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A Comeback of Wind Power in Shipping: An Economic and Operational Review on the Wind-Assisted Ship Propulsion Technology

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Abstract: Wind-assisted ship propulsion (WASP) technology seems to be a promising solution toward accelerating the shipping industry's decarbonization efforts as it uses wind to replace part of the propulsive power generated from fossil fuels. This article discusses the status quo of the WASP technological growth within the maritime transport sector by means of a secondary data review analysis, presents the potential fuel-saving implications, and identifies key factors that shape the operational efficiency of the technology. The analysis reveals three key considerations. Firstly, despite the existing limited number of WASP installations, there is a promising trend of diffusion of the technology within the industry. Secondly, companies can achieve fuel savings, which vary depending on the technology installed. Thirdly, these bunker savings are influenced by environmental, on-board, and commercial factors, which presents both opportunities and challenges to decision makers.

Keywords: wind-assisted ship propulsion; innovations in shipping; sustainable maritime solutions; green shipping



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1. Introduction

The earliest known sailing ship can be dated back to 3100 BC, when Egyptians utilized the north wind to travel south on the Nile [1]. In the following centuries, maritime transportation had relied heavily on the mercy of wind, before a major transition occurred in the 19th century, when steamships greatly enhanced the flexibility and reliability of transporting cargoes and passengers. The world tonnage share of steamships increased from 15.8% in 1855 to 97.1% in 1910, making sailing ships practically irrelevant [2]. The pursuit of efficiency has sidelined wind power for nearly two centuries, until recently, when decarbonization goals moved it to the top of many company agendas. In order to align with the emission reduction goals set out in the United Nation's 2015 Paris Agreement, the International Maritime Organization (IMO), the regulatory body of the maritime industry, launched its first-ever emission reduction strategy in 2018 [3].

As a result, the interest in wind power has been reignited as the maritime industry sees its potential in reducing the propulsive power from fossil fuels by introducing wind power. This would allow a ship to maintain the same speed for reduced engine power or increase ship speed for the same engine power [4]. Simply put, the main benefits of using wind power on ships are the same as for the general wind power industry, namely, low carbon emissions and reducing exposure to the price volatility of fossil fuels [5]. To harness wind power on modern ships, a range of wind-assisted ship propulsion (WASP) products have been developed and trialled. Following primarily [6], the WASP commercial technologies are taxonomized in rotors, towing kites, suction wings, rigid sails/wingsails, soft sails, wind turbines, and hull sails.

Notwithstanding the appealing character and the broad variety of available WASP technologies, the diffusion of this technology within the maritime transport sector is still limited.

The high capital costs required for this investment and the uncertainty of its implications in terms of fuel consumption reduction represent some of the factors that slow the technology's diffusion. Key industry's stakeholders (i.e., shipping companies, associations, and academic institutions) have also highlighted these factors during the International Wind Propulsion for Shipping Forum of the Green Ship Technology (GST) 2020 conference.

The scientific literature has shown various topics so far: from the potential of wind to reduce emissions in shipping [7] over the possible energy efficiency enhancement of ships [8] to the importance of bunker prices and policy action for the uptake of wind technologies [9]. Therefore, the present study explores the status of WASP uptakes and its underlying commercial fundamentals in more detail, also taking into consideration the uncertainty as regards the implications of wind technological innovation [9]. In this context, this paper aims to provide a literature review following the methodology in [10], where a range of topics of wind energy technology development are discussed.

The present manuscript sheds light on the aspects that industry stakeholders (e.g., shipping companies, policy makers) should take into account when assessing available WASP technologies and can have an influence in their uptake. The paper identifies the importance of regulatory drivers, market alternatives, latest market developments, economic impact, and operational considerations related to WASP technological installations as key aspects. These areas of focus were also indicatively evident during the International Wind Propulsion for Shipping Forum of the GST2020 conference. The review encompasses a broad range of secondary data. Particularly, in the first step of developing this manuscript, we looked into scientific literature with a focus ranging from engineering over policy to transportation aspects related to wind propulsion technologies. Nevertheless, recent WPT developments and their implications have not reached the scientific literature yet. Therefore, the review was expanded to include industry reports (e.g., from classification societies), online news articles (e.g., from Tradewinds, Lloyd's List), and commercial companies websites.

The review covers, mainly, the cases of commercial transport ships that exceed 5000 gross tonnage (GT), as those account for about 85% of CO₂ emissions from international shipping [11]. Some smaller commercial ships are also included, as the installations of the WASP technology are recent, and their gross tonnage is close to 5000. Container ships, bulk carriers, and oil tankers are the focus of the study, as those ships represent the largest shares of global fleet with 17.6%, 33.6%, and 25.4% in gross tonnage respectively in 2018 [12] and are the leading pollutants. Their main engines consume the most marine fuels, 22.5%, 18.7%, and 13.4% respectively in 2015 [13]. The study does not investigate the cases of private yachts and small exhibition ships, as leisure shipping operates in a distinctively different manner, and those ships account for a proportionally small portion of emissions.

The contribution of the study is fourfold. Firstly, the article establishes the relevance of the WASP technology in the context of current regulatory changes and growth of alternative fuels toward a greener maritime industry. Secondly, it presents a detailed record of the WASP technology adoption in different shipping segments, showing a critical trend of high growth and increased diversity. Then, it provides a quantitative compilation of single-ship fuel saving of various WASP technologies in a range of parameters from diverse types of ships and routes to different technology dimensions. Last, the study sheds light onto a broad range of factors that can influence the operational efficiency of WASP technologies under different operating conditions and constraints.

