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Harnessing the Wind: The Rise of Wind-Assisted Ship Propulsion (WASP) in the Transformation of Maritime Transport

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ABSTRACT: The global maritime sector, which transports over 80% of international trade, is under increasing pressure to reduce greenhouse gas (GHG) emissions, which have risen by 20% over the past decade. Among emerging decarbonisation strategies, Wind-Assisted Ship Propulsion (WASP) stands out as a promising solution that harnesses renewable wind energy, with the potential to reduce emissions by up to 100%. This paper explores the technical maturity, regulatory context, and market viability of key WASP technologies, including rotor sails, suction sails, hard wing sails, and kites. It outlines the evolving regulatory landscape, such as carbon pricing and fuel intensity standards coming into effect from 2025, which is driving increased interest in WASP. A comprehensive technical analysis of the three systems is provided, focusing on aerodynamic principles, installation requirements, and operational performance. The article concludes with an assessment of market trends, noting that as of early 2025, 52 vessels are already equipped with WASP and an additional 97 are on order. The study affirms WASP's strategic role in enabling near-term emissions reductions and supporting the maritime industry's transition toward full decarbonisation.

1 INTRODUCTION

Marine transportation plays a crucial role in global trade, accounting for over 80% of international commerce due to its cost-efficiency and ability to handle large cargo volumes. However, due to their size and the massive volume of goods they carry, ships are among the largest emitters of carbon dioxide (CO_2) and other greenhouse gases (GHG) in the transportation sector. Currently, the primary fuel used in maritime transport is heavy fuel oil (HFO) — a low-quality diesel fuel that poses significant environmental risks. The combustion of HFO releases a range of harmful pollutants into the atmosphere, including sulphur oxides (SOx), nitrogen oxides (NOx), fine particulate matter (PM2.5) and carbon dioxide (CO_2) – for reference see table 1.

According to a UNCTAD report from December 2024 [1], GHG emissions from maritime transport have increased by 20% over the past decade, driven by sustained global economic growth, port expansions, and intensified shipping activity. This alarming trend underscores the urgent need for the shipping industry to move away from an ageing, fossil fuel-dependent fleet toward more sustainable and renewable energy solutions [2].

Addressing the dual challenge of reducing GHG emissions and transitioning to cleaner energy sources has become critical [3]. As emphasised by Rebeca Grynspan, Secretary-General of UN Trade and Development (UNCTAD): "Building sustainable and resilient maritime transport and future-proofing global supply chains is not just an option – it's a strategic necessity."

In response to the environmental impact of heavy fuel oil (HFO), the maritime industry is increasingly turning to alternative fuels. The most considered options include Marine Diesel Oil (MDO), Marine Gas Oil (MGO), Liquefied Natural Gas (LNG), biofuels, and hydrogen.

Furthermore, as illustrated in Figure 1, broad-based decarbonisation efforts can progress across five key areas, each offering distinct potential for GHG reduction and presenting specific challenges to large-scale implementation [2]. Among the wide range of solutions — such as improvements in logistics and digitalisation, enhancements in ship hydrodynamics and machinery, or post-combustion carbon capture and storage — wind-assisted ship propulsion (WASP) stands out as a particularly promising approach.

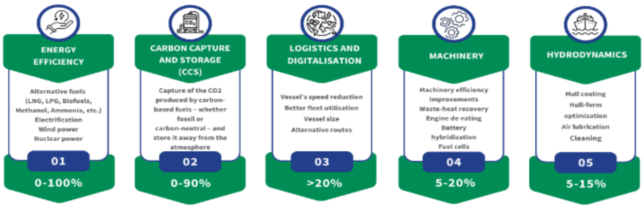

Figure 1. Solutions for shipping decarbonisation and their GHG reduction potentials. Source: Own research based on [2, 5, 14, 22].

In addition to its environmental benefits, wind energy also offers tangible financial advantages for shipowners who choose to invest in such solutions. The potential of innovative wind propulsion is considered substantial for green shipping, primarily due to the abundance and availability of wind as a free energy source [4]. This paper explores the key regulatory drivers, technological advancements, and market developments shaping the adoption of WASP technologies, highlighting their pivotal role in supporting the maritime industry's decarbonisation objectives.

