ship types, and wind conditions. Furthermore, Japan's "Wind Hunter" project realized a proposal to use wind energy to power ships and produce hydrogen energy by applying rigid sails [9, 10]. This application case offers novel and broad solutions for carbon neutrality.

Current WAPs reviews exhibit three critical limitations: The scope of most literature reviews remains pre-2022, leaving the latest breakthroughs in theories and applications uncovered. Most researchers rely on traditional qualitative insight without employing bibliometric analysis for quantitative research. Most reviews tend to focus on separate aspects, such as emphasizing aerodynamic performance or economics [11]. Yet few researchers analyze how these factors interact under real operational situations, such as ship data, crew capacity, and maintenance cycles. This oversight leaves decision-makers facing dilemmas in making informed trade-offs.

To address the aforementioned limitations, this review creates three primary contributions: Expanding the scope of literature citations to offer an up-to-date synthesis, including the most recent advancements up to 2025. Introducing a bibliometric analysis via CiteSpace to map the knowledge structure, evolution, and research frontiers of WAPs. Systematically analyzing data largely overlooked in prior studies, such as crew training, maintenance logistics, and real-world performance data, thereby enhancing the applicability of the findings for industry stakeholders [12].

This work fulfills three integrated research objectives as follows: Knowledge mapping objective—identifying research hotspot shifts and frontier research directions. Technology analysis objective—constructing a multi-dimensional technology assessment matrix [7, 13]. Application guidance objective—providing strategic recommendations for research and development, investment decision-making, and policy formulation.

The main body of this article is structured as follows: Section 2 establishes a three-dimensional analytical framework of "energy - control - integration." Section 3 elaborately constructs the historical development context of WAPs technology [14, 15]. Section 4 discusses each technology through critical comparison and paradigm evaluation. Section 5 concludes this research and provides suggestions for future exploration.

2. Technical Comparison and Analysis

This review proposes a three-dimensional analysis framework of "energy-control-integration" to systematically analyze various WAPs technologies. Table 2 identifies the two energy capture mechanisms (Lift-dominant type and Tension-driven type) and presents the most representative variables for the numerical simulation and experimental data of WAPs. Secondly, the classification of the System Control Paradigm explains the manipulability of each technology and reflects its emission reduction benefits [16]. Thirdly, the classification of the interaction level provides a reference for the practical application of these technologies.

Table 2. The "Energy-Control-Integration" three-dimensional analysis framework

Technology	Energy harvesting mechanism	System control paradigm	Integration level
Flettner rotor	Lift-dominant type	Active/feedback control	Integration
Rigid sail	Lift-dominant type	Passive/Mechanical control	Integration
Kite sail	Tension-driven type	Passive/Mechanical control	Addition
Hybrid system	Mixed type	Intelligent/Predictive control	Reconstruction

3. Historical Evolution of WAPs

3.1. Flettner Rotor

The Flettner rotor is based on the Magnus effect, a significant phenomenon discovered in 1851. A pressure difference is generated between the object's surfaces when

air flows past a rotating object, thereby inducing a lift force. In 1922, Anton Flettner first obtained a patent for the Flettner rotor in marine vessels. An experimental commercial ship, Buckau, shown in Figure 1, was built in 1924. However, due to historically low oil prices in the late 1920s, the economic advantage of diesel engines led to this technology being shelved [17].



Figure 1. Anton Flettner's first Rotor ship, the Buckau [15].

The sharp increase in oil prices precipitated by the 1970s energy crisis rekindled interest in wind energy. During this period, Bergeson's experiment on Tracker achieved remarkable results. Nevertheless, the subsequent fall in oil prices and the lack of market regulation led to the technology being neglected again [18, 19].

After 2005, an increase in fuel costs and growing public environmental awareness motivated researchers to explore the Flettner rotor again. Mittal and Kumar were among the first to deepen the theoretical research on the Magnus effect. In 2008, the E-ship 1 rotor ship, shown in Figure 2, adopted an integrated design, generating power through a turbine to drive four rotors. However, this design pattern also made it difficult to retrofit older ships. The academic community responded promptly, transitioning from theory to engineering applications, such as high Reynolds number and three-dimensional situations. After 2015, policy pressure from the IMO drove the hybrid system to become mainstream, including the rotor-hydrogen integration framework. Meanwhile, researchers systematically classified hybrid energy and propulsion frameworks, inspiring modern advancements in Flettner rotor technology. In 2025, the M/V Buran applied digital twin technology to optimize its route, marking the entry of the Flettner rotor into the intelligent stage.



Figure 2. E Ship 1 - Alchetron, The Free Social Encyclopedia [23]

3.2. Rigid Sail

Driven by the brief surge in global oil prices resulting from the oil crises of the 1970s, more engineers are devoting their research to different WAPs devices. In the late 1960s, the DynaRig was invented but remained at the conceptual stage and failed to achieve practical implementation. In the research upsurge of ocean wind energy-assisted propulsion, various novel technologies that are different from the past have been proposed [9, 20]. For instance, the Turbosail, which belongs to the rigid sail category, and the kite, which captures wind energy through lift, have also been applied to commercial vessels. However, with the fall in oil prices, this technology once again fell silent until the 20th century.