The structure of the article is as follows: Section 2 highlights the decarbonization effort of the shipping industry and the potential role of WASP technology toward its acceleration. Section 3 provides a detailed record of the recent installations of the technology, identifies future trends, and presents the technology's fuel-saving potential. Section 4 identifies and discusses specific key considerations, which should be taken into account by shipowners, as they can shape the operational efficiency of the technology. Section 5 concludes the article and paves the way for future research.

2. The Environmental Regulatory Context and WASP Technologies

The present section provides a brief review of the shipping's regulatory context and efforts for decarbonizing the industry. Consequently, having highlighted the urgency to reduce emissions and enhance the sector's energy efficiency, the current section also presents the potential role of the WASP technology toward this direction and describes the available commercial technologies.

2.1. Regulatory Developments toward Decarbonization

International shipping accounts for around 2.9% of global anthropogenic greenhouse gas (GHG) emissions according to the latest IMO greenhouse gas (GHG) study. These can even increase from 90% to 130% by 2050 compared to the baseline year of 2008 depending on economic growth [14]. As a result of this disquieting projection, industry stakeholders—e.g., mainly policy makers—have been taking action, especially during the last years, to decarbonize the industry.

Particularly, in 2016, the IMO Marine Environment Protection Committee (MEPC) agreed at the 70th session that ships over 5000 GT are required to submit fuel consumption data along with their transport work from 2019 on a yearly basis [11]. This agreement followed the similar European Union (EU) Monitoring, Reporting and Verification (MRV) regulation, which was ratified in 2015 for ships calling at EU ports [15]. At the MEPC's 72nd session in April 2018, the IMO, aligned with the United Nation's 2015 Paris Agreement, set goals to cut shipping's GHG emissions by at least 50% by 2050 and CO₂ emissions per transport work by at least 40% by 2030 and 70% by 2050 compared to the 2008 level [3].

The IMO emission reduction strategy was followed by efforts to accelerate or toughen the already set abatement measures. For instance, at its 74th session, the MEPC approved the acceleration of the Energy Efficiency Design Index (The Energy Efficiency Design Index (EEDI) is an energy efficiency measure designed by the IMO to govern the design of new ships since 1 January 2013. A ship's efficiency level is expressed in grams of carbon dioxide per ship's capacity-mile. Each new ship must meet the minimum level determined by the IMO, who reviews and tightens the minimum level every five years [16]) "phase 3" requirements, which, subject to final adoption in April 2020, not only require more types of ships to be built more fuel efficient but also tighten the requirements of energy efficiency of new-build container ships [17]. In November 2020, the MEPC's 75th session agreed on further regulation through the development of the Energy Efficiency Existing Ship Index (EEXI) and of an Annual Operational Carbon Intensity Indicator (CII) among other short-term measures [18]. Another noticeable regulatory action is the recent decision by the European Parliament of shipping's inclusion in the EU emission trading scheme (ETS) [19].

In addition to the regulations in place, the pressure for more drastic changes is mounting. In March 2020, the Clean Shipping Coalition and Pacific Environment tabled a new regulatory proposal to the IMO aiming for a minimum reduction of CO₂ emissions by 80% by 2030, instead of the 40% target initially set out in April 2018. The same proposal also attempted to bring charterers into the picture with the suggestion of a calculation of carbon intensity based on each journey so that they also become more accountable for their operational decisions [20]. Furthermore, the potential enforcements of a bunker fuel levy of 2 USD per tonne [21] was also put on the table for discussion.

2.2. WASP Technology and Its Role in Greening the Maritime Industry

Given the current developments in the maritime sector, it seems that regulatory bodies and other stakeholders have grown more determined in their attempt to cut emissions. On the other hand, the maritime industry has, over the years, explored different abatement measures including changes of hull design, power and propulsion system, alternative fuels, alternative energy sources, and operation [22]. Currently, the most discussed abatement measure is the development and adoption of alternative fuels such as hydrogen, methanol, ammonia, liquified natural gas, and biofuels. Notwithstanding the alternative fuel's promise to significantly lower tank-to-propeller ship emissions, depending on the

production method and source of feedstock, some fuels could result in high well-to-tank emissions comparable to conventional heavy fuel oil and marine gas oil. In other words, there is a high risk of emissions being transferred upstream. As a result, recent studies have not yet arrived at a conclusion about alternative fuels' impact on total life cycle emissions and impacts e.g., [23–25]. Moreover, the capital requirement and cross-sector collaboration required for alternative fuel are enormous. The Global Maritime Forum [26] estimated that—assuming ammonia being the primary alternative fuel adopted, as it has cost and storage advantages over hydrogen and a cost advantage over methanol—an investment of USD 1–1.4 trillion into new fuel over 20 years is needed for land-based infrastructure of the supply chain and ship retrofits in order to meet the current IMO 2050 goal.

In view of the above discussion, relying solely on alternative fuels may not produce the most optimal result in terms of emission reduction and economic efficiency. The importance of adopting a variety of abatement measures and the potential of wind power are evident in a recent study [22]. Having reviewed 22 technological and operational practices, the authors concluded that relying on a single technology is not sufficient for meeting the IMO 2050 target, whereas a combination of measures could lead to better emission reduction results (i.e., up to a 75% reduction). Another noteworthy finding of the study is the potential emission decline that can be achieved by the adoption of WASP technologies, whose CO₂ reduction potential falls above 20%. This finding is in line with existing literature, which identified the WASP technology as a strong option to increase the energy efficiency profile of the maritime transport industry and decrease the CO₂ emissions produced by its operations as indicated in Table 1 [8,22–24,27]. Therefore, the WASP technology has its place in the decarbonization transition—as well as the reduction of ships' GHG emissions per transport work following the IMO GHG strategy—and can act as a valuable complement to the adoption of alternative fuels. The appealing role of wind within the decarbonization process was also put officially on the policy-making table by the submission of the Comoros Island at the recent MEPC 75 of the IMO [28].