2 METHODOLOGY

The content of this article is based on statistical data collected from shipowners, as well as from reputable sources such as the International Maritime Organization (IMO), the European Commission (EC), and classification societies including DNV, PRS, LR, ABS, RINA, among others. It also draws upon the insights of environmental protection experts and the authors' personal experience and observations accumulated over more than twenty years in the transport industry.

3 DRIVERS FOR WASP ADOPTION BY REGULATORY FRAMEWORKS

Decarbonisation throughout the 2020s and beyond is expected to be driven by three fundamental pillars: regulatory frameworks and policies, access to investors and capital, and the evolving expectations of cargo owners and consumers [2]. These drivers, supported by structured frameworks and standards that define sustainability assessment criteria, GHG emission calculation methodologies, and reporting requirements, are creating favourable conditions for the continued development and implementation of various WASP technologies.

The implementation of the GHG Strategy has become one of the primaries focuses of the International Maritime Organization (IMO), which now works to ensure the industry's alignment with key decarbonisation milestones. These include a reduction in total GHG emissions by 20%—with an ambition of reaching 30% by 2030; a 70% reduction striving for 80% by 2040 (all relative to 2008 levels); and ultimately achieving net-zero GHG emissions by or around 2050 [5]. At the 81st session of the Marine Environment Protection Committee (MEPC) held in March 2024 [6], an agreement was reached on how the proposed "IMO Net-Zero Framework" could be formally incorporated as amendments to MARPOL Annex VI. This framework is structurally similar to the previously introduced Carbon Intensity Indicator (CII) and Energy Efficiency Existing Ship Index (EEXI). According to Lloyd's Register (LR), this evolving framework is expected to serve as the foundational structure for future regulations, once consensus is reached on the implementation mechanisms and selected policy measures.

While it remains, uncertain which specific measures will ultimately be adopted, it is already clear that both a fuel standard and economic incentives will be integral components of the forthcoming regulatory framework [2,6]. The development of these regulations is ongoing at the IMO, and according to the agreed timeline, they are expected to be adopted in 2025 and enter into force around mid-2027.

Two additional regulatory processes are currently progressing independently [7]. The first concerns the Carbon Intensity Indicator (CII), which establishes the annual reduction factor required to ensure continuous improvement in a ship's operational carbon intensity within a defined rating level. The second is the Energy Efficiency Existing Ship Index (EEXI), which measures a ship's energy efficiency against a designated baseline.

Both regulations are scheduled for review by the end of 2025, with proposed amendments to their provisions and associated guidelines. Expected updates include revised CII reduction targets for the 2026–2030 period, the introduction of new or modified correction factors, and potentially the inclusion of additional performance metrics [8]. The review may also propose a strengthened enforcement mechanism and the broader integration of life-cycle assessment (LCA) methodologies to capture the full emissions profile of non-fossil fuels.

The infographic (see Figure 2) illustrates the evolving regulatory framework within the maritime industry, focusing on decarbonisation measures expected between 2025 and 2027. It begins with "Forthcoming Regulations", which will likely include fuel standards and economic incentives. These regulations are scheduled for implementation between 2025 and 2027. From this central framework, three regulatory components are highlighted:

1. Carbon Intensity Indicator (CII): Scheduled for review by the end of 2025, CII determines annual reduction targets for ships' carbon intensity based on operational data.

2. Energy Efficiency Existing Ship Index (EEXI): Also set for review by the end of 2025, EEXI assesses the technical energy efficiency of existing ships compared to a reference line.
3. Life-Cycle Assessment (LCA): Positioned as a complementary measure, LCA may be proposed for broader application. It would evaluate emissions across the full lifecycle of fuels and technologies, including alternative and non-fossil fuels.

The diagram effectively conveys how these initiatives are interrelated and contribute to the broader maritime decarbonisation strategy.

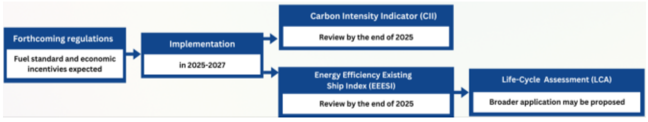

Figure 2. The infographic illustrates the evolving regulatory framework within the maritime industry, focusing on decarbonisation measures expected between 2025 and 2027. Source: Authors own researches.