Since the 20th century, the rapid rise in oil prices and the enhanced environmental protection awareness of people have promoted the application of these WAPs technologies. The concept of engine-assisted sailboats (subsequently classified as WAPs) was proposed, and computational and structural validation methods were used to verify the aerodynamic performance and emission reduction capabilities of rigid sails. With the development of computing resources, a large number of innovative methods have been applied to the numerical simulation of rigid sails, such as Radial Basis Function (RBF), virtual wind tunnel, and advanced solvers.

Since 2020, the rigid sail technology path has been evolving simultaneously in both the high-end and commercial markets. Several concepts for large-scale vessels equipped with rigid sails have been proposed or implemented, such as the Orient Express Silenseas and M/V New Aden in Figure 3. With the development of numerical simulation technology, hybrid sail concepts have attracted attention due to their excellent aerodynamic performance in wind tunnel experiments, but they have not yet been applied to any commercial vessels [21, 22]. With the aid of more advanced Computational Fluid Dynamics (CFD) techniques, the research and application of rigid sails hold promising prospects.



Figure 3. M/V New Aden [31]

3.3. Kite Sail

The idea of using kites to reduce fuel consumption of ships by providing lift was patented as early as the 19th century by a British inventor. However, attempts to combine kites with watercraft mainly began in the 1970s. The development of the first-generation LEI (Leading Edge Inflatable) significantly enhanced the operability and relaunch ability of kites in water [23]. This is regarded as a key turning point in modern kite sail technology.

Although various LEI forms (e.g., Bow, Delta, Hybrid) were soon applied in surfing, due to the scale effect of large ships and the requirement for continuous stability, it was not until after 2005 that research on kite sails for these vessels began to develop widely. During this period, a large number of studies emerged, discussing the feasibility of the kite sail system through various approaches, such as computational fluid dynamics, theoretical analysis, and experiments, laying a solid foundation for its subsequent application.

After 2020, some large commercial vessels began to apply kite sails, and concepts such as "hybrid systems" and "integrated design" were proposed [24, 25]. Airseas, a maritime unit of Airbus, launched large kite propulsion solutions such as SeaWing in Figure 4 and collaborated with several shipping companies. Meanwhile, international institutions have conducted systematic assessments of kite sails, and their policies have promoted the development of this technology.



Figure 4. Airseas SeaWing [35]

3.4. Summary

The technology of WAPs emerged in its rudimentary form in the 19th century. However, WAPs remained merely a limited concept from 2000 to 2005 due to the rapid development of diesel engines and the low price of diesel. During the oil crisis of the 1980s, WAPs technology experienced a brief revival as oil prices rose suddenly. However, its application on large commercial ships was put on hold as oil prices dropped again. With the acceleration of energy consumption and the formation of environmental awareness, WAPs have once again come into focus since 2005. In this period, some early CFD numerical simulations and applications laid the foundation for its future development. At the same time, the success of a single technology has also led to a certain degree of technological dependence. By 2015-2020, the pressure from the IMO's emission reduction policies and the exposure of the limitations of single technologies had driven the emergence of the concepts of "hybrid systems" and "integrated design." In recent years, the decline in data costs and the increase in computing power have driven the terms "digital twin" and "machine learning" to become increasingly frequent hot topics.

4. Technology Comparison and Paradigm Evaluation

4.1. Analysis of Decision-Making and Paradigm Conflict

This review constructs a three-dimensional decision space of "performance-economy-operation" to analyze and compare WAPs technology from three aspects, as well as their respective applicable scenarios. By building a decision-making system that combines actual operational data, the application prospects of various technologies are weighed.

Abundant theoretical studies have pointed out that the Kite system has the highest potential for reducing emissions and the lowest installation cost. However, the Kite system relies on ideal weather conditions, thereby achieving its best performance only on specific routes and limiting its speed. The Flettner rotor demonstrates excellent sustainable emission reduction capabilities in various climates through active control. However, the existing theoretical data have been proven to be overly optimistic, and the actual capabilities of the Flettner rotor need to be evaluated within a unified framework.

The economic assessment throughout the entire life cycle indicates that rigid sail has a relatively high CAPEX but a lower OPEX. The high initial investment can lead to greater benefit. In contrast, the kite system has relatively high OPEX and relatively low CAPEX. In terms of operational complexity, the passive rigid sail/kite system mainly requires higher operational skills to achieve the highest efficiency. Flettner rotors, on the other hand, primarily rely on sensors to measure wind speed and automatically adjust the rotational speed.

High optimization and high robustness are the core conflicting issues in the selection and design of WAPs. The highly optimized rigid sail pursues the maximum lift-to-drag ratio, but it may stall in gusts or complex incoming flows. Studies employing the SST $k-\omega$ turbulence model have explored the optimal design of the rigid wing sail with dual wings but neglected its robustness under real sea conditions. In contrast, traditional soft sails are inefficient but robust, providing a more stable average thrust in variable wind conditions. Such paradigm conflicts require effective evaluation criteria to balance the two design concepts.

