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Review

Review of Wind-Assisted Propulsion Systems in Maritime Transport

Marcin Kolodziejski [1,*] and Mariusz Sosnowski [2]

[1] Faculty of Mechanical Engineering, Maritime University of Szczecin, ul. Willowa 2, 71-650 Szczecin, Poland
[2] Faculty of Mechatronics and Electrical Engineering, Maritime University of Szczecin, ul. Willowa 2, 71-650 Szczecin, Poland; m.sosnowski@pm.szczecin.pl
* Correspondence: m.kolodziejski@pm.szczecin.pl

Abstract: The maritime industry is going through a technology transition, aiming to have carbon-neutral propulsion systems. A significant trend of orders for ships with alternative propulsion has been observed. A favorable means to meet the decarbonization requirements imposed by IMO (International Maritime Organization) is to operate vessels with sustainable energy. Harvesting wind power and its conversion into ship propulsion are gaining popularity due to emission reductions and expected reductions in fuel consumption. This paper reviews recent studies on wind-assisted propulsion systems (WAPSs), the different aspects of using sail applications in the maritime industry, and the types of wind-assisted propulsion systems. The study also presents the latest developments in WAPS systems offered by leading maritime market manufacturers and their applications on existing vessels. The article is based on a literature review (peer-reviewed articles), the information provided by wind propulsion systems manufacturers and internet research.

Keywords: wind-assisted propulsion systems; rotor sails; suction wings; rigid sails; decarbonization; energy harvesting; energy-saving drives; energy conversion

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1. Introduction

Maritime transport accounts for approximately 3 percent of global greenhouse gas (GHG) emissions. If no actions are taken, this figure is predicted to grow to 15 percent by 2050. Vessel operators have already experienced increasing demand to reduce GHG emissions. This demand has been exerted by regulatory bodies. The Initial International Maritime Organization (IMO) Greenhouse Gas Strategy, adopted in 2018, regulated policy development within maritime transport. In 2023, a revision of the strategy was adopted during a meeting of the Marine Environment Protection Committee (MEPC 80). The revised strategy aims to reach net-zero emissions in 2050 with a commitment to ensuring the uptake of alternative near-zero-emission fuels in 2030 [1]. Additionally, more stringent regulations (SEEMP Part III [2], CII and EEXI [3]) came into effect on 1st January 2023. Shipowners must respond to the new regulations and are required to introduce alternative fuels and new technologies to reduce GHG emissions. There is a broad spectrum of alternative fuels and Energy Efficiency Technologies (EETs) considered to meet the IMO requirements. Wind-assisted propulsion systems are considered one of the technologies that could reduce GHG emissions and fuel consumption. For many centuries, wind provided free propulsion for sailing ships. Nowadays, it does not have enough energy to be a stand-alone propulsion system for modern vessels; however, novel WAPSs have been developed on several ships. The number of vessels equipped with wind propulsion technologies is relatively low, but the number of planned implementations of WAPS is increasing. According to [4], there are

101 ships on which WAPSs were installed or are to be installed. The number of orders is accelerating rapidly, with 29 systems installed between 2018 and 2023 and 72 orders in 2024. Out of +100 applications of WAPS known today, more than 90% were installed/developed before 2024. The number of ships equipped with each technology shows that the market is at an early growth stage. Suction wings and some forms of rigid sails were introduced in 2018/19 and other rigid sails and second-generation kites were first installed in 2020/21. So far, each vessel segment has reached a good level of demonstrators (three to five ships). So far, these demonstrator vessels have enabled the technology providers and the shipowners to gain limited experience, validate performance data and trial these systems in various weather and operational situations.

2. Literature Review

The maritime industry faces major challenges caused by greenhouse gas emission limits imposed by the IMO and climate legislation. Shipowners and operators have to develop and implement new solutions to reduce the emission of greenhouse gases. Among the different technologies and fuels being considered, WAPS is the technology that could reduce the fuel consumption generated by shipping and, consequently, reduce GHG and other harmful emissions. Wind energy is sustainable, inexhaustible, and abundant. WAPS allows vessels to convert wind energy into thrust and supplement the main engines. This will reduce the fuel consumption and emissions.

The peer-reviewed literature contains a relatively small number of articles focusing on using WAPS as an alternative means of propulsion in maritime transport. The research presented in the following review has been carried out in recent years. Most of the available scientific publications present theoretical case studies only. The following review is based on peer-reviewed scientific articles. However, to describe the latest developments in wind propulsion, the authors used sources like the Internet and manufacturers' publications; there are no peer-reviewed articles available yet, as some projects presented in the paper were introduced very recently. WAPS propulsion applications in the maritime industry are still in the experimental stage. This is also reflected in the limited number of available publications. Ships equipped with WAPS serve as a kind of platform for evaluating the applicability of different technological solutions.

2.1. Flettner Rotors

Flettner rotors, first utilized on a merchant ship in 1924, are a type of rotary cylindrical sail that can be used to harness wind energy to support a ship's propulsion, reducing greenhouse gas emissions and improving its fuel efficiency. They use the Magnus effect, which is a phenomenon that occurs when a rotating cylinder generates lift perpendicular to the flow of air. Anton Flettner initially attempted to apply the Magnus effect in aviation; however, later on, he realized that the Magnus force could be used in shipping as a means of ship propulsion. The first application in 1924 was successful; however, it was not economically beneficial. The Flettner concept remained a curiosity for almost a century. It has changed in recent years due to the drive for greener shipping. Most of the research papers in the field of Flettner rotors have been published in the last 4–5 years, and it is reflected in the following review.

2.1.1. Flettner Rotors—Case Studies and Numerical Models

Even though Flettner rotors have been known for more than a century now, their applications in maritime transport are relatively new, and it is reflected in the literature; most of the articles present theoretical case studies and numerical models of the rotors' application in different propulsion configurations. A method to perform the preliminary sizing of vessel propulsion consisting of a diesel engine, a CPP (controllable pitch propeller), and Flettner rotors is presented in [5]. The RoPax ferry has been used as a case study. A mathematical model describing the behavior of the rotor in terms of propulsive thrust and power is proposed in the article. The authors presented the integration of the rotor model into an existing diesel propulsion model to assess the vessel's fuel consumption and CO_2 emissions and to provide a comparison of wind-assisted propulsion solutions with conventional systems. A 6DOF (a six-degree-of-freedom) vessel performance model set up to evaluate the most economical way of using two Flettner rotors is presented in [6]. The paper analyzes the propulsion system performance in the context of sea and weather conditions, evaluating the reduction in fuel consumption. A simulation of Flettner rotors and a parafoil system in combination with the traditional propulsion of a 60,000 DWT ship in different wind conditions is presented in [7]. The article examines the benefits of using two alternative propulsion-assisting systems. The analysis of a 3 m diameter, 30 m height rotating structure of a rotor sail is presented in [8]. The authors derived a 4DOF (four-degree-of-freedom) model of the rotor sail to simplify its dynamics. They calculated the natural frequencies of the rotor sail and predicted support points' frequency responses and carried out validation and comparison with the finite element model of the sail. The possibility of utilizing WAPS in the maritime industry is explored in [9]. The authors proposed a new type of Flettner rotor sail installed on the superstructure of a sea-going vessel. This proposal is numerically simulated in the study. The study in [10] focuses on the applicability of WAPS for ships and introduces Flettner rotor sails as a zero-emission propulsion technology for the maritime industry. The authors presented a case study of a bulk carrier operating between Dunkirk in France and Damietta in Egypt. The results presented in the study showed how the interaction between wind speed/direction and the ship course influenced the Flettner rotors' output power. Two numerical models of a towing kite and Flettner rotor are presented in [11]. The methodology used by the authors combines wind data along trade routes and technology models. Authors concluded that WAPSs have the potential to reduce shipping emissions. A new empirical method to research WAPS cargo vessels is presented in [12]. The authors introduced a physical model of the vessel, including the conventional propulsion system which interacts with a numerical sail model. The method is used to assess the benefits of the application of the WAPS for a 190 m bulk carrier equipped with four Flettner rotors.

2.1.2. Flettner Rotors—Validated Trial Data

Several demonstrator vessels equipped with rotating sails have enabled the industry to gain experience, trial the systems and validate performance data in various conditions. However, there is a lack of credible performance information. It is caused by the complexity of the comparison with many variables, the limited number of pilot installations (demonstrators) for each technology and the reluctance of the systems' suppliers to share sensitive information. It is reflected in a limited number of peer-reviewed articles presenting validated performance data. The article in [13] presents the results of the sea trials of the general cargo ship Fehn Pollux following the installation of a single Flettner rotor. The power potential of the rotor sail was in the range of 100 kW to 150 kW in addition to the main engine power. The measured fuel savings were 10–20%. Real data derived from a wind-assisted tanker, a Maersk Pelican equipped with Flettner rotors, was presented in [14]. The authors developed a 6DoF (six-degree-of-freedom) PPP (Performance Prediction Program) for WAPS cargo vessels. It can predict the performance of three different wind-assisted propulsion systems: rigid wing sails, rotor sails, and DynaRigs. The authors compared the theoretical results with real trial data derived from the Maersk Pelican.