Of particular relevance to vessels operating within EU and European Economic Area (EEA) ports is the EU Emissions Trading System (EU ETS), which requires emitters to pay for their greenhouse gas (GHG) emissions. The system applies to all voyages to and from ports within the EEA—including Iceland, Norway, and the outermost regions under the jurisdiction of EU Member States. For voyages involving ports outside the EEA, ship operators will be required to surrender allowances covering 50% of the emissions generated during the journey. In contrast, voyages between EEA ports, as well as emissions produced while the vessel is at berth, will necessitate surrendering allowances for 100% of the associated emissions [9].

The inclusion of the maritime sector in the EU Emissions Trading System (EU ETS) will be implemented gradually. Beginning in 2025, general cargo vessels between 400 and 5,000 gross tonnage (GT) and offshore vessels from 400 GT will be required to report their greenhouse gas (GHG) emissions; however, they will not yet be subject to the ETS. Offshore vessels exceeding 5,000 GT will fall under the EU ETS starting in 2027, while the inclusion of general cargo and offshore vessels between 400 and 5,000 GT will be reconsidered following a review in 2026. Additionally, the reporting scope is expanding to cover more GHGs. Methane (CH_4) and nitrous oxide (N_2O) emissions must be reported from 2024, and from 2026, these gases will also be subject to allowance surrender under the EU ETS [10].

Another key European Union regulation aimed at reducing greenhouse gas (GHG) emissions in the maritime sector is FuelEU Maritime, which promotes the adoption of renewable and low-carbon fuels and energy sources. Introduced as part of the European Commission's Fit for 55 legislative packages, the regulation came into full effect on 1 January 2025. It applies to ships above 5,000 gross tonnage (GT) that transport cargo or passengers for commercial purposes. FuelEU Maritime sets maximum limits on the annual GHG intensity of the energy used onboard, requiring a 2% reduction starting in 2025, progressing incrementally to an 80% reduction by 2050 [11]. Ship operators can achieve compliance through several options: by using fossil LNG or LPG, qualified low-GHG-intensity fuels (with an incentive factor for Renewable Fuels of Non-Biological Origin), connecting to shore power while at berth, or utilising wind-assisted propulsion systems.

As part of the broader effort to reduce air pollution in ports, passenger and container ships will be required to use on-shore power supply (OPS) or other alternative zero-emission technologies while at berth or moored alongside. This mandate will take effect on 1 January 2030 in ports covered under Article 9 of the Alternative Fuels Infrastructure Regulation (AFIR). The requirement will be further extended to all EU ports equipped with OPS infrastructure starting from 1 January 2035. Additionally, EU Member States may choose to enforce this obligation earlier—from 2030 onward—in ports not explicitly covered by Article 9 [12].

Complementing the EU ETS, the FuelEU Maritime Regulation adopts a goal-based and technology-neutral framework, aimed at fostering innovation and supporting the development of sustainable fuels and energy conversion technologies. This flexible approach allows ship operators to select fuels and solutions best suited to their vessels' operational profiles, without mandating a specific technological pathway. The regulation also introduces several flexibility mechanisms to facilitate compliance across the existing fleet, while offering incentives for early adopters and investors engaged in the maritime energy transition [11,12]. Together, the GHG pricing structure under the EU ETS and the performance-based standards of FuelEU Maritime create a new landscape of regulatory challenges. These include increased demands in administration, reporting, third-party verification, contractual structuring, and cost forecasting (see Figure 3). However, as with any evolving regulatory framework, these challenges are accompanied by strategic opportunities. Stakeholders who effectively streamline and optimise their compliance strategies may gain a competitive edge in an increasingly decarbonised maritime sector.

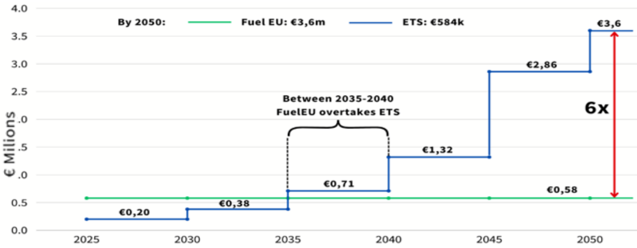

Figure 3. EU ETS and FuelEU Maritime cost comparison. Source: [13]. Note: EUA and Fuel EU penalty costs for vessel emitting 9,725 tonnes of CO2 equivalent (CO2 eq.) on voyages to and from the EU, and 1,399 CO2 eq. tonnes on intra-EU voyages or at berth in EU ports; excludes EUA price changes, potential impact of FuelEU penalties and penalty multipliers port calls without using onshore power supply or failing to meet 2% RFNBO usage.