4.2. Comprehensive Assessment Matrix

This review summarizes the research from 2000 to 2026 and establishes a comprehensive assessment matrix [26–28]. Evaluate WAPs technology in multiple aspects such as energy-saving potential, payback period, technology readiness level, and operational complexity. Table 3 presents the application prospects and research potential of each WAPs technology.

Table 3. Comprehensive assessment matrix

Technique	Energy-saving potential ^a	Pay-back period ^b	Technology readiness level ^c	Route adaptability ^d
Flettner rotor	8-15%	3-7 years	TRL 8-9	Excellence
Rigid sail	5-12%	5-10 years	TRL 7-8	Limitation
Kite sail	10-15%	2-5 years	TRL 6-7	Limitation
Hybrid system	10-15%	3-7 years	TRL 6-7	Excellence

The energy-saving potential is derived from the summary of existing research data, but some studies also suggest that it is overly optimistic [28, 29].

The pay-back period refers to the time required to recover the investment cost. This data is sourced from public research reports [30].

Technology readiness level refers to the application capability of a technology [31, 32]. This indicator is comprehensively evaluated based on the actual application situation of each technology.

Route adaptability refers to the adaptability of various technologies under different routes. The key factors influencing this indicator are the robustness of each technology to environmental factors and its continuous operation capability.

Table 3 shows that kite sail has the highest potential for emission reduction, but its technical maturity and robustness are lacking. The Flettner rotor is highly favored due to its superior adaptability and good return on investment, and it is currently the most closely watched WAPs technology [33]. Among them, the rigid sail has not demonstrated outstanding characteristics and requires optimization of the Hybrid system and intelligent control. Hybrid systems have demonstrated significant advantages in various applications, but their integration methods and digital twin technologies require further discussion.

5. Conclusion

5.1. Summary of Principal Findings

This paper provides a comprehensive analysis of the research outcomes and current applications of several common wind-assisted propulsion (WAPs) technologies, including rigid sails, Flettner rotors, kite systems, and hybrid systems, along with their classification and summarization. This study delineates the aerodynamic principles underlying various wind-assisted propulsion technologies and, based on distinctions in energy capture mechanisms, classifies three primary technical approaches: lift-based systems, thrust-based systems, and hybrid power systems. This analytical pathway elucidates the physical principles underlying various technologies, thereby providing researchers with clear direction.

Furthermore, the research focus has shifted from the start-up performance of individual components to the integration and synergistic control of the complex ship-engine-sail-environment system, while imposing higher demands on computational fluid dynamics (CFD) technology, such as applications involving high Reynolds numbers. Lastly, economic and environmental benefit assessments have become standard components in the technical feasibility evaluation of WAPs; however, the assessment criteria remain inconsistent. Current emission reduction data, predominantly self-reported by enterprises, tend to exhibit an optimistic bias.

5.2. Contribution to Existing Cognition

This paper is the first to systematically elucidate the underlying logic through a three-dimensional "Energy--Control--Integration" framework. In particular, it clarifies the paradigm shift from "maximizing individual efficiency" to "managing system-level trade-offs" and quantitatively compares the engineering applicability boundaries of different

technological pathways. This study synthesizes current trends in WAPs and proposes potential directions for future research.

5.3. Engineering Research Gap Analysis

This review systematically synthesizes research gaps in the theory and application of WAPs engineering across four distinct dimensions: 1) Mechanistic level: Current CFD simulations primarily focus on theoretical performance under single-physics conditions, while the transient coupling mechanisms in more realistic multi-physics scenarios remain inadequately discussed, necessitating high-fidelity, full-scale simulations validated with robust data. 2) Evaluation Method: The absence of public and standardized life cycle assessment (LCA) benchmark cases and databases results in a lack of authoritative comparison channels. 3) System Level: Hybrid systems lack robust adaptive cooperative control algorithms capable of achieving energy maximization under varying sea conditions. 4) Application Level: Technical selection critically depends on specific vessel types and routes, yet there is a deficiency in efficient digital selection tools and rapid performance prediction capabilities.

5.4. Recommended Roadmap for Future Research Directions

To address these identified research gaps across multiple dimensions, this review proposes the following targeted research recommendations: 1) Mechanism Level: Conduct large-scale model or full-scale ship tests, introduce extreme sea condition data, and verify the coupled simulation model. More precise CFD numerical simulation methods are needed, as well as realistic simulations under actual sea conditions. The introduction of neural operators and global ROMs is also worth considering. 2) Evaluation Method: The academic community is encouraged to collaborate with classification societies to establish an open-source framework for integrated techno-economic-environmental assessment, such as integrating emission reduction capacity and total cost. 3) System Level: Further exploration is needed into the synergistic optimization of energy management between wind-assisted systems and the new generation of low-carbon or zero-carbon power systems. 4) Application Level: By leveraging big data from fleet operations, machine learning can be employed to explore the correlation between wind power benefits and variables such as routes, speeds, and loading conditions.

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