They also compared fuel savings for the three different wind-assisted propulsion systems; Flettner rotors proved to be the most efficient.

2.1.3. Flettner Rotors—Design, Economic and Technical Aspects

Several peer-reviewed articles present various theoretical studies of design features, proposals of combined propulsion systems equipped with the rotors, results of rotor wind tunnel experiments, environmental impact of rotor applications, simulations of different weather conditions and vessel routes concerning the rotor effectiveness. A novel concept of a liquefied hydrogen tanker equipped with six Flettner rotors as a WAPS in combination with a hydrogen-fueled turbine as a main propulsion system is explored in [15]. The assessment of the environmental and technical aspects of the vessel design is included in the study. The authors simulated the operational condition of the vessel in different routes and weather conditions to assess the benefits of using wind energy to assist the gas turbine. Another study [16] presents a review of the feasibility of using Flettner sails in coastal shipping in challenging conditions of varying wind direction and intensity. The authors carried out a structural design to reduce the rotor weight for better performance. The study suggests utilizing the concept of magnetic bearing for the rotor sail to reduce the frictional forces. An optimization-based workflow to establish the optimal design of a Flettner rotor sail for a target ship was proposed in [17]. As the performance of a Flettner sail depends on the design of the sail and its operational conditions, the authors proposed a two-level optimization, separated for rotor design and operational conditions. The study in [18] highlights the economic, technical, and environmental aspects of WAPS consisting of Flettner sails. Four Flettner rotors are proposed for use on a bulk carrier as a case study. The article considers different routes of the ship, which, along with wind characteristics, are the main aspects that affect the economic results of the installation of Flettner rotors. The impact of Flettner sails on the roll motion of ships is explored in [19]. It also presents the opposite effect of the roll motion on the effectiveness of the Flettner rotors. The calculation presented by the authors shows that Flettner sail performance decreases with the increased heeling angle of the vessel. Large heel angles will reduce the rotor driving force to almost zero. However, adding the rotors will have no impact on the roll motion. The research in [20] applies an environmental and techno-economic analysis to assess the benefits and possibilities of using wind energy in maritime transport. The authors attempted to establish the potential of WAPS technologies (Flettner rotors) in reducing CO_2 emissions. According to the presented results, the implementation of Flettner sails could reduce CO_2 emissions by up to 20%. The paper in [21] presents several wind tunnel experiments carried out on the Flettner rotor in which the forces and pressures acting on the cylinder were measured to establish the influence of the Reynolds number on the performance of the Flettner sail. The aerodynamic interaction effects between two Flettner rotors are explored in [22]. A series of wind tunnel experiments indicated that the performance of the rotors is affected by their location, the distance between them and their layout on the vessel's deck.

The Flettner rotors seem to be the most mature technology within the WAPS market. It is also reflected in the number of scientific articles exploring wind-supported propulsion technology; most of them refer to Flettner rotors. The number of articles describing the other technologies (suction wings, hard sails and kites) is substantially lower.

2.2. Wing Sails

Wing sails (also referred to as hard sails) are another innovative wind propulsion technology. They work like conventional soft sails but are more advanced in their performance and design. The difference is in the materials they are fabricated from; hard sails are made of strong and light materials like carbon fiber and have rigid geometry. The interaction between the wind and the sail creates aerodynamic lift and drag force. The wind sails can be rotated/adjusted to the wind direction to achieve maximum force. The aerodynamics of the hard sails is based on airplane physics principles and their geometry is similar to that used in aviation. The geometry of the hard sails provides a higher lift-to-drag ratio and creates more lift (in comparison to conventional soft sails). An analysis of a KVLCC2 vessel equipped with a hard sail in different weather/wave conditions is presented in [23]. The authors carried out a numerical simulation of a sail system's aerodynamic performance and compared it with experimental data. The added resistance of the hull and motion response were numerically predicted. The results in regular waves show good accuracy in predicting the hydro-dynamic responses of the vessel in comparison to the experimental data. Analyses of a model of a bulk carrier equipped with five rigid sails fitted with a 180° rotating mechanism are provided in [24]. The authors verified the stability of the vessel through the calculations of dynamic stability, initial stability, and static stability by using MAXSURF software. They also carried out various flow simulations to predict the value of the thrust created by the sails in different wind conditions. Analysis proved that hard sail WAPS can reduce the demand for the main propulsion by 20–30 percent. The paper in [25] explores the interference characteristics between multiple wing sails. The authors investigated the interference characteristics by establishing a model of a two-element wing sail considering the wind direction. This study can provide a good reference for the design of the wind sail arrangement on vessels.

2.3. Kite Sails

Kite sails, known also as wind kites or kite propulsion systems, use large kites or parachute-like sails to harness wind energy to assist ship propulsion. They capture the wind energy at higher altitudes (compared to other WAPS technologies), where wind speeds are typically stronger and more consistent. The kite development is still in the experimental phase and it is reflected in a small number of scientific articles. The paper in [26] presents a theoretical model to perform a numerical assessment of the wind speed and the planform area influence on the aerodynamic performance of a kite sail. The kite sail assists the propulsion system of a 75 m long ship. The authors concluded that a 320 m^2 kite sail will suffice to provide the propulsion of the vessel in appropriate weather conditions.

2.4. Vessel Voyage Optimization

In recent years, many WAPSs, such as wind tails, rotors, etc., have been designed and investigated to utilize wind power. As the effectiveness of WAPS highly depends on wind speed and direction along the shipping route, the optimization of the vessel voyage becomes more important to achieve maximum efficiency of the propulsion system. Both wind propulsion and weather routing provide immediate solutions to reduce fuel consumption and emissions. Combining efficient routing with WAPS will amplify the benefits of utilizing wind energy. An improvement in the vessel routing framework to determine the optimal vessel voyage and highly efficient operation of WAPS is explored in [27]. The framework proposed by the authors utilizes various data sources like the design of the ship, weather forecasts, and historical weather information. The authors also applied the proposed method to the test case of a VLCC ship operating between the Middle East and China. Another study [28] presents rigid hard sail operating conditions in the context of optimization of the vessel's route. The objective of [29] is to present novel research that utilizes fuel consumption calculations for more than a thousand departures for three different routes to characterize stochastic uncertainty. The authors proved that routes with long voyage times and ideal wind conditions are most sensitive to uncertain weather forecast inputs. Savings from Flettner rotors and weather routing can be reduced by up to 44% when a priori weather routing strategies are used. Using an adaptive weather routing strategy instead can be used as an accurate prediction tool. The impact of weather routing on a post-Panamax vessel equipped with different WAPSs is explored in [30]. The presented WAPSs were wing sails, rotor sails, and suction wings. The analyzed route was a route between Brazil and China. A 4-DoF (four-degree-of-freedom) performance prediction program was used by the authors to create a performance model of the vessel with different WAPSs. Those models were used in the route optimization. The authors carried out route optimization simulations using historical weather data from the years 2015 to 2019. The study proves that it is possible to achieve a significant reduction in fuel consumption when applying weather routing. A model of wind-assisted propulsion on globally distributed shipping routes is presented in [31] to show how route optimization can reduce fuel consumption. A theoretical case study of a RoPax ferry, which explores the potential performance of wind-assisted propulsion in realistic wind/weather conditions, is provided in [32]. The authors discussed different system layouts and design alternatives; they also analyzed uncertainties related to WAPS performance prediction and provided guidelines for modeling and designing a ship with wind-assisted propulsion. A new energy-saving evaluation method based on analysis of typical shipping routes of vessels equipped with WAPS is proposed in [33]. The authors presented a case study of a WAPS oil tanker sailing on the Middle East–China route. The results showed that fuel saving was 5.37%, potentially increasing to 9.54%. The limitations and the feasibility of a vessel with propulsion derived from renewable energy and simulated ship routes are researched in [34]. The vessel concept incorporates photovoltaic cells, wind turbines, Flettner rotors, batteries, and dual-mode propeller producing energy for the Flettner rotors, and the ship's auxiliaries which are used for the propulsion. The authors modeled the entire system numerically and simulated ship routes using ShipCLEAN (ship performance model).