Table 1. Comparison of Gas Emissions from 1 kg of Marine Fuel Combusted by Ship vs. Wind-Assisted Ship Propulsion (WASP)

Type of Emission	HFO	MDO	MGO	LNG	Biofuel (e.g. FAME)	Hydrogen (H_2, via fuel cell)	WASP
CO_2	≈3.11 kg	≈3.20 kg	≈3.15 kg	≈2.75 kg	≈0–3.1 kg (biogenic)	0 kg (if green hydrogen)	🌀 0 kg
SO_x	10–20 g (very high)	1–3 g (low sulphur content)	0.5–1.5 g (very low)	< 0.001 g	< 0.01 g (negligible)	0 g	0 g
NO_x	6–12 g	5–10 g	4–9 g	1–3 g	2–6 g	< 1 g (in fuel cells)	0 g
CO	0.5–2 g	0.3–1.5 g	0.3–1.5 g	0.1–1 g	0.1–0.5 g	0 g	0 g
PM2.5	1–5 g (very high)	0.3–1 g	0.1–0.5 g	< 0.01 g	0.05–0.5 g	0 g	0 g
CH_4	almost none	almost none	almost none	0–5 g (fugitive)	negligible	negligible	0 g

Note: Emissions values for HFO are approximate and depend on engine type, fuel quality, and operating conditions. Wind-assisted systems use mechanical energy generated by wind and do not emit pollutants directly. In hybrid systems (wind + engine), emissions are reduced proportionally depending on wind contribution. Source: Authors own research based on: [2,4,6,8,14,16,23,30].

All of this underscores the urgent need for decisive action. The maritime sector must embrace major operational transformations, invest in innovation, and commit to the modernisation of fleets through more efficient, environmentally responsible technologies. Central to this transformation is a transition to cleaner energy sources and alternative fuels. While the financial cost of decarbonisation will undoubtedly be significant, retreating from the sector's climate and sustainability objectives is not a viable option [13]. In this context, supporting the adoption of wind-assisted propulsion - a technology capable of reducing both emissions and operational costs - emerges as a strategically sound and forward-thinking decision.

4 MARKET AND INVESTMENT DRIVERS

Beyond regulatory compliance, market forces and investment dynamics are playing an increasingly pivotal role in accelerating the adoption of Wind-Assisted Ship Propulsion (WASP) technologies [2]. As the shipping industry faces rising fuel costs, increased investor scrutiny, and shifting customer expectations, WASP is emerging as a commercially viable and future-proof solution.

The potential savings achievable through the implementation of WASP technology are difficult to quantify due to the multitude of factors influencing system efficiency. Different levels of fuel savings can be expected depending on the type of WASP installed. It should also be noted that all WASP technologies require at least a small amount of energy to operate — for example, to adjust orientation or activate tilting mechanisms — while dynamic systems such as rotor sails or suction wings demand greater energy input to generate thrust. Increasing the number and size of WASP units generally leads to greater thrust and, consequently, higher potential savings. However, interaction effects between multiple units can reduce overall efficiency, necessitating careful consideration of their arrangement. When WASPs are installed on newbuilds, greater opportunities exist for design optimisation, which can further enhance system performance [14].

Given the complexity and the numerous factors influencing WASP performance, it is more appropriate to determine the average annual fuel savings of each system on a case-by-case basis rather than by vessel segment. Such assessments should consider the vessel's specific operational profile, intended routes, and the distribution of weather conditions along those routes.

As wind propulsion technologies generate thrust from wind energy, greater fuel savings could potentially be achieved if routes are optimised based on prevailing weather conditions. Therefore, more significant savings can be expected when voyage (route) optimisation is implemented. Available data on the fuel-saving potential of wing sails and suction sails remain limited. Reported savings vary widely, from approximately 2% to 50%, depending on the vessel type, number of sails, and operational conditions.

Table 2. Review of fuel-saving performance of rotor sails on different type of ships.