Table 1. Review of potential benefits of wind-assisted ship propulsion (WASP) technology.

Research	Key Strengths and Advantages of the WASP Technology
[8]	10–40% improvement in the EEOI (along with improved block coefficient)
[22]	1–50% CO ₂ emission reduction (ranked third in alternative fuels and energy)
[29]	1–32% CO ₂ emission reduction; applications could be combined
[24]	2–60% fuel saving; particularly suitable for high sea shipping
[23]	No infrastructure required; proven technology from long-term development
[27]	High cost-effectiveness (negative marginal abatement cost)

The currently available commercial WASP technologies vary; thus, a brief description of those is provided below [6].

Rotors: Rotating cylinders installed on deck that generate forward thrust from the *Magnus Effect*; these are often referred to as Flettner-rotors, as they were initially patented by Anton Flettner. They have attracted the attention of policy makers, academic institutions, shipping [30], and energy companies [31].

Towing kites: Towing kites provide thrust to ships with the lift generated by high altitude winds. From 2008 to 2012, some commercial applications of towing kites were developed by Skysails [6]. Airseas, a spin-off of the Airbus Group, is also currently developing automated products [32].

Suction wings: Suction wings create an upward lifting force similar to the wings on airplanes. One active developer is eConowind. Its Ventfoil and eConowind unit are non-rotating wings with vents and internal fans that generate force with boundary layer suction [33]. The former has the benefit of achieving a larger size, which translates to larger thrust, while the latter has the flexibility to be moved around [33]. In [6], suction wings are considered either under the category of rotors or sails. However, given suction wings' recent rise of popularity, it is discussed separately in this paper.

Rigid sails/wingsails: Rigid sails or wingsails are foils that could be adjusted to produce aerodynamic forces. Japanese ship owners had applied the technology in the 1980s but soon ran into various operational issues before calling off the projects. Recently, the development has been restarted exemplified by the “Wind Challenger Project” led by ship owner Mitsui O.S.K. Lines, shipyard Oshima Shipbuilding, and University of Tokyo [34]. Additionally, Chinese ship owner China Merchants Energy Shipping [35] received a newbuild Very Large Crude Carrier (VLCC) called “New Vitality” with two aerofoils in 2018, and it has ordered one more from the same ship yard: Dalian Shipbuilding Industry Corporation [36].

Soft sails: Soft sails are traditional sails with modern features. One example is the DynaRig, which is currently primarily used on large sailing yachts [23]. Currently, the actual application of this technology on commercial ships is limited.

Wind turbines: Wind turbines are turbines installed on deck of the ship that generate thrust or electricity to be used for propulsion [6]. Currently, the actual application of this technology on large commercial ships is still limited as a result of the technology’s size and small potential energy that can be gathered or saved; however, they are found in yachts [37].

Hull sails: Hull sails are hulls that use relative wind with its symmetrical hull foils to generate aerodynamic lifts [6]. Currently, the application of this technology on commercial ships is limited. One noticeable example is the design of the commercial ship *Vindskip* by Lade AS [38].

3. Adaptation of WASP Technology and Demonstrated Economic Impact

In view of the WASP technology’s potential role within the shipping’s environmental regulatory context, this section examines the status quo of recent technological installations on commercial vessels. Furthermore, it highlights the fuel-saving benefits for different ship types, technologies, and trade routes that come along with using WASP technologies.

3.1. Uptakes of the WASP Technology

In the wind power industry, the technical system has gone through a series of development, most notably the number of blades, the size of the rotor diameter, and different designs such as vertical axis wind turbines [10,39]. The WASP technology has been going through the same development with a wide range of products of different designs in the market. Due to their varying benefits, costs, restrictions, and technical requirements, the commercial uptake of WASP technologies does not materialize at the same pace for each product. Table 2 provides a detailed summary of the recent commercial adoptions of *Flettner-rotors*, *kites*, *suction wings*, and *aerofoils* from an extensive content analysis on academic literature, industry reports, industry news, expert interviews, and company releases. The adoptions captured meet the studies selection criteria outlined in section one (e.g., ships of over 5000 GT). In addition, the focus of the examination is placed on the relevant commercial adoptions since 2008, as an increased number of ships started installing WASP technology, and many researchers started investigating the WASP technology during this period. Although it is too early to call a winner, at the moment of writing this study, it appears that *rotors*, *kites*, and *suction wings* are the most popular, as 15 commercial adoptions have been recorded, including five being planned for 2021. Meanwhile, also rigid wings and aerofoils have been gaining momentum. When measured in tonnage, rigid sails have risen to the top as one Very Large Crude Carrier (VLCC) has installed aerofoils and another one with this technology is planned for 2022.