2.5. WAPS—Models, Numerical Simulations and Theoretical Case Studies

Out of +100 applications of WAPS known today, more than 90% have been installed/developed in the last 3 years. The number of ships equipped with each technology shows that the market is at a very early growth stage. So far, each vessel segment has reached a good level of demonstrators (three to five ships). These demonstrator vessels have enabled the technology providers and the shipowners to gain limited experience, validate performance data and trial these systems in various weather and operational situations; however, it has not been reflected in the number of publications yet. Many articles show different kinds of numerical simulations, models and theoretical case studies. They also present design studies, market analysis, theoretical studies on potential energy savings and guidelines on performance predictions. The paper in [35] presents two models of propulsion system optimization aiming at GHG emission reduction. The first model used a WAPS with rigid wind sails; the second model optimized the vessel deck area assigned to wind and solar systems. The authors used bulk carrier ships as a case study. The results of the study show that optimization of the deck area for installation of wind-assisted systems and solar panels combined with sailing at an optimal angle can reduce GHG emissions by 36%. A method to assess the unsteady and steady performances of WAPS vessels with six degrees of freedom is presented in [36]. The method was inspired by system-based modeling; it consists of independent modeling of forces acting on the vessel as a function of environmental conditions and the vessel's six degrees of freedom. The method is suitable for both pure wind and hybrid propulsion. A numerical simulation tool for a WAPS container ship is presented in [37]. The tool is used to assess ship performance on realistic shipping routes. The model presented by the authors includes the dynamics of the CPP (controllable pitch propeller), rudder, and hull. It also includes the fuel consumption characteristics of the ship's main propulsion system and the thrust profile generated by two suction sails. A KVLCC2 vessel dynamics model was built and presented in [38]. The model consists of a sailing system, hull, propeller, and rudder with consideration of the effects of waves and wind. The authors examined the energy consumption for both systems under different wind speed and direction. One sailing system proved to reduce fuel consumption by up to 10%. The authors also investigated the effects of the position of the sails, their number, and the vessel speed on fuel consumption. The effects of different market scenarios (fuel price, subsidies) and policies on WAPS retrofitting are explored in [39]. The model proposed by the authors incorporates two decision steps for each ship to determine the most suitable WAPS option. The authors also modeled three WAPS options and integrated them into the simulations of fuel savings and technology costs. The study in [40] explores perspectives of retrofitting a no-emission wind–hydrogen-powered propulsion system to a benchmark vessel with conventional propulsion. The authors created a model of the ship's hybrid propulsion and analyzed power demand for the vessel during a one-year sailing schedule on realistic routes and in realistic weather conditions. A new approach to capturing hydrodynamic and aerodynamic interactions on ships equipped with WAPS is presented in [41]. The authors applied the low-aspect-ratio wing theory and modified it so it could be used for the prediction of drag and lift forces acting on hulls sailing at drift angles. The study in [42] presents a design procedure for developing autonomous sailing that can be deployed on long-term cruises. The authors described the electronic and mechanical design strategies and focused on power management and boat reliability. The research in [43] focuses on potential energy savings through building more slender ships in combination with WAPS. Results presented by the authors indicate that GHG emissions and fuel consumption can be reduced by up to 30–40%. The objective of [44] was to present the status of the wind-assisted ship propulsion systems' technological development. The authors also focused on the potential GHG emission limitations, fuel savings, and operational efficiency of WAPS. The research in [45] presents solutions that could reduce emissions in the maritime industry. It focuses on three technologies: rotors, sails, and kites. The authors also provide guidelines on the risks and benefits associated with each technology. They also recommend guidelines for their performance prediction. The study in [46] investigates the design process of the propeller for a WAPS Oceanbird-type car carrier. The authors also focus on ship automation optimization procedures. It was decided to use CPP as suitable for the operation of the WAPS vessel. The authors explored propeller functions such as feathering, windmilling, and harvesting. The study in [47] analyzes the viability of WAPS technologies in maritime transport and various barriers inhibiting the implementation of those technologies. The analysis is carried out from the perspective of both the technology users and providers.

3. Current and Planned Applications of WAPS

WAPS are designed to convert wind energy into vessel propulsion. In energy conversion, various physical principles are used, depending on the type of technology used. There are four main categories of WAPS propulsion:

- Flettner rotors;
- Wing sails (hard sails);
- Suction wings;
- Soft kites.

Apart from the above designs, wind turbines have been developed to generate electricity on board ships. However, this paper focuses on WAPS systems. At the beginning of 2024, 29 vessels were equipped with wind-assisted propulsion systems. Flettner rotors were retrofitted on 10 ships (general cargo vessels, RO-RO ships, a tanker, and ferries).

They were also installed on two new builds (VLOC and RO-RO/LO-LO). Suction wings were retrofitted on eight ships (four general cargo vessels, one fishing vessel, one cement carrier, and one RO-RO). Seven vessels were equipped with hard sails. Four hard sails were installed on new builds (one pilot project on a passenger/car ferry, one bulk carrier, and two VLCCs), two retrofits on bulk carriers and one pilot retrofit on a catamaran. Only two kites have been installed so far: one on a RO-RO ship and one on a bulk carrier (both retrofits) [48]. Currently, WAPSs are being installed or are planned to be installed on another 72 ships [49]. Table 1 presents the current installations and future orders for wind-assisted propulsion systems. An 'order' is considered a unique instance applicable to a single range in the tables below.

Table 1. Wind-assisted propulsion systems—current installations and future orders [49].

	2018–2023	2024 and on Order	Total Number of Vessels
Rotor sails	13	25	38
Rigid sails	7	9	16
Suction Wings	7	37	44
Kite sails	2	1	3
Total	29	72	101

According to the data presented in Clarksons World Fleet Register [4], 101 ships have wind-assisted propulsion systems installed or will have them installed.

The number of orders is accelerating rapidly, with 29 systems installed between 2018 and 2023 and 72 orders in 2024. For the range of 2018–2023, the distribution of the WAPS installation is not uniform. According to [48], four systems were installed in 2018, one in 2019, two in 2020, eight in 2021, five in 2022 and nine in 2023. There is an increasing trend; however, the COVID-19 outbreak impacted the number of completed installations. A distinctive increase in installations and orders is visible in the 2024 figure. As per the data presented in Table 1, rotor sails are the technology with the largest share of the current WAPS market. However, with 37 orders for suction wings over the coming years, this proportion may change. Kite sails, with only two existing applications and one order, will remain a niche market [49].

Table 2 presents the current installations and future orders for WAPS divided by the ship's type and number of current applications/future orders. With 10 existing vessels and 18 orders, the largest share in the WAPS market comprises bulk carriers. RO-RO vessels, tankers and passenger ships have a similar number of orders compared with already-existing WAPS applications. There is a significant number of orders for the first WAPS installations on container ships, gas carriers, and car carriers. It is a reflection of the increasing uptake of WAPS into the shipping industry [49].

Table 2. Wind-assisted propulsion systems—vessel type/number [49].

	2018–2023	2024 and on Order	Total Number of Vessels
Passenger ship	4	3	7
RO-RO	4	5	9
Bulk carrier	10	18	28
Gas carrier	0	5	5
Container ship	0	6	6
Tanker	3	5	8
Car carrier	0	1	1
Other	8	29	37
Total	29	72	101

As per the data presented in Table 3, the majority of WAPSs were applied as retrofits to existing ships. So far, only five newly built vessels (17 percent of the total number) have had wind propulsion systems installed since the design stage. But this trend seems to be changing. A total of 72 percent of orders are for new vessels. However, it is also expected that the number of orders from the existing fleet will increase to meet the decarbonization requirements imposed by regulators [49].

Table 3. Wind-assisted propulsion systems—number of vessels, orders/installations: newbuild vs. retrofit [49].

	2018–2023	2024 and on Order	Total Number of Vessels
Retrofit	24	20	44
Newbuild	5	52	57
Total	29	72	101

Worldwide Statutory Framework of WAPS

WAPS can impact several environmental regulations, e.g., the IMO regulations specific to international shipping, EU Fit for 55 legislation, especially FuelEU Maritime and EU ETS, which regulate ships calling at EEA anchorages and ports. WAPS will also impact several national GHG regulations (not presented in this article) and contribute to emissions reduction from ships, as stipulated by regional regulators and the IMO.

The IMO EEDI (Energy Efficiency Design Index) and EEXI (Energy Efficiency Existing Ship Index) are the regulations established to reduce the shipping industry's carbon footprint. Both regulations take into account the energy-saving potential of WAPS technologies since the adoption of Guidance on Treatment of Innovative Energy Efficiency Technologies for Calculation and Verification of the attained EEDI and EEXI in 2021.

The IMO Revised GHG Strategy is part of the IMO effort to deal with climate change by reducing GHG emissions caused by the maritime industry. The GHG Strategy was initially adopted in 2018 and revised in 2023. It defines the statutory framework for how the shipping industry can reduce its carbon footprint and contribute to global efforts to meet climate goals, particularly those outlined in the Paris Agreement. Following the adoption of the revised strategy, The IMO MEPC (Marine Environment Protection Committee) and the ISWG-GHG (Intersessional Working Group on Reduction of Greenhouse Gas Emissions from Ships) were given a task to develop economic and technical measures to reduce greenhouse gas emissions, aligned with reaching net-zero emissions in 2050. WAPS can contribute to complying with the IMO Revised Strategy by reducing emissions, especially with its intention of "uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources to represent at least 5%, striving for 10%, of the energy used by international shipping by 2030". However, it is not clear how WAPS applications will meet the initiative's long-term targets, such as indicative checkpoints for the years 2030 and 2040. To meet those requirements, 20–30% GHG emission reduction for 2030 and 70–80% for 2040 (compared to 2008 emissions), and other no-emission or energy efficiency propulsion solutions would be needed.