Ship's name	Performance parameters	Ship type	Routes	An average emission reduction and fuel saving target
M/V Annika Braren	one 18x3 m rotor sail	general cargo ship	Not given	2-4.5%
M/V Estraden	two 18x3 m rotor sails	Ro-Ro vessel	Rotterdam and Teesport (UK)	6.1%
M/V Copenhagen	one 30x5m rotor sail	hybrid ferry	Rostock (DE) and Gedser (DK)	4%
M/V Viking Grace	one 24x4 m rotor sail	Ro-Pax vessel	Turku (FI) to Stockholm (SE)	reduced power consumption of 207 kW to 282 kW / 231 to 315 tonnes of fuel per year
M/T Maersk Pelican	two 30x5m rotor sails	tanker	mainly trading between Middle and Far East	8.2%
M/V SC Connector	two 35x5 m rotor sails	Ro-Ro ship	Not given	20-25%
M/V Afros	four 16x2 m rotor sails	bulk carrier	Nantong (CN) to Vancouver (CA)	12.5%
M/T Sea Zhoushan	five 24x4 m rotor sails	VLOC	Not given	8%

Source: Own research based on [22, 25].

For instance, the Wind Challenger project aims to achieve a 50% reduction in fuel consumption by equipping a capsize bulk carrier with nine telescopic sails, while route-specific simulations (Yokohama–Seattle) suggest savings in the range of 20–30%. Single-sail installations, such as on the Shofu Maru, have demonstrated fuel reductions of 5% and 8% on the Japan–Australia and Japan–North America routes, respectively [15]. Tests conducted on Ro-Pax vessels, such as Ciudad de Mahón, indicated potential fuel savings ranging from 7% to 22%, depending on the operational scenario. These findings stem from a case study based on simulations involving two 35×12 m^2 wing sails and the assumption that the vessel operates in the Mediterranean Sea at a design speed of 21 knots [16].

A manufacturer of suction wings reports that their systems could reduce fuel consumption by up to 20% and 40%, respectively, depending on the number and size of wings installed, as well as the vessel type [17]. However, only limited performance data is currently available for suction wings. Speed trials were conducted on the multi-purpose dry cargo vessel M/V Frisian Sea, which was fitted with two suction wings, each measuring 10 × 3 metres [18]. During testing, the vessel maintained a constant speed of 10 knots, with wind energy partially replacing engine output. Data from these trials was used to estimate power savings across a range of wind conditions, with calculated savings on specific routes ranging from 0.7% to 4%, and an average of 2.2%.

During 2022–2023, several speed trials were conducted with the general cargo vessel M/V Ankie, which was equipped with two suction wings, each measuring 13 × 2.1 metres, to verify their power-saving potential. During testing, the true wind speed was 10 m/s and the vessel maintained a speed of 9.5 knots. Power savings reached up to 15% at the most favourable wind angle, while the estimated average power reduction on typical routes was approximately 3.5%, corresponding to a saving of around 40 kW [19].

One of the strongest commercial incentives for adopting WASP technologies is their potential to deliver immediate and measurable fuel cost reductions. However, the lack of robust empirical data confirming the predicted savings remains a barrier to the wider adoption of WASP systems. Further research on these technologies is therefore of significant importance. Nevertheless, all savings achieved to date translate directly into lower operational expenditures, thereby enhancing the competitiveness of WASP-equipped vessels.

5 OVERVIEW OF WIND PROPULSION TECHNOLOGIES

Wind-Assisted Ship Propulsion systems, which are recognised as a promising solution to reduce, and in some cases replace, conventional fuel use in shipping, convert wind energy into propulsion power, allowing ships to partially, or depending on the design, significantly substitute main engine output with wind power. When properly applied and appropriately designed to suit a vessel’s operational profile, WASP can reduce greenhouse gas (GHG) emissions, air pollution, fuel consumption, and underwater noise [20]. While all Wind Propulsion Systems operate based on the same fundamental physical principles, the specific technologies differ in terms of their mechanisms and performance characteristics. Selecting the most suitable WASP for a particular vessel depends on multiple factors, including average sailing speed, operational routes, prevailing weather conditions, and practical considerations such as available deck space and compatibility with cargo operations [21]. Optimising ship design and navigation strategies to align with the dynamics of wind propulsion is essential for maximising the effectiveness of WASP. Furthermore, ship structure and weather routing play a critical role in the overall system performance.