In spite of the limited adoption of WASP technology when compared to the number of vessels composing the global commercial shipping fleet, there is a steadily growing diffusion. The following trends showing the experimentation of the maritime transport industry with the technology are observed: increased ship size, increased diversity of ship types, increased diversity of ship owners, and increased size of the installations. Initially, the majority of the installations were done on small general cargo ships up to 10,000 deadweight tonnage (DWT) by northern European ship owners, who may have

more familiarity and more enthusiasm from their domestic success of the wind power industry. Now, also large tankers and bulk carriers ([9] mentions that certain technologies could be more appropriate to certain ship types; for instance, “sail hybrids” would be preferable to bulk carriers and kites would be preferable to containerships.) have entered the space joined by Greek, Japanese, and Chinese ship owners, who are the top global tonnage owners [40]. *Rotors* and *kites* are now competing with increasingly popular *suction wings* and *rigid sails*.

As the size and number of the installations continue to grow, the impact of the WASP technology is likely to increase and become more visible. The development in the wind power industry could serve as a reference. Although the initial actions came from the USA in reaction to the energy crisis during the 1970s, it was the more dedicated European countries whose share of capacity peaked in early 2000, before China and the USA started to catch up [10]. The rotor diameter and tower height have steadily increased from the 1990s along with continuous expansion into offshore wind parks where the wind energy is stronger, despite a more challenging environment and even higher costs [5,10,41]. Whether the WASP technology will continue on the expansionary path walked by the wind power industry before depends heavily on its economic rationale, which will be closely examined in the following sections of this paper.

Table 2. Recent WASP technology adoptions.

Ship Name	Ship Type	DWT	Technology Characteristics	Ship Built Year ^c	Installation Year
Flettner-Rotor			No. of Rotors/Diameter (m)/Height (m)		
E-Ship 1 ^a	General Cargo/Ro-Lo	10,020	4/4/27	2010	2010
Estraden ^a	Ro-Ro	9700	2/3 ^b /18	1999	2014
Viking Grace ^a	Passenger	6107 ^c	1/4/24	2013	2018
Fehn Pollux ^a	General Cargo	4250	1/3/18	1997	2018
Maersk Pelican ^{a,b}	Tanker	109,647	2/5/30	2008	2018
Afros ^d	Bulk Carrier	64,000	4/-/-	2018	2018
Copenhagen ^e	Ferry	5088	1/5/30	2012	2020
Annika Braren ^f	General Cargo	5100	1/18/3	2020	Oct 2020 expected
SC Connector ^g	Ro-Ro	8843	2/35/5	1997	Q4 2020 expected
Kite			Kite's dimension (m²)		
Michael A. ^h	General Cargo	4884	160	1994	2008
BBC Skysails ⁱ	General Cargo	9832	320 ⁱ	2008	2008 ^j
Theseus ⁱ	General Cargo	3667	160 ^g	2009	2009 ^h
Aghia Marina ⁱ	Bulk Carrier	28,522	320 ⁱ	1994	2012 ^j
Ville de Bordeaux ^{k,l}	Ro-Ro	5200	500	2004	Nov 2020 expected
TBA ^k	Bulk Carrier	TBA (Capesize)	1000	TBA	2021 expected
Suction Wing			No. of wings/height (m)		
Ankie ^m	General Cargo	3600	2/10	2007	2020
Frisian Sea ⁿ	General Cargo	6477	2/TBA	2013	2020
Rigid sails/wing sails			No. of foils/height (m)/width (m)		
MV Tharsis ^o	General Cargo	2364	2/9/3	2012	2021 expected
New Vitality ^{p,q}	Tanker	306,751	2/32/15	2018	2018
TBA ^r	Tanker	TBA (VLCC)	TBA	2022	2022

Note on sources: ^a [42]; ^b [43]; ^c marinetrffic.com; ^d [44]; ^e [45]; ^f [46]; ^g [47]; ^h [48]; ⁱ [6]; ^j [49]; ^k [32]; ^l [50]; ^m [51]; ⁿ [52]; ^o [53]; ^p [54]; ^q [35], ^r [36].

3.2. Economic Impact—Fuel Saving

Shipping is an energy-intensive industry, and fuel costs account for a large share of a vessel's operating cost and total costs [55–57]. Therefore, ship owners/operators are generally informed and concerned about fuel consumption [58,59]. Improved fuel efficiency does not only increase the expected profitability of the asset but also provides an operational hedge against volatile fuel costs. For instance, this can be seen in other transport industries.

Particularly, Refs. [60,61] showed that operational hedge of airline companies (i.e., fleet composition and fleet fuel efficiency) is more effective in reducing exposure to jet fuel price than using derivatives instruments as a hedging approach. Given the volatility of bunker prices within the maritime transport sector as is seen in Figure 1—marine fuel has been traded in the range between USD 100 and USD 600 per tonne from 2014 to 2019 in two major bunker ports Rotterdam and Singapore—the WASP technology can also act as a hedging instrument for ship owners/operators against this exposure.