WAPS will also impact the pricing mechanism on GHG emissions and a global-based fuel standard; however, both of those measures are still under development. WAPS was also included in the IMO LCA Guidelines (Lifecycle Analysis Guidance of Marine Fuels), which will be used in new measures as a zero-emission benchmark.

Maritime transport was included in the EU ETS (Emissions Trading System) on the 1st of January 2024. TtW (tank-to-wake) carbon dioxide emissions from vessels of 5000 GT and higher, reported under the procedure of monitoring, reporting and verification (MRV) in 2024, have been subject to the ETS since 1 January 2025. For general cargo and offshore vessels of 400–5000 GT and offshore ships of above 5000 GT, MRV reporting has been applicable since 1 January 2025. The inclusion of those ships into the ETS regime is expected from 2027. Shipowners will be required to purchase and surrender EUA (EU Allowances) to cover 50% of their CO_2, NOx and CH_4 emissions for voyages to and from EEA ports, and to cover 100% of their emissions for voyages between EEA ports and in ports. Initially, in 2024, the vessel operators were required to surrender EUAs to cover 40% of emissions. However, it is rising to 100% from 2026. Rewards for the vessels using WAPS were not considered by the EU; however, there are incentives in the EU FuelEU Maritime regulation.

The FuelEU regulation has been applicable since the 1st of January 2025. To reduce the GHG intensity in maritime transport, FuelEU set targets based on the 2020 emissions to incentivize low-emission propulsion systems on ships over 5000 GT. The GHG emission quotas within the FuelEU are similar to those covered by the EU ETS: half of the emissions on voyages to and from EEA ports, and all emissions for trips between the EEA ports and alongside berths in EEA harbors. The reduction in GHG intensity of fuels is measured on reported fuel consumption and the factors of emissions used on a WtW (well-to-wake) basis. The reduction will gradually increase. It will start with a 2% GHG reduction in 2025 to an 80% GHG intensity reduction in 2050. GHG emissions above the reference levels will be penalized [49].

According to the FuelEU Maritime Regulations, vessels with WAPS will be granted up to a 5% reduction in the GHG intensity calculation of energy used by the ships, on the condition that the wind harvesting accounts for at least 15% of the propulsion energy. For ships with a minimum of 5% wind energy used for the propulsion, there is a reward factor available that offers a 1% discount on the GHG intensity calculation. Those rewards are subject to the availability of a verifiable method for monitoring and accounting for wind propulsion energy. Vessels equipped with WAPS can reduce the penalties imposed by FuelEU Maritime and also extend the period until their emissions reach the penalty levels. If a ship achieves an additional (surplus) emissions intensity before 2030, this banked energy intensity can be used in the following year or used for other ships sailing in the same pool. According to [49], WAPS will continue to pay dividends even after 2030. It will allow shipowners to save penalties of up to EUR 100 per ton of fuel until 2025.

4. Applications of Wind-Assisted Propulsion Systems

4.1. Rotor Sails

For many centuries, wind provided free propulsion for sailing ships. Nowadays, it does not have enough energy to be a stand-alone propulsion system for modern vessels; however, a novel method of wind support auxiliary propulsion has been developed on several ships. This method uses the physical force of wind first utilized on a merchant ship in 1924. In the 1850s, German physicist Heinrich Gustav Magnus researched a force created by spinning cylinders and spheres. Since then, the force known as the Magnus Force can be seen in sports, e.g., when a tennis ball spins it will cause curving of its trajectory. Seventy years later, German engineer Anton Flettner attempted to apply this force in aviation; however, later on, he realized that the Magnus force could be used in shipping as a means of propulsion for the vessels. Flettner discovered that when fluid flows around a rotating cylinder, it is deflected on one side and slowed on the other. Consequently, the airflow will exert a force toward the lower-pressure side of the rotating cylinder. In 1922, Anton Flettner patented the spinning cylinder rotor sail. In 1924, his design was developed and implemented on the ship Buckau (Figure 1); traditional sails were replaced with spinning rotors. The two cylinders were powered by 37 kW electric motors. Flettner's experiment was successful; however, due to low fuel prices at the time, it was not economically beneficial [50]. For almost a century, Flettner rotors remained a curiosity, but it changed with the drive for greener shipping and focus on energy efficiency.

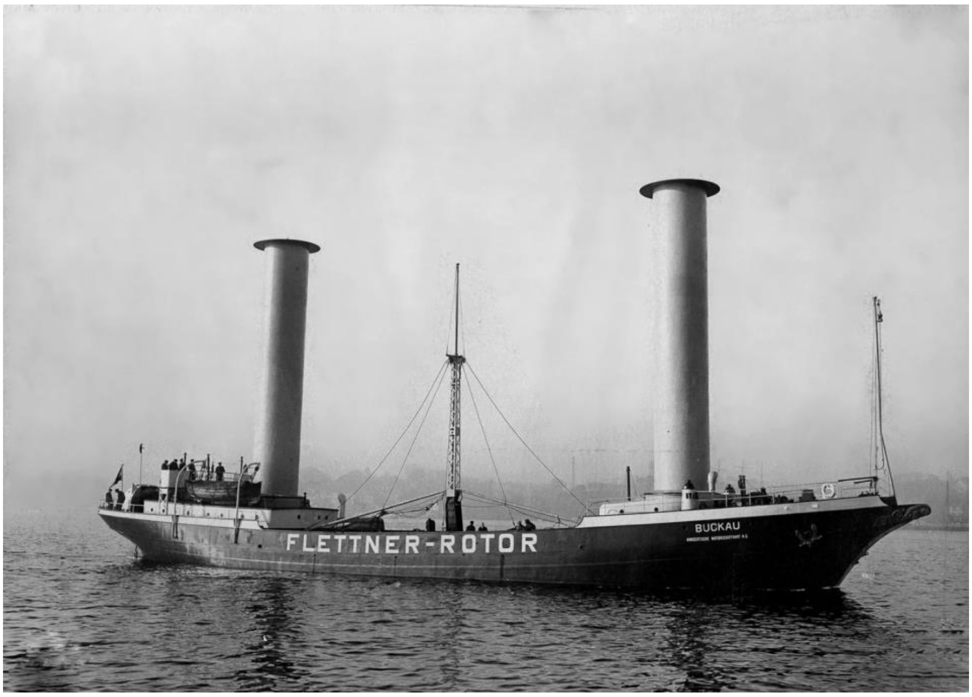

Figure 1. Buckau's Flettner rotors [51].

In 2010, Enercon, the German wind turbine manufacturer, launched RoLo (roll on lift off) E-Ship 1 (Figure 2). The vessel was equipped with four 25 m high, 4 m diameter Flettner rotor sails. The cylinders are rotated by steam turbines; steam is produced by the exhaust gas boilers. The 12,800 DWT vessel has been used to transport wind turbine elements. The vessel is 130 m long, 22.5 m wide, and its maximum speed is 17.5 knots. Its main propulsion is diesel engines, with a total output of 3.5 MW.

Figure 2. E Ship 1 [52].

During the first three years of operation, the vessel covered more than 170,000 Nm. According to Enercon [53], four Flettner rotors accounted for 15% of fuel savings during this period.

Finish company Norsepower, established in 2012, also revived Flettner's concept and added automatic control systems to it. They produced rotor sails up to a height of 35 m and a diameter of 5 m. The rotors are made of composites, which makes them lighter than aluminum and more fatigue-resistant. Several cargo vessels have been equipped with Norsepower rotors, including RO-RO ships, tankers, bulkers, tankers, and ferries. So far, 16 Norsepower Rotor Sails™ have already been installed on eight ships. The Rotor Sail systems are provided with an automation system that gives the crew control of the sails through the operating panel located on the bridge. The automation system monitors the wind direction and speed and adjusts the rotors' correct rotational direction and optimal vessel speed to minimize emissions and maximize fuel savings. The first Norsepower Rotor Sail was installed on the M/V Estraden (Figure 3) in November 2014. ESTRADEN is a RO-RO built in 1999.

Its gross tonnage is 18,205 tons, deadweight 9741 tons, length 162 m and breadth 25 m. The installation of the rotor took only seven hours during a routine port call. After a substantial reduction in fuel consumption, the vessel operator decided to install a second unit one year later. The rotor sails proved to be an effective solution due to the route of the ship (North Sea), which is affected by crosswinds most of the time. According to verified measurements, the installation of two rotor sails reduced fuel consumption by 6.1% [54,55].

Figure 3. M/V Estraden [56].

Another RO-RO ship, M/V SC Connector (Figure 4), operating in the North Sea, was retrofitted with two 35 m × 5 m Norsepower sails in 2021. Additionally, a 339 kW Corvus Orca Energy battery was installed, which allows emission-free sailing in ports. SC Connector is a RO-RO built in 2020. Its gross tonnage is 12,251 tons, deadweight 8843 tons, length 154.5 m and breadth 22.74 m. The ship sails between Denmark, Norway, Sweden, Poland, and the Netherlands. As it passes under multiple powerlines and bridges, the rotors can be tilted to almost horizontal if required. Roto sails' manufacturer predicted emission reduction to be about 25%, and, according to [54,57], this has been achieved.