Up to January 2025, 52 vessels registered in DNV [2,22] have been equipped with modern wind-assisted propulsion systems. While this represents only a small fraction of the global fleet, adoption is expected to increase significantly. The recent acceleration in uptake is clearly evident, with 44 of these installations occurring on ships built or retrofitted after 2020. Larger vessels dominate this trend, accounting for a combined total of 3.4 million deadweight tons (DWT) equipped with WASP. As illustrated in Figure 1, the adoption of WASP in the global fleet is currently concentrated around four main technologies: rotor sails, suction sails, wing sails and kites [22]. Therefore, this section of the article will focus on and describe only these technologies.

Flettner rotors, also known as rotor sails, were first applied on a merchant vessel in 1924. These are rotating cylindrical sails that harness wind energy to assist with ship propulsion. Their operation is based on the Magnus effect, a phenomenon in which a spinning cylinder generates lift perpendicular to the airflow. While the initial trial was technically successful, it lacked economic viability, and as a result, the concept remained largely dormant for nearly a century. However, in recent years, renewed interest has emerged, driven by the push for more sustainable shipping solutions [23]. A major advantage of this technology is that the sails can be installed on newbuilds or retrofitted to existing ships, provided there is sufficient deck space and unobstructed airflow, even if the vessel was not originally designed to accommodate sails. However, newbuilds offer better optimisation by integrating WASP from the start. Rotor sails are particularly suited to vessel types such as tankers, LNG carriers, RoRos, RoPaxes, general cargo ships, bulk carriers, as well as cruise ships and ferries [24]. Currently, bulk carriers and tankers dominate the use of rotor sails, accounting for 54% of all WASP technologies installed on vessels in operation.

Rotors offer the advantage of being easily adjusted to the wind direction by varying their rotational speed, enabling effective wind utilization on both legs of a voyage—something that is not always achievable with other wind-assisted propulsion technologies. However, a key drawback is the additional drag they generate when not in operation, particularly when sailing close to the wind. This added resistance can increase engine power demand and fuel consumption. In response, recent innovations, such as folding rotors, have been developed to reduce this drag penalty when the system is inactive.

Another consideration is that rotor sails require a continuous supply of electrical power to maintain the rotational speed necessary for optimal aerodynamic performance. However, the power demand is relatively low compared to the thrust generated. The aerodynamic efficiency of a rotor sail is primarily influenced by the ratio between wind speed and the surface speed of the rotating cylinder, with rotational speed constrained by practical and operational limitations. Interrupting the power supply halts the rotor's rotation, thereby ceasing lift generation [22].

Suction sails, also known as suction wings, are vertical, aerofoil-shaped sails affixed to the vessel's main deck. Unlike Flettner rotors, the outer surfaces of suction wings remain stationary. However, these sails are capable of automatically adjusting to align with prevailing wind directions. The wing sails are equipped with integrated fans and vents that utilize boundary layer suction to augment the aerodynamic force produced, in addition to the conventional thrust generated by the sail's shape.

Similar to rotor sails, suction wings achieve maximum efficiency when exposed to crosswinds. In contrast, they generate negligible or zero thrust when subjected to headwinds or tailwinds [21]. To optimize aerodynamic efficiency, wind suction quantities and pressures must be adjusted for different wind conditions. Interrupting the electrical power supply halts the operation and lift generation. Suction wing sails can reach heights of up to 36 meters. Typically, vessels are fitted with two or four units, although configurations with a single suction wing are also in operation. Smaller units, with heights under 10 meters, are available as containerized systems, allowing for easy transfer between vessels. When foldability is required, some manufacturers offer a tilting system that moves the suction sail from a vertical to a horizontal position. This feature can help lower the air draft of the vessel in specific situations, such as when sailing under bridges or during cargo loading and unloading operations [22].

Wing sails, also known as hard sails, operate on similar aerodynamic principles as conventional soft sails, utilizing wind interaction to generate both drag and lift forces. However, they differ significantly in construction materials and structural design. Hard sails are typically made from lightweight, high-strength materials such as carbon fibre and have a rigid, fixed geometry. These sails can be rotated to align with the wind direction, optimizing propulsion efficiency. This adjustment process is usually fully automated. The aerodynamic design of hard sails is based on aviation principles, with shapes modelled after aircraft wings to maximize performance. As a result, they achieve a higher lift-to-drag ratio and generate greater lift compared to traditional soft sails [22]. Wing sails come in various sizes, with the largest reaching heights of up to 50 meters and surface areas of up to 1,000 square meters. To ensure maximum aerodynamic efficiency, they must be aligned with the incoming wind direction at an optimal angle of attack. In configurations comprising multiple elements, the wing sail can be cambered to further enhance aerodynamic force generation. For operational flexibility, wing sails are often designed to be tiltable. This feature facilitates port operations, reduces air draft when necessary, and provides protection during periods of high wind conditions [21, 27]. One challenge associated with wing sail systems—particularly when more than two units are installed on board, concerns compliance with IMO visibility and safe navigation regulations. This issue is currently under review and is being assessed on a case-by-case basis.