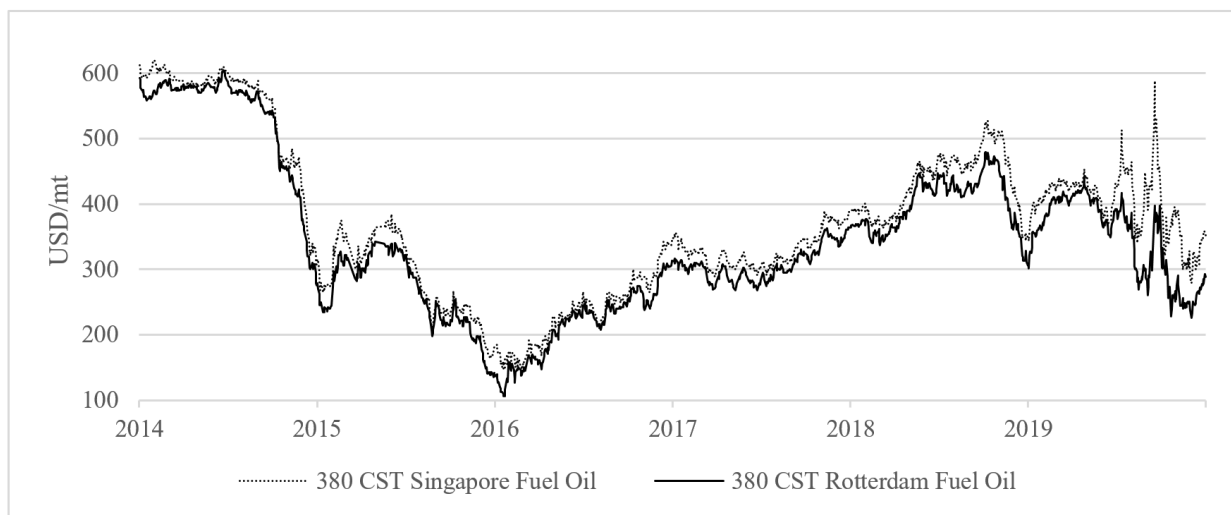


Figure 1. Heavy fuel oil price from February 2015 to February 2020 (Reuters, accessed on 2 March 2020).

Unsurprisingly, WASP technology developers claim substantial fuel savings when promoting their products. As observed also during the GST 2020 International Wind Propulsion for Shipping Forum in Copenhagen in March 2020, ship owners who have adopted WASP technology clearly pointed out the importance of legitimate economic benefit for their investment. In other words, emission reduction alone is not sufficient to justify investment in WASP due to the capital investment and operational risks involved. An economic case has to be made, so the potential financial upside compensates the costs and risks.

Additional research is needed in regard to the economic viability of WASP investments and its implications on shipping operations, despite the recent growth seen in the scientific literature in this area. The majority of existing studies conducts ship-side simulations of ships' fuel consumption in steps, as described in [62]:

- Parameterization of the physics of a wind-assisted ship and its WASP technology,
- Parameterization of the performance of a wind-assisted ship taking weather variability into account,
- Aggregation of performance data from multiple simulations.

The aim of the simulations conducted is to model the wind power contribution toward ship propulsion. Despite the similarities in the processes that are mainly followed in every study, differences are identified in terms of the methodological approaches that are applied. Among the studies, three approaches are observed:

1. The first approach is a non-route-based simulation [63–66], which makes assumptions about parameters of modeled technologies, ships, and weather conditions based on literature and databases, calculates net energy output of the technologies in a simulation model, and translates the net energy output to fuel saving.
2. The second approach is a route-based simulation, which in addition to the first approach reconstructs specific routes from ships' Automatic Identification System (AIS) data and takes into account wind condition along the voyage of each route [7,42,62,67–69].

- The third approach not relies on simulation but also requires measured fuel consumption data from ships sailing with WASP technology. The amount of fuel saving is found by switching the technology on and off in identical sea and wind conditions [70] and comparing the amount of fuel consumption.

The methodology using parametric simulations has several advantages. Firstly, it allows the researchers to study several technologies, ship types, routes, and other conditions in an efficient manner. Secondly, the researchers are not limited by the existing specifications of available technologies, so more experimental studies can be conducted. Thirdly, the researchers can study different parameters in detail and more dynamically. For example, in reality, the ships are unlikely to be able to follow precisely the routes and speed the researchers aim for, as the ships have to prioritize their commercial commitments. However, the scarcity of verifiable studies done on actual sailing ships is concerning. Without actual data, it is difficult to verify if the simulations have been sufficiently comprehensive and if the results have accounted for all important variables.

The results of existing studies consistently show that WASP technologies have the potential to help ships save a considerable amount of fuel under different conditions, as illustrated in Tables 3–7. It is important to note that available studies make use of different parameters in their models in terms of technology specification (e.g., number, dimensions, and technical specifications), ships (e.g., type and size of the ships, speed), wind conditions, and routes. As shown in the parametric study of [68], for ships fitting a *Flettner-rotor*, the diameter, height, rotating speed, installed location, and average voyage speed have an impact on the resulting fuel saving. Therefore, a direct comparison of results between different studies is challenging. In addition to the amount of potential fuel saving, the studies reveal a number of generic and technology-specific considerations, which have direct and significant impacts on the economics of WASP technologies. These considerations are described in the next section.

Table 3. Review of fuel-saving performance of *rotors*.