Figure 4. SC Connector [58].

Flettner Rotors have also been installed on passenger vessels. Ferry company Scandlines operates the world's largest fleet of hybrid ferries, which combine diesel and battery power. Initially, they upgraded two ferries, "MS Berlin" and "MS Copenhagen", to hybrid propulsion and carried out berth adaptation for battery charging and terminal improvements of the two ports, Rostock and Gedser. MV Copenhagen (Figure 5) and Berlin are RO-PAX ferries with a car capacity of 230 and passenger capacity of 1300. Their gross tonnage is 22,319 tons, deadweight 4814 tons, length 169.5 m and breadth 25.4 m each. Both vessels have been in hybrid propulsion operation since 2016, which allowed a reduction in GHG emissions [59]. Installation of the Flettner rotor in 2020 reduced M/V Copenhagen emissions even further. The wind conditions on the 47 km shipping route between Rostock and Gedser are favorable for WAPS systems, and fuel consumption/emission reduction was as predicted by the manufacturer of the rotors; according to [60], it was 7%. Following a successful implementation of rotor sails onboard M/V Copenhagen, in 2022 Scanlines decided to replicate the same installation on a sister ship sailing on the same route—M/V Berlin.

Figure 5. M/V Copenhagen [61].

M/S Viking Grace (Figure 6), when built in 2013, was one of the most environmentally friendly cruise ships in the world. It was the first passenger vessel to operate on LNG (liquified natural gas) [62]. It allowed a reduction in GHG emissions of 15% and a reduction in particulate emissions of 85%. Viking Grace has a gross tonnage of 57,565 GT and a deadweight tonnage of 6107 DWT. Its length is 218 m, draft 6.8 m, and beam 31.8 m. The passenger capacity is 2800. The vessel has 1275 lane meters for RO-RO cargo and 1000 lane meters for cars [55]. In 2018, the vessel owner decided to install a 24 m × 4 m Flettner rotor. The ship was the first passenger vessel to use WAPS technology to reduce its environmental impact. Installation of the rotor sail allowed a further reduction in the ship's fuel consumption and emissions; CO_2 emission was reduced by approximately 900 tons per year, which is equivalent to 300 tons of LNG [54]. During the test period in 2018–2021, three independent third parties (Chalmers University, ABB and NAPA) carried out a testing campaign to check the long-term emissions reduction and fuel savings. The research confirmed that the rotor sail installation reduced annual fuel consumption by 231–315 tons (with power consumption reduction of 207–315 kW) [63].

Figure 6. M/V Viking Grace [64].

Rotor sails, due to the available deck space and their explosion-proof design, are suitable for tankers. In August 2018, two 30 m × 5 m rotor sails were installed onboard the Maersk Pelican (Figure 7) (current name: M/V Epanastasea). MV Epanastasea is an oil tanker built in 2006. Its cargo tank capacity is 117,922 m^3, gross tonnage 51,724 tons, deadweight 109,647 tons, length 244.6 m, and breadth 42.03 m. Following the rotor installation, the ship underwent testing and data analysis, which was carried out until the end of 2019. Tests carried out by LRS (Lloyd's Register of Shipping) confirmed fuel savings of 8.2% from 1 September 2018 to 1 September 2019 (equivalent to an emission reduction of 1400 tons of CO_2 [54,65]). It is expected that two 30 m × 5 m rotor sails installed on an LR2 (long-range 2) tanker can reduce fuel usage on typical shipping routes by up to 10%.

Another MR2 (middle-range tanker) retrofitted with rotor sails was M/V Alcyone. MV Alcyone (Figure 8) is a chemical/oil product tanker built in 2022. Its gross tonnage is 29,507 tons, deadweight 49,990 tons, length 183 m, and breadth 32 m. It sails on the route between French Polynesia and South Korea. In 2024, the ship was retrofitted with two 35 m × 5 rotor sails. The rotor manufacturer estimates that the fuel consumption reduction will be at least 8%. However, if voyage optimization is implemented, there is a potential for further savings, reaching the equivalent of an annual reduction of 2000 tons of CO_2 emissions [66,67].

Figure 7. Maersk Pelican [54].

Figure 8. M/V Alcyone [68].

Bulk carriers, due to available deck space, are another type of ship well suited for Flettner rotors. The rotors can be provided with a tilting function, which enables efficient cargo operations. The first bulk carrier fitted with rotor sails was M/V Sea Zhoushan (Figure 9). M/V Sea Zhoushan is a VLOC (very large ore carrier) built in 2021. Its gross tonnage is 173,666 tons, deadweight 325,000 tons, length 340 m, and beam 62 m. The vessel was equipped with five 24 m × 4 m rotor sails. At the time of the installation, the vessel was the largest ship ever outfitted with a WAPS system. The rotor sail manufacturer estimated that the sails installed on board the VLOC would allow an 8% reduction in fuel consumption, which is an equivalent of 3400 tons of CO_2 emission every year [69,70].

Figure 9. M/V Sea Zhoushan [54].

In June 2024, one 35 m × 5 m tilting rotor sail was installed onboard M/V Koryu. M/V Koryu (Figure 10) is a bulk/oil carrier built in 2013, sailing on the route Chile/Japan/Chile. Its length overall (LOA) is 189.95 m, width 32.26 m, gross tonnage 30,476 tons, deadweight 53,762. According to the simulation provided by the rotor sail's manufacturer, the use of the WAPS system is estimated to provide up to 6% fuel savings [71,72].

Figure 10. M/V Koryu [73].

In May 2024, four tiltable 35 × 5 m Flettner Rotors were retrofitted onboard bulk carrier Berge Neblina. Installation time was only 4 days. The sails can be folded during cargo operations. Mv Berge Neblina (Figure 11) is an ore carrier built in 2013. Its gross tonnage is 195,199 tons, deadweight 392,099 tons, length 361 m, and beam 65 m. According to the sail manufacturer, the expected reduction in emissions and fuel consumption will be around 8% [74].

Figure 11. M/V Berge Neblina [75].

In June 2023, three rotor sails (24 m × 5 m) were installed on TR Lady. Each rotor has a transverse rail deployment system which enables the rotors to be moved to starboard or port during cargo operations. TR Lady (Figure 12) is a bulker built in 2017. Its length overall (LOA) is 229 m, beam 32 m, gross tonnage 44,642 tons, and deadweight 81,587 tons. The rotor manufacturer estimated the reduction in emissions and fuel consumption to be around 10%. A manufacturer representative sailed with the vessel during its first trip with rotors from China to Australia. Initial testing suggested that the vessel exceeded the original estimation [76,77].

Figure 12. M/V TR Lady [77].

In June 2018, an 18 m × 3 m Flettner rotor was installed on the general cargo ship Fehn Pollux—Figure 13 (now Goldy Seven). Goldy Seven was built in 1997, its gross tonnage is

2844 tons, its length is 89.77 m and its width is 13.7 m. Monitoring and control systems for the Flettner sail were developed by Leer University of Applied Sciences. Scientists from the university evaluated the efficiency of the WAPS in operational conditions during the first year of the operation. According to the gathered and processed data, model calculations predicting a 10% reduction in fuel consumption were correct. The power potential of the rotor sail was in the range of 100 kW to 150 kW in addition to the main engine power. Measured fuel savings were 10–20%, depending on the power of the main engine and the vessel speed. Higher fuel savings were recorded with a reduced ship's speed.

Figure 13. M/V Fehn Pollux [78].

In April 2021, an 18 m × 3 m Flettner rotor along with its weather station and automated operating system was installed on the general cargo ship Annika Braren (Figure 14). Anika Braren was built in 2020, its gross tonnage is 2996 tons, its length is 86.93 m and its width is 15 m. Trials carried out following the installation reported 15% fuel savings with favorable wind angles; however, the average reduction was determined to be in the range of 2–4.5% [48].

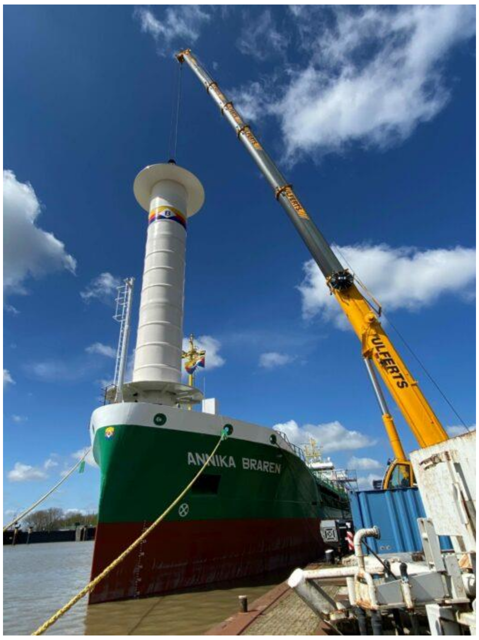

Figure 14. M/V Annika Braren [79].