Kite Sails are tethered sails constructed from lightweight and high strength fabric materials, controlled using ropes, and flown at significant altitudes to utilise stronger winds. They can use wind to propel them forward, reducing the need for engine power and they can also generate electricity, which can be used to power the ship or stored for later use. During operation, the kite moves in a dynamic figure of 8 motion, increasing its apparent wind speed to over ten times that of the vessel. By rapidly flying into the oncoming wind, the kite significantly increases traction force, effectively towing the ship. Despite having a considerably smaller surface area than other on-deck wind propulsion systems, the kite generates substantially greater thrust due to its dynamic manoeuvring. Additionally, kites operate at altitudes where wind speeds are approximately double those experienced at sea level. Unlike the previously described systems, a kite achieves optimal performance primarily when positioned in the downwind area.

Kite sails offer fuel savings from 5% to 20%, depending on weather conditions and route. Their advantages are minimal structural interference with the vessel and therefore they have relatively little impact on heel and yaw angles on the ship and have a positive contribution to the course keeping of the ship and it requires much less corrections on the rudder and much less rudder action than deck mounted systems. Kite sails can be retrofitted on existing ships. As for disadvantages kite sails require advanced automation and control systems. They have limited effectiveness in downwind conditions and ports. Kites require designated space for deployment and storage. Another down factor is that the surface material and the towing rope need regular replacement, counted in few thousands of operating hours.

6 WASP LIMITATIONS AND CHALLENGES

Most Wind-Assisted Ship Propulsion systems require significant deck space for installation, which presents a greater challenge for retrofitting than for newbuilds. The availability of deck space varies depending on ship type and size for instance, container and passenger vessels typically offer less space compared to bulk carriers or tankers. Interference with cargo handling operations and onshore infrastructure is another important consideration. This issue is often mitigated by the use of foldable or tiltable systems, which are now common and help reduce safety risks during high wind conditions. Additional placement requirements must also be considered to ensure the safe and practical use of WASP, such as avoiding the creation of blind spots or installing units too close to passenger accommodation areas [20].

Figure 4. WASP installations on different types of ships. Source: Own research based on Source: Based on [24, 25, 26, 28].

The weight of WASP devices varies across technologies, but the impact on cargo capacity is generally considered minimal. From a design perspective, the ship's structure must be capable of safely transferring the forces generated by the WASP, which may require local reinforcement, though this is not regarded as a significant technical barrier. Wind availability significantly affects the efficiency of WASP, depending on the vessel's route, direction, seasonal weather patterns, and proximity to land [28]. To maximise efficiency, route optimisation is essential, balancing favourable wind conditions with overall route length. Proper integration of the WASP into the ship's design and operations further enhances performance.

Since 2021, the adoption of Wind-Assisted Ship Propulsion systems within the global fleet has accelerated significantly. As of January 2025, a total of 52 seagoing vessels equipped with WASP are in operation, with an additional 97 newbuilds featuring WASP currently on order. These systems have been implemented across a broad spectrum of vessel types, with bulk carriers, tankers, and general cargo ships representing the primary categories. Recent industry developments have demonstrated that the installation of Wind-Assisted Ship Propulsion Systems is not limited to specific ship types. Retrofitting WASP is technically feasible on nearly any vessel with adequate deck space and unobstructed airflow, regardless of whether it was originally designed to accommodate sail systems. Currently, approximately 75% of the WASP-equipped fleet consists of retrofitted vessels.

This adaptability enables the deployment of WASP across a wide range of existing ships and operational profiles [22]. To date, only two significant studies have attempted to forecast the future market potential of Wind-Assisted Ship Propulsion Systems (WASP). The first was commissioned by the UK government as part of the Clean Maritime Plan (July 2019). This study assessed the global annual market for wind propulsion systems in the context of broader alternative propulsion technologies and fuels. The market for wind technologies, which included both WASP and vessels utilizing primary wind propulsion, was projected to grow from a conservative estimate of £300 million per year in the 2020s to approximately £2 billion annually by the 2050s [29]. In this analysis, wind propulsion technologies were ranked as the second most significant category of maritime propulsion innovation, following alternative fuels (estimated at £8–11 billion per year by the 2050s), and were expected to represent around 15% of the total propulsion systems market.