Study	Dimensions of the Technology	Ship Type	Route	Fuel Savings Found
[62]	Unspecified	10K dwt Chemical Tanker	Buenos Aires–Western Approaches	10–50%
		7k dwt Ro-Ro	Dunkirk–Dover	4%
[7]	1 Flettner rotor: height (h) = 0.35 m, diameter (d) = 5 m	8k dwt Product Tanker	London–Milford Haven	14%
		6k dwt General Cargo	Varberg–Gillingham	21%
		50k dwt Bulk Carrier	Tubarao–Grimsby	5%
		30k dwt Container Ship	Yantian–Felixstowe	2%
	2 Flettner rotors: h = 22 m, d = 3 m	5k dwt Tanker		5–7%
[6]	3 Flettner rotors: h = 48 m, d = 6 m	90k dwt Tanker	Worldwide trades of each ship type according to AIS data	9–13%
	2 Flettner rotors: h = 24 m, d = 3.5 m	7k dwt Bulk Carrier		5–7%
	2 Flettner rotors: h = 48 m, d = 6 m	90k dwt Bulk Carrier		17–23%
[67]	1 Flettner rotor: h = 25 m, d = 4 m	17k dwt General Cargo	Baltimore–Wilhelmshaven	14–36%
[63]	2 Flettner rotors: h = 28 m, d = 4 m	75k dwt Product Tanker	N.A.	Up to 30%
		10k dwt General Cargo/Ro-Lo	Porto–Montevideo; Eemshaven–Porto	8.3–47%
	4 Flettner rotors: h = 27 m, d = 4 m	10k dwt Ro-Ro	Rotterdam–Middlesbrough	1.6–9.0%
[42]	2 Flettner rotors: h = 18 m, d = 4 m	6k dwt (2.8k pax) Passenger	Stockholm–Turku	0.4–2.8%
	1 Flettner rotor: h = 18 m, d = 3 m		Livorno–Mostaganem;	1.0–6.6%
	2 Flettner rotors: h = 30 m, d = 5 m	4k dwt General Cargo	Huelva–Alexandria	1.8–4.7%
		110k dwt Tanker	Skikda–Singapore; Yeosu–Spain	
[68]	1 Flettner rotor: h = 18 m, d = 3 m	Aframax Tanker	Cape Lopez–Point Tupper	8.9%
			Angra dos Reis–Rotterdam	6.5%
[70]	1 Flettner rotor: h = 18 m, d = 3 m	4k dwt General Cargo	Unspecified	10–20%

Table 4. Review of fuel-saving performance of *kites*.

Study	Dimensions of the Technology	Ship Type	Route	Fuel Savings Found
[65]	1 kite: area (a) = 500 m ² , length of the rope (l) = 150 m 1 kite: area (a) = 500 m ² , length of the rope (l) = 350 m	50k dwt Tanker	N.A.	Up to 35% Up to 50%
[66]	1 kite: a = 640 m ² , l = 600 m	73k dwt Tanker 7k dwt RoRo	N.A. Dunkirk–Dover	40% 3%
[7]	1 kite: a = 500 m ² , l = 350 m	8k dwt Product Tanker 6k dwt General Cargo 50k dwt Bulk Carrier 30k dwt Container Ship	London–Milford Haven Varberg–Gillingham Tubarao–Grimsby Yantian–Felixstowe	24% 32% 6% 1%
[6]	1 kite: a = 400 m ² , l = 350m	5k dwt Tanker 90k dwt Tanker 7k dwt Bulk Carrier 90k dwt Bulk Carrier 1k teu Container Ship 5k teu Container Ship	Worldwide trades of each ship type according to AIS data	9–15% 3–4% 9–14% 5–9% 2–4% 1–2%
[64]	1 kite: a = 320 m ² , l = 300m	50k dwt Tanker	N.A.	10–50%

Table 5. Review of fuel-saving performance of *rigid sails*.

Study	Dimensions of the Technology	Ship Type	Route	Fuel Savings Found
[69]	9 wingsails: height (h) = 50 m, width (w) = 20 m	180k dwt Bulk Carrier	Yokohama–Seattle	20–30%
[62]	Unspecified	10K dwt Chemical Tanker	Buenos Aires–Western Approaches	20–60%
[6]	3 wingsails: h = 25 m, w = 9 m 5 wingsails: h = 50 m, w = 17 m 3 wingsails: h = 27 m, w = 10 m 5 wingsails: h = 50 m, w = 18 m	5k dwt Tanker 90k dwt Tanker 7k dwt Bulk Carrier 90k dwt Bulk Carrier	Worldwide trades of each ship type according to AIS data	5–8% 9–13% 5–7% 18–24%
[68]	1 wingsail: h = 50 m, w = 20 m	Aframax Tanker	Cape Lopez–Point Tupper Angra dos Reis–Rotterdam	8.8% 6.1%

Table 6. Review of fuel-saving performance of *soft sails*.

Study	Dimensions of the Technology	Ship Type	Route	Fuel Savings Found
[62]	1 Dynarig	10K dwt Chemical Tanker	Buenos Aires–Western Approaches	15–35%
[68]	1 Dynarig: area = 1000 m ²	Aframax Tanker	Cape Lopez–Point Tupper Angra dos Reis–Rotterdam	5.6% 4.2%

Table 7. Review of fuel-saving performance of *wind turbines*.

Study	Dimensions of the Technology	Ship Type	Route	Fuel Savings Found
[6]	1 turbine: height (h) = 20 m, diameter (d) = 38 m 3 turbines: h = 20 m, d = 38 m 1 turbine: h = 20 m, d = 38 m 3 turbines: h = 20 m, d = 38 m	5k dwt Tanker 90k dwt Tanker 7k dwt Bulk Carrier 90k dwt Bulk Carrier	Worldwide trades of each ship type according to AIS data	1–2% 1–2% 1–2% 2–4%

4. Operating Considerations

This section presents the key factors that influence the operational performance of the WASP technology. They range from the importance of wave height to trade patterns and the role of the crew, and they are categorized accordingly to environmental factors as well as on-board and commercial factors. A comparison of the most popular and most studied WASP technologies concludes the section.

4.1. Environmental Factors

The speed and direction of wind are two major factors that determine the fuel saving in the models found in the existing literature. In general, it is shown that with all other factors being identical, the higher the wind speed, the larger the energy output of the WASP technology, which results in higher fuel savings. This is not unexpected, as WASP technologies utilize wind power to produce thrust for ships [6,62,64–67,69].