M/V Afros (Figure 15), built in 2018, is the first Flettner Rotor Ultramax bulk carrier. Its gross tonnage is 36,452 tons, deadweight 63,223 tons, length 199.9 m and breadth 32.3 m. The ship was equipped with four rotor sails (16 m × 2 m). The rotors were installed on the starboard side of the vessel; however, they sit on a carriage structure which can be repositioned to allow cargo operations. The efficiency tests were carried out from November 2019 to January 2020 when the vessel sailed on a regular route between Vancouver and Nantong. The calculated fuel savings were 12.5%, which is the equivalent of 73 tonnes of fuel/235 tonnes of CO_2 emissions [80].

Figure 15. M/V Afros [80].

M/V Delphine (Figure 16), having a cargo capacity of 8000 m, is the largest operating short-haul RO-RO vessel in the world. In February 2023, the vessel was equipped with a WAPS system consisting of two foldable 35 m × 5 m rotor sails. M/V Delphine was built in 2018. Its length overall (LOA) is 234 m, width 35 m, gross tonnage 74,273 tons, and deadweight 27,687 tons. The ship navigates between Ireland, Europe, and England. Since the installation of the rotors, fuel consumption and GHG emissions have been reduced by 10% [81].

Figure 16. M/V Delphine [82].

4.2. Hard Sails

Wing sails (also referred to as hard sails) work like conventional soft sails. The interaction between the sail and the wind creates drag force and aerodynamic lift. The difference is in the materials they are fabricated from; hard sails are made of strong and light materials like carbon fiber and have rigid geometry. It is possible to rotate the wing sails to adjust them to the direction of the wind to achieve maximum propulsion; this function is usually fully automatic. The aerodynamics of the hard sails is based on airplane physics principles and their geometry is similar to that used in aviation. The geometry of the hard sails provides a higher lift-to-drag ratio and creates more lift (in comparison to conventional soft sails). Wing sails vary in size; the largest ones can be 50 m high and have up to 1000 m^2 surface.

M/V Pyxis Ocean is the first vessel retrofitted with two hard sails. Pyxis Ocean (Figure 17) is a bulk carrier built in 2017. Its length overall (LOA) is 229 m, beam 32.26 m, gross tonnage 43,398 tons, and deadweight 80,962 tons. Two wing sails 37.5 m in height were installed in August 2023. The operation of the sails is automatic; they self-adjust to an optimal configuration. During 6 months of testing, the ship sailed the Pacific Ocean, Indian Ocean, and Atlantic, passing the Cape of Good Hope and Cape Horn. After the trial period, it was concluded that wing sails achieved performance equivalent to a reduction in fuel consumption of 3 tons per day—14% of average daily consumption. This equates to 11 tonnes of CO_2 emissions. The results were verified by DNV, who were hired to review the fuel consumption calculations. In optimal wind conditions, the ship was able to achieve savings of 11 tonnes of fuel daily. Further savings are possible with the installation of an additional wing sail onboard the vessel. A vessel of this size can easily be equipped with three wind sails. This could further improve the fuel savings and emissions [83].

Figure 17. M/V Pyxis Ocean [83].

In October 2023, M/V Berge Olympus (Figure 18) became the second vessel fitted with wing sails. They are expected to achieve a double-digit percentage reduction in CO_2 emissions and fuel consumption. Mv Berge Olympus is a bulk carrier built in 2018. Its length overall (LOA) is 300 m, beam 49 m, gross tonnage 109,716 tons, and deadweight 211,153 tons. The vessel sails between China and Brazil; this route is known for favorable wind conditions. With four 20 m wide, 37.5 m tall wing sails, and the total surface area of the four wings at 3000 m^2, Berge Olympus will reduce fuel consumption by six tonnes per day on an average route. CO_2 emissions will be reduced by 19.5 tonnes per day.

Figure 18. M/V Berge Olympus [84].

In September 2022, DSIC (China's Dalian Shipbuilding Industry Co.) delivered the WAPS wing sail-powered supertanker M/V New Aden. Back in 2018, DSIC also fitted two wing sails to the VLCC mv New Vitality; however, the results of sea trials of this WAPS application are unknown. M/V New Aden (Figure 19) is a VLCC (very large crude carrier). Its gross tonnage is 162,925 tons, deadweight 306,474 tons, length 332 m and breadth 60 m. The vessel was designed to sail between the Far East and the Middle East; this route is known for favorable wind conditions. The vessel was equipped with four rigid wing sails. The raised sail has a surface of 1200 m^2 each and a height of 40 m. The blades are made of carbon fiber. As a result, they have good corrosion resistance, low weight, and high strength. The efficiency of the sails is maximized with a fully automatic system used to raise and turn the sails. DSIC estimated that the vessel would achieve a 9.8% reduction in fuel consumption, which is equivalent to 2900 tons of CO_2 emissions [85,86].

Figure 19. M/V New Aden [86].

M/V SHOFU MARU is the first cargo ship equipped with Wind Challenger WAPS. The system, developed in Japan, uses telescoping wing sails to harness the power of wind. SHOFU MARU (Figure 20) was delivered in October 2022. Its gross tonnage is 58,209 tons, deadweight 100,422 tons, length 235 m and breadth 43 m. The vessel transports coal to Japan from North America, Australia, and Indonesia. The installation of the wing sails was expected to reduce fuel consumption by about 8% on the North America–Japan route and by 5% on the Australia–Japan route [87].

Figure 20. M/V Shofu Maru [88].

4.3. Suction Wings

Suction wings are vertical sails that have a wing shape. They are mounted to the vessel structure (main deck). The opposite of Flettner rotors, their outer cylinders do not rotate. The sails, however, can be adjusted automatically to the direction of wind. The wing sails have internal built-in fans and vents that use boundary layer suction to create force in addition to the thrust conventionally generated by the sails. Similar to rotor sails, suction wings generate optimal force under a side wind. Under tail and head winds, their thrust is zero. Suction wings' sail height can be up to 36 m. Usually, two or four wings are installed per ship; however, there are vessels with only one suction wing. Small units (height less than 10 m) can be provided as containerized systems. It makes it easy to move them from one vessel to another.

In 2020, two retractable suction wings were installed onboard MV Ankie. Ankie (Figure 21) is a general cargo ship built in 2007. Its gross tonnage is 2528 tonnes, deadweight 3636 tonnes, length overall (LOA) 89.99 m and beam 12.5 m. The initial height of the sails was 10 m; however, later on, they were extended to 13 m. The built-in fans are propelled by 2×15 kW electric motors. The sails can be lowered during port operations or when sailing against a headwind. The estimated fuel savings resulting from the installation of the sails reached 4.5%.

Figure 21. M/V Ankie [89].

Econowind VentoFoil suction wings have been installed on five vessels in total, mainly small general cargo vessels and a chemical tanker. According to the manufacturer, the expected reduction in fuel consumption/emissions was up to 10% [89,90].

4.4. Kites

Kites are fixed to the bow of a vessel to generate drag and lift. They have automatic systems to launch/retract depending on the weather conditions. As they are deployed at altitudes higher than rotor sails and hard sails, they can utilize higher wind speeds; however, there is a detrimental effect of higher elevation angle. The kites can be passive, following the direction of the wind, or dynamic, moving to increase the generated lift. Their size can be up to 1000 m^2. Kite development is still in the experimental phase. The first kite-supported propulsion system was installed onboard the ship Ville de Bordeaux. Ville de Bordeaux (Figure 22) is a RO-RO cargo vessel built in 2004. Its gross tonnage is 21,528 tonnes, deadweight is 5291 tonnes, overall length (LOA) is 154 m, and beam is 24 m. Two 250 m^2 and 500 m^2 prototypes were used for testing the kites. Tests included elements such as kite take-off, landing, ascent and descent. In May 2023, it was reported that the kite generated thrust for the first time. The wing manufacturer predicts a 16% reduction in fuel consumption; however, this assumption needs to be verified during sea trials [91,92].

Figure 22. M/V Ville de Bordeaux [91].

5. Emission Reduction Potential of WAPS

The fuel consumption and emission reduction potential of wind-assisted propulsion systems can be determined either by numerical simulation or by measuring fuel consumption during trials. Simulation models calculate the reduction of fuel consumption based on several factors, such as thrust generated by sails, ship route, wind direction and speed, vessel characteristics, etc. Measurements are carried out during the trials, which provide data on the difference in speed, propulsion power, fuel consumption, and emissions for the ship's operation with and without the WAPS.

WAPSs also consume energy, and it should be considered in the fuel saving calculation. The thrust produced by sails depends on the wind speed and direction. Higher wind speed and favorable wind direction are expected to increase the amount of thrust produced by

WAPS. However, this condition will also deteriorate the hull performance due to wave impact. Maneuverability and stability of the ship will dictate the maximum wind speed limits for the operation of WAPS. In harsh conditions, WAPS will have to be switched off due to safety considerations.