The second key study, conducted by CE Delft for the European Commission in 2017, preceded the surge in WASP adoption post-2018 and the commercial maturation of several technologies, such as suction sails. The report projected that, if wind propulsion technologies reached market viability by 2020, the potential market for installations across bulk carriers, tankers, and container vessels could range from 3,700 to 10,700 systems by 2030, including both retrofits and newbuilds. These figures were based on variables such as bunker fuel prices, vessel speeds, and applied discount rates [30]. While some WASP technologies did achieve maturity before 2020, and regulatory clarity has improved since 2017, the initial uptake fell significantly short of expectations. By the end of 2023, only 29 WASP installations had been completed, far below the several hundred forecasted in the CE Delft model.

However, the underlying assumptions of the CE Delft analysis remain relevant. The study posited that, once the number of installations surpassed 100, the industry would experience sufficient learning effects to significantly reduce costs, making WASP a financially viable option for all suitable newbuilds and retrofits under the modelled economic conditions. With 101 planned installations now on record, the industry may be approaching the inflection point of the model's projected S-curve: a phase of accelerated adoption followed by a plateau, as WASP become a standard feature on appropriate newbuild vessels.

7 CONCLUSION

Comparison of four main WASP technologies including kite sails, wing sails, rotor sails (Flettner rotors), and suction sails (Ventifoils) has been presented in Table 3 considering fuel savings, technical and operational complexity, aero efficiency, installation and operational cost, spatial and structural constraints, integration with existing ship propulsion system.

Table 3. Comparison of Wind-Assisted Ship Propulsion (WASP) systems considering fuel savings, technical and operational complexity, aero efficiency, installation and operational cost and retrofit friendly.

Technology	Market share by WASP Type [%]	Fuel Savings [%]	Installation Ease [Factor 1 to 5]	Aero Efficiency [Factor 1-5]	Cost & Complexity [Factor 1-5]	Retrofit Friendly [Factor 1-5]
Kite Sails	2%	5–20%	4	2	3	5
Wing Sails	19%	10–30%	2	5	2	2
Rotor Sails	48%	5–25%	3	4	3	4
Suction Sails	31%	10–20%	4	4	3	4

Note: Rating factor on a scale of 1 to 5, where 1 indicates the lowest rating, least efficiency, 5 the highest rating, most efficiency. Source: Own researches based on [2,22,30].

Based on our researches it must be noted, that wing sails offer the highest aerodynamic potential, but require significant space and are more difficult to retrofit. Kite sails and suction sails are the easiest to implement, especially on existing vessels. Rotor sails are the most proven commercial solution, with a realistic return on investment within a few years. The best choice depends on ship type, route, vessel design, and shipowner priorities (e.g., ROI, sustainability, operational costs).

Kite sails offer fuel savings from 5% to 20%, depending on weather conditions and route. Advantages: Minimal structural interference with the vessel. Operates at high altitudes (stronger winds). Can be retrofitted on existing ships. Disadvantages: Requires advanced automation and control systems. Limited effectiveness in downwind conditions and ports. Needs space for deployment and storage.

Wing Sails offer fuel savings: 10–30%, depending on size and alignment. Advantages: High aerodynamic efficiency. Can be automated (angle of attack adjustment). Effective on beam and broad reach courses. Disadvantages: Large space and height requirements. May interfere with cargo operations. Retrofitting is more challenging (deck reinforcement needed).

Rotor Sails (Flettner Rotors) offer fuel savings: 5–20%, sometimes more (>25% in favourable conditions). Advantages: Effective even in side wind conditions. Fully automated operation. Successfully implemented in commercial shipping (e.g., Norsepower). Disadvantages: Requires electrical power for rotation. Tall structures may impact stability and visibility. Requires robust deck structure.

Suction Sails (Ventifoils) offer fuel savings: 10–20% (according to manufacturer Econowind). Advantages: High efficiency in a compact design. Easy installation (containerized or foldable units). Fully automated. Disadvantages: Requires power for air compressors. Lower thrust compared to larger wings or rotors.

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