On the other hand, wave heights are often higher where wind speed is higher, which has a negative impact on ships' performance [62]. When modeling the performance of ships with WASP technologies, more sophisticated models that account for side forces and yaw moments should be used to obtain more accurate fuel consumption predictions [71]. Many of the studies use reconstructed routes from AIS data and/or shortest paths [6,7,68]. Ref. [67] argues that when route optimization is utilized, fuel saving of the WASP technology increases from 14–36% to 28–53%. Ref. [62] showed that an additional fuel saving of 5–10% can be achieved when the ship is free to deviate from the Great Circle route to utilize optimal wind and waves, which is supported by [69], who observed a 30% fuel saving on a wind-optimal route compared to 22% on the Great Circle.

Seasonal differences in fuel savings are observed in the simulation of [62] for the Argentina–UK trade lane, where *Flettner-rotors* perform better in the winter and a *wingsail* performs better in the summer period. Ref. [42] shows that the wind speed is higher in the Northern Hemisphere in the winter and enables *Flettner-rotors* to create larger fuel savings. In [7,62,67], the direction of the voyage is found to cause variances in fuel saving. The dominant west–east wind direction occurring in the Atlantic Ocean resulted in a significant difference in fuel savings between Baltimore to Wilhelmshaven (36%) and Wilhelmshaven to Baltimore (14%) [7]. Longer-haul voyages are found to have a lower variability of fuel savings than short ones [7], and they are more likely to enable larger fuel savings as wind speed tends to be higher in open waters [6].

4.2. On-Board and Commercial Factors

In practice, ship operators are unlikely to have perfect foresight of weather conditions through the entire voyage; hence, actual fuel savings might deviate from simulations of reconstructed voyages [62,65]. In cases where a route is optimized for the WASP technology to achieve a lower fuel consumption, the trip duration and irregularity of the trip duration may deteriorate when trying to maximize the most favorable wind, resulting in a suboptimal economic result [65]. Even when the route and the trip duration, including its irregularity, are all optimized, operational limits of the WASP technology present another issue. As it is the ship's crew that is responsible for the navigation of the ship and the deployment of the machinery, they may experience a larger workload and need additional training to operate and maintain WASP technology effectively. Additionally, the change of the crew takes place on a regular basis, and thus, the level of operational efficiency could be difficult to maintain [6]. As the shipmaster is in charge of the navigation of the ship, a fully automated system may not allow the flexibility of a competent shipmaster with good sailing skills to achieve an optimal result [4]. At times, it might be beneficial to change a ship's speed and course to catch favorable wind to maximize fuel saving, which demands good decision making from the shipmaster.

Trade patterns are also identified to have a significant impact on the fuel-saving potential of WASP technologies, as wind and ocean current in different geographic locations affect the performance of a ship. It is important to match the right technology to the right trade pattern. Ref. [72] show that for dry bulk carriers ranging from 0 to 35,000 DWT, there is a match between areas of higher wind speed and areas where ships consume more fuel (North Pacific, North Atlantic, Indian Ocean), which is a positive sign for the type of ship to consider WASP technologies. Ref. [42] found that fuel saving in the western coast of Europe, South China Sea, the Indian Ocean, and the Arabian Sea are the largest, while the fuel saving is the smallest in the Mediterranean Sea and off the west coast of Africa. Other studies also suggest that in different trading areas, significantly different fuel savings

are found [6,7,68]. Last but not least, shipping companies could face risks associated to cargo-handling operations—such as potential damage to the technology [9]—hindering them from calling at specific ports with improper infrastructure [73].

Table 8 summarizes the interrelations among the environmental, on-board, and commercial factors that are identified to have an impact on the operational efficacy of the WASP technology. In order to achieve optimal economic benefits from the adoption of the WASP technology, it is crucial to take a systematic approach instead of treating each factor independently. For example, a chosen trade pattern determines the wind speed and wave height at the given season the ship encounters, which requires the shipmaster to make reasonable sailing decisions to not only maximize fuel saving but also reduce trip irregularity to be in compliance with the ship operator's contractual obligation. Given these alterations in the performance of the installations as a result of the different conditions and various factors, without loss of generality, the authors of this paper are hypothesizing that the cost savings/investment costs ratios will vary accordingly for different WASP technologies.

Table 8. Operational factors affecting the performance of the WASP technology.

Environmental Factors Effect on the wind energy available to be utilized by the WASP technology	<ul style="list-style-type: none"> • Wind speed • Wave height • Seasonal pattern
On-board Factors Effect on how effective the WASP technology is operated	<ul style="list-style-type: none"> • Route optimization • Master's decision making • Crew training
Commercial Factors Effect on the compatibility of the WASP technology with the ship's commercial commitments	<ul style="list-style-type: none"> • Trade pattern • Trip duration • Trip irregularity • Port calls

4.3. Indicative Comparison among the WASP Technologies

Flettner-rotors achieve more fuel savings, while *DynaRigs (soft sails)* save less according to the studies by [6,62,68] that provided direct comparisons between technologies under the same conditions. Ref. [7] found that the power output of *kites* is more volatile than that of *Flettner-rotors*, as by nature, the latter generates propulsive power over a wider range of wind directions; thus, the performance of *Flettner-rotors* is less sensitive to geographic location and weather conditions. This is also observed in [6] with similar analysis results. On the other hand, Ref. [65] observed that *kites* have a number of advantages over conventional *sails*, as they can catch stronger winds that are at higher altitude, as well as having a lower attachment point to the ship and therefore create a smaller roll heeling moment. They also take less deck space. In terms of scalability, both *Flettner-rotors* and *wingsails* have the potential to scale up as the ship size increases. There may be some advantage to *Flettner-rotors* because the power contribution is expected to increase linearly with the number of *rotors* [63]. Although *kites* may have less scalability, the advantage that they do not take much deck space makes them particularly attractive for container ships [6].

Differences in the nature of technologies lead to different technology functions under the same wind condition. For example, *kites* produce the largest amount of propulsive power under tailwind, while *Flettner-rotors* thrive on sideway winds [6,7,63,64,66,68]. Although absolute fuel saving increases for *rotors* and *wingsails* when ship speed increases, relative fuel savings decrease. The reason is that as energy demand increases, the power demand of the ship has a greater effect on the fuel consumption than the contribution of *rotors*/rigid sails [6,62,68]. *Kites* not only generate more savings in relative terms under lower speed, but they also generate more or equal absolute savings, as the apparent tailwind is likely to be stronger [6,66].

Given the higher number of studies on rotors and kites, a concise comparison between *Flettner-rotors* and *kites* is presented in Table 9 based on the above discussion. The purpose of such a comparison is not to provide a prescriptive judgement but instead to motivate

further investigation in the areas of wind power utilization and compatibility with ship operation. The actual operating performance of each WASP installation depends on many factors, and the existing amount of literature has not yet found a clear frontrunner.

Table 9. Operational comparison between *rotors* and *kites*.

	<i>Kites</i>	<i>Flettner-Rotors</i>	
Wind power utilization	Absolute Power	Stronger winds at higher altitude	Slower winds on lower altitude
	Volatility of Power	Most effective with wind aligning with navigation direction	Wider range of wind directions
	Scalability	Less scalability compared with rotors	Power output increases linearly with number of installations
Compatibility with ship operation	Wind direction	Most effective with tailwinds	Most effective with winds from side
		Less deck space needed	Fundamental deck construction

5. Concluding Remarks

As a result of the decarbonization efforts in the maritime industry, the international community is currently investigating various options to decarbonize shipping. Although under less of a spotlight than other alternative forms of propulsion, WASP technologies could act as an integral piece in this transition process that requires a variety of abatement measures to work in conjunction with alternative fuels. In addition to niche operators that have been driving the development of WASP technology since day one, an increasing number of other actors such as regulatory authorities, classification societies, and large international ship owners have joined the “WASP community”. This increased enthusiasm and participation has led to a greater diffusion of different technologies and opened new research opportunities as well. This review paper provides a detailed record of the most relevant recent installations of the WASP technology, identifies a trend of growth of diffusion, quantifies the fuel-saving potential of different WASP technologies, and analyzes the operational factors in various conditions for different WASP technologies.

WASP has come a long way in terms of its development and commercial adoptions. An uncertainty remains over just how much longer it will take to make a larger economic and environmental impact. Ref. [74] noted referring to the wind power transition in Germany that “all transitions contain periods of slow and fast development. Nor is a transition usually a quick change, but a gradual, continuous process typically spanning at least one generation (25 years)”. Germany’s transition to wind power from the formative phase of the 1970s to the continued growth phase of the 2000s appears to confirm this requirement of at least one generation’s effort [75]. Nevertheless, the transformation from sail to steam ships realized in the maritime sector suggests that the time frame required for this transition can also extend up to almost one century [76]. Following [9,76], we can argue that WASP innovations can complement existing technologies at least in their early phase of adoption. The transition toward WASP technologies has begun thanks to a cluster of dedicated industry and academic participants. From now on, there is clearly much more potential to be realized before WASP technologies reach the diffusion level suggested in [6] (3700–10,700 ships in 2030) and [77] (37,000–40,000 ships by 2050).

The sense of urgency for decarbonization is present in the maritime industry, as discussions intensify to bring radical long-term and short-term changes. WASP is a strong option for policy makers to support ship owners to adapt to the transition. A good amount of research in academia and industry have quantified ship-side fuel-saving potentials and studied the impact of variability in wind speed and directions, trade patterns, geographical areas, seasonal effects, long vs. short-haul voyage, ship operation profile and limits, and route optimization. The results consistently show that WASP has significant potential to make ships more energy-efficient (rotors: 0.4–50%; kites: 1–50%; rigid sails: 5–60%; soft sails: 4.2–35%; wind turbines: 1–4%). To achieve the most desirable fuel consumption reduction in the most favorable way to ship owners/operators, a range of factors mentioned in the previous sections must be taken into consideration. As the main ship-owning countries,

such as Greece, Japan, and China started to install WASP technologies on larger and more diverse ships, it is foreseeable that the impact of WASP will grow, which will drive competition and the improvement of different technologies, creating a positive feedback loop, including lower costs, as observed in the wind power industry [10,39].

Despite the promising trend of technological diffusion and the appealing character of WPT, the current adoptions represent only a small percentage of the total fleet. As different technologies have distinct performance characteristics under different conditions, a one-size-fits-all solution is unlikely to emerge. Therefore, it is crucial to produce more verified third-party research with actual commercial uptakes to gain better understanding of a range of operating factors that influence the WASP technology performance. Such factors include the environment, and on-board and commercial factors, which are closely linked to the factors that influence the choices of a particular WASP product in relation to the utilization of wind and its compatibility with ship operation. In addition, more research must be done to establish the risk and return relationship of WASP technology and how it contributes to the operational hedge of ship owners and operators. A higher management perspective on the organizational transformation, the design of viable business cases and business models, is also a future area of research, as such a green transition entails significant challenges for organizations. In addition, an important aspect that deserves study