Implementation of WAPS may, in some cases, decrease the main propulsion efficiency and increase the SFOC (Specific Fuel Oil Consumption). Main engines are optimized in such a way that SFOC is lowest at the engine load that corresponds to the designed speed. With sails in operation, with the same speed, a vessel will sail at a lower engine load. The overall fuel consumption will decrease; however, the engine will operate with the sub-optimal load. This will affect SFOC and total fuel savings unless it is possible to adjust the tuning of the engine.

The reduction in fuel consumption and related emissions will also depend on the type of WAPS.

5.1. Rotor Sails Fuel Saving Potential

A single rotor sail, according to the information provided by the manufacturers, can produce thrust up to 385 kN, depending on the height and diameter of the rotor. Many measurements and simulations have been carried out to determine sails' potential to reduce fuel consumption/emission. It seems that, so far, most studies have been carried out on the saving potential of Flettner rotors. As per the information provided in Chapter 3 of this article, the measurements revealed the following fuel consumption reduction:

- M/V E-Ship 1 (RO-LO ship)—Four Flettner rotors accounted for 15% of fuel savings during the first three years of operation.
- M/V Estraden (RO-RO ship)—According to verified measurements, the installation of two rotor sails reduced fuel consumption by 6.1%.
- M/V SC Connector (RO-RO ship)—It was predicted that the retrofit of two rotor sails would reduce fuel consumption by 25%; according to the sail manufacturer, it has been achieved.
- M/S Copenhagen (ferry)—It was reported that the installation of the Flettner rotor reduced fuel consumption by 7%.
- M/S Viking Grace (cruise ship)—Installation of a 24 m $\times$ 4 m rotor sail allowed reduction in the ship's annual fuel consumption by 231–315 tons.
- M/V Maersk Pelican (tanker)—Installation of two 30 m $\times$ 5 m rotor sails allowed fuel savings of 8.2% during 1 year of verified testing.
- M/V TR Lady (bulk carrier)—Three rotor sails (24 m $\times$ 5 m) were retrofitted in 2023. The rotor manufacturer estimated the reduction in emissions and fuel consumption to be around 10%. However, the initial testing suggested that the vessel exceeded the original estimation.
- M/V Afros (Ultramax bulk carrier)—The ship was equipped with four rotor sails (16 m $\times$ 2 m). The efficiency tests were carried out from November 2019 to January 2020 when the vessel sailed on a regular route between Vancouver and Nantong. The calculated fuel savings were 12.5%.
- M/V Delphine (RO-RO ship)—Since the installation of two foldable 35 m $\times$ 5 m rotor sails in 2023, fuel consumption and GHG emissions have been reduced by 10%.

5.2. Hard Sail Fuel Saving Potential

The number of hard sail installations has increased in recent years, but the data on the fuel reduction potential of this wind technology remain limited. Available information is mainly derived from simulations, which are not as accurate as trial measurements:

- M/V Pyxis Ocean (bulk carrier)—Retrofit of two wing sails of 37.5 m in height in August 2023 allowed fuel consumption reduction of 14% of daily consumption. These results were measured during trials and verified by an independent body.
- M/V Berge Olympus (bulk carrier)—According to the simulation data, the installation (retrofit) of four 20 m wide, 37.5 m tall wing sails will reduce fuel consumption by six tonnes per day on an average route.
- M/V New Aden (supertanker)—In 2022, the vessel was equipped with four rigid wing sails. The raised sail has a surface of 1200 m^2 each and a height of 40 m. The trial results of this WAPS application are unknown. According to the simulation data, it is estimated that the vessel would achieve a 9.8% reduction in fuel consumption.
- M/V Shofu Maru (cargo ship)—As per the simulation data, the installation of Wind Challenger rigid wing sails is expected to reduce fuel consumption by 5–8%, depending on the route of the vessel.

5.3. Suction Wings Fuel Saving Potential

According to the manufacturers, a single suction wing of a height up to 16 m can reduce the main propulsion load by approximately 200 kW. Other suppliers advertise their products to be able to reduce fuel consumption by up to 40%. However, speed trials carried out on dry cargo vessel M/V Frisian Sea, equipped with two 3 × 10 m suction wings, proved savings of only 2–4% [48]. In 2020, two retractable suction wings were installed onboard general cargo vessel MV Ankie. The initial height of the sails was 10 m; however, later on, they were extended to 13. The estimated fuel saving resulting from the installation of the sails was 4.5%. Ecowind suction wings have been installed on five vessels in total, mainly small general cargo vessels and a chemical tanker. According to the manufacturer, the expected reduction in fuel consumption/emissions was up to 10% [93]; however, trial measurement data are not publicly available.

5.4. Kites Fuel Saving Potential

The development of kites is still in the experimental phase, and less modelling and research have been carried out on their performance compared to other WAPS technologies. It is difficult to estimate their fuel consumption saving potential due to a lack of available data. There are numerical simulations available in the literature; however, so far, they have not been verified during ship trials. A kite-supported propulsion system was installed onboard the RO-RO ship M/V Ville de Bordeaux. In May 2023, it was reported that the system generated thrust for the first time. The kite manufacturer predicts a 16% reduction in fuel consumption; however, this assumption has not been verified during sea trials.

Fuel savings and effectiveness of WAPS may be determined by the level of automation of the sail systems; the orientation of sails to the wind direction will affect the thrust generated by the sails. To increase fuel savings, vessels may change their routes to benefit from better wind conditions. The unoptimized (conventional) sailing route of the vessel is the shortest one, so after voyage optimization is applied, a trade-off between increased route length and the efficiency of sails must be calculated. Fuel savings generated by the higher effectiveness of WAPS must exceed increased fuel consumption caused by a longer sailing route. However, if the voyage optimization results in the elongation of the vessel's trip, it will have a negative impact on the revenue generated by the ship over time, as transportation of the same cargo will take longer.

6. Market Forecast/Future Trends and Barriers in Wind-Assisted Propulsion System Development

Only a few studies attempted to size the future WAPS market and describe possible future trends. A study sponsored by the UK government (Clean Maritime Plan) assessed the global market of alternative maritime fuels, technologies and, among others, wind-assisted propulsion systems. According to the study, the market is expected to grow to GBP 2 billion a year by the 2050s, compared to the current GBP 300 million in the 2020s. In the study, wind technologies, which include wind propulsion as a primary system and wind-assisted propulsion systems, are considered as one of the most important Energy Efficiency Technologies (EETs) capable of meeting the IMO requirements. According to [94], in the 2050s, wind technologies will cover approximately 15% of the maritime propulsion market.

Another study carried out by CE Delft for the European Commission [95] predicted an increase in the uptake of WAPS technologies (mainly suction wings), with some of them reaching commercial maturity. The study concluded that WAPS technologies would be widely available for the maritime industry in the 2020s. According to the research, the peak market for the container ship, tankers and bulkers is estimated to be approximately 3700–10,700 systems installed by 2030 (both newbuilds and retrofits). The variation in the estimated figure is caused by the uncertainty of future bunker costs. Some wind-assisted propulsion technologies reached maturity even before 2020. The timing of the initial implementation of WAPS into the maritime market did not match the CE Delft forecast. The report predicted hundreds of WAPS installations at the beginning of the 2020s. The reality was 29 installations by the end of 2023. Lower-than-expected fuel prices could have caused this discrepancy. However, recent dynamics in the WAPS implementations may prove that the CE Delft research was correct. By 2024, more than 100 WAPS were installed or ordered; the installation peak projected by the research model may be just about to happen. If this is the case, the majority of the installation will occur in the coming years (both newbuild vessels and retrofit projects), and then, the demand will be reduced and limited to the newbuild vessels only. To be able to meet the existing orders, the technology suppliers would need to annually deliver 2.5 times the number of units delivered in the past 5 years. To achieve a predicted uptake of WAPS technology by 15% of the global fleet, the global production capacity of the WAPS would have to increase by 75 times. Another challenge is with the installation capacity. In the years 2018–2023, there were only five newbuild vessels equipped with WASP. In anticipation of fast and strong growth, shipyards will be required to build up their capacities and competencies to meet demand.

The CE Delft research also predicts that installation of WAPS on existing vessels will continue for some years and represent up to 50 percent of all installations. The number of newbuild projects observed recently contradicts this prediction. However, according to the International Windship Association (IWSA), shorter lead times for retrofit projects may result in a significant increase in announced retrofit projects. There is another forecast based on public announcements and 2022/23 figures provided by IWSA members (vessel operators and technology providers) [95]. This forecast lags behind the current status of WAPS implementations; however, it is in line with the earlier CE Delft study. According to the IWSA report, the retrofit market can expand very fast, as the WAPS delivery time for existing vessels is relatively short, depending on foundation and deck reinforcement required. It can be completed in a few days or even in a matter of hours.

The report in [49], based on the studies carried out by Lloyds Register, predicts that the uptake of wind-assisted propulsion technologies is reaching a tipping point; the number of installations will increase dramatically in the next few years, and the number of 10,700 container ships, tankers and bulkers equipped with WAPS estimated in [96] is realistic. The analysis presented in the CE Delft research overestimated the timing and pace of the WAPS implementation but, according to [49], the fundamental dynamic of the WAPS market was accurate.

A possible trend in WAPS technology implementation is the development of wind-ready vessels. With vessel operators assessing WAPS for new ships and acknowledging that wind-assisted propulsion technology may be beneficial for them in the future, the option exists to prepare the vessels for the implementation of a specified WAPS or in general to adopt the vessel to be ready for WAPS installations in the future. It entails building a new ship with some minor changes/improvements at the design and build stages that can reduce the cost of later WAPS retrofit. Such changes are reinforcement of the deck and superstructure, adjustment of navigation equipment and other vital systems, electrical system mods, etc. It may also entail making adjustments and retrofitting structures of existing ships to make them capable of WAPS implementation at a later date. As of August 2023, only eight ships have been built as wind-ready; however, recently, six wind-ready 50,000 DWT MR tankers have been delivered to Greek shipowner Capital Ship Management with ABS Class Notation Wind-Ready. Another possible and already observed trend in the WAPS development is WAPS modularization. There are ships with modular versions of wind-assisted propulsion systems, including both suction wings and wing sails. They are deployed on Flatrack systems or in containers. A lot of existing, retrofit installations can be considered modular too, since their installation takes only a few hours once the structural/foundation work has been completed at an earlier stage (e.g., during the scheduled yard stay of the vessel). Modularization could allow different business approaches to the installation of WAPS, where wind-assisted propulsion systems can be relocated to the vessels that operate in windier geographical regions.

Another trend that can be observed in the information provided in Section 4 of this article is the increase in the number of units installed on each ship. It has been increasing since 2022, as wind-assisted propulsion systems were just about to move past the demonstration and testing stage, e.g., in 2018, two out of four vessels. Flettner rotor installations deployed just one unit per vessel. In 2023, all four vessels with Flettner sails installed were fitted with more than one unit. This trend illustrates a lower risk level associated with the installation of WAPS perceived by the vessel operators and increasing acceptance of the systems by the maritime industry.

There are many potential barriers to the diffusion of wind-assisted propulsion systems in maritime transport. As there are no standardized criteria for assessing the saving claims, the first barrier is uncertainty related to actual fuel savings following WAPS implementation.

Another barrier is the possible hidden costs related to the WAPS implementation, including operational costs and the entire scope of engineering work. Savings resulting from WAPS installation should be evaluated in comparison to other Energy Efficiency Technologies. WAPS can offer a fuel cost reduction of up to 10% but at an estimated investment cost of up to USD 2.5 million. The installation costs for retrofit are higher compared to newbuild; they are around 25% of the unit cost compared to 18% for newbuild [48,49]. This is due to the additional cost of adding new structures that have not been included in the original design. Apart from the CAPEX cost of the installation, the shipowners also have to consider the OPEX cost of the energy consumption, maintenance, surveys and training of the crew.

If the WAPS demand grows according to the prognosis presented in [94–96], the supply chain may be a bottleneck for meeting this demand. To meet the orders, the suppliers would have to deliver now 2.5 times the number of systems they have delivered in the past five years. The most optimistic prognosis predicts a 15% uptake by the global fleet. To achieve such an uptake, it would be required to have a 75-fold increase in the WAPS production capacity [49]. To meet the top range of the prognosis for 2030 presented in [95], a 100-fold increase in the supply chain would be required over the next six years. Until now, only around 16 shipyards carried out WAPS installation. Additionally, the International Wind Ship Association identified 20 companies in the development and research stage and 10 in the premarket stage. It is a clear indication that the production/installation capacity needs to increase if future demand is to be met. One of the possible options is to introduce a two-stage retrofit of the WAPS. Cabling and foundations can be prepared during the scheduled vessel refit or the newbuild (Wind-Ready Class Notation). The wind-assisted propulsion system could be installed during the following yard stay or even during a scheduled port call.

Operator and crew experience can be another potential impediment to the diffusion of WAPS. Wind-assisted propulsion systems are installed on less than 0.03% of the worldwide fleet. It is stretched across four technology types and different suppliers. This means that there is very limited industry experience with any of the wind technologies.

Credible WAPS performance information is another collective bottleneck. System providers have third-party performance information. However, this information is only available for future, prospective clients. Individual suppliers are reluctant to share the data. Aggregation and collation of the data are challenging too. There have been projects aiming to improve the information sharing between the stakeholders. One of them was the EU Interreg WASP Project [97], which presents the study of WAPS installations on five vessels. The lack of credible and comparative data is caused by the complexity of the comparison with many variables, the limited number of pilot installations (demonstrators) for each technology, and the reluctance of the system suppliers to share sensitive information.

7. Conclusions

Maritime transport and ship owners have already been subjected to increasing pressure to eliminate or at least reduce greenhouse gas emissions. In response to the new regulations, vessel owners will have to apply alternative fuels or new technologies, including wind-assisted propulsion systems, to reduce emissions.

The analysis presented in this article suggests that the number of wind-assisted propulsion system applications will increase substantially as ship operators introduce solutions that reduce fuel consumption and decarbonization costs. However, there are several issues that still to be resolved before widespread development of the WAPS technology. The main one is the uncertainty regarding the fuel consumption reductions following the implementation of WAPS. Cost–benefit analysis of WAPS installation is not straightforward. Reduction in fuel consumption achieved by each WAPS solutions will depend on ship type, position and number of WAPSs, wind condition (speed and direction), vessel speed and route. There are no standards or criteria for the validation of fuel savings. It is difficult to compare fuel savings for different types of ships, and different WAPS models. From the data presented in chapters 3 and 5 of this paper, it can be concluded that there is a large variation in the fuel consumption reduction advertised by WAPS manufacturers and the actual savings achieved during sea trials carried out by independent bodies.

Regardless of the WAPS model, savings are expected to increase over time (due to the required implementation of more expensive alternative fuels). Fuel savings will also depend on the specific route of the ship. To improve the WAPS efficiency, it may be required to optimize ships' routes to balance the route length and availability of favorable wind—to apply voyage optimization. However, it is not possible for all WAPS applications, e.g., this option is not available for ships like ferries and container ships, which have fixed routes.

With the current number of orders and installations, it is expected that the number of ships with WAPS will pass 100 within the next few years. It is apparent that the WAPS market is increasing. New systems are ordered for a wider segment of vessels. When pilot systems initially consist of only one unit, new orders involve more units per ship. To date, most of the current WAPS applications have been retrofitted to existing ships (83%), and only five newbuilds had WAPSs included from the design stage. However, there is a growing number of orders for newbuild ships. A total of 72% of orders are for new vessels. However, this proportion may change, as the ship operators may consider WAPSs to reduce emissions, and subsequently to meet the IMO decarbonization requirements.

Looking at the number of WAPSs in operation, presented in chapter 3 of this article, it is apparent that the majority of the systems are based on the Flettner rotor principle. However, a review of the orders shows that this trend may change; suction wings may dominate the market of WAPSs. Kite sails are still in an experimental stage and remain a niche market.

However, even with uncertainty related to the actual cost–benefit balance of WAPS installation and fuel savings, retrofitting WAPS may expand the lifetime of existing vessels. IMO implemented the Carbon Intensity Indicator (CII) to monitor/reduce carbon emissions by ships. Ship efficiency is grouped into five bands on a scale of A, B, C, D and E. Stepped improvements of the ship's ratings are required. An initial reduction of 5% was introduced in 2023; however, subsequent annual reductions of 2% will be needed until 2026. CII will have a major impact on the implementation of Energy Efficiency Technologies (EETs) in the maritime industry, particularly for existing ships, which will be required to extend their compliance by prolonging their lifetime in a better CII group. All ships will be required to achieve at least a C rating. According to [49], the percentage of ships achieving band A, B, or C will drop from 58% to 35% before 2026, which is equivalent to 3000 ships that will be required to implement some sort of EET. As the implementation of WAPS will enable ships to decrease their fuel consumption (compared with conventional propulsion systems), it will also improve their CII rating [96]. The implementation of WAPS may allow shipowners to increase the lifetime of fully compliant vessels by a few years.

However, the IMO decisions on further CII reductions beyond 2026 can have a major impact on the implementation of EETs. The vessel operators may decide to use alternative fuels, as they would offer greater emission reductions, especially in a longer-term perspective. The higher cost of alternative fuels, though, may make investments in WAPS more attractive, with reduced spending on fuel and improved CII. It is expected that the installation cost of WAPS will decrease over time, and it will improve the trade-off between the investment and fuel savings required to recover the investment.

Wind-assisted propulsion systems are mature technologies, with various vessels equipped with WAPS; rotor sails, hard sails, and suction wings have been proven to be technologically ready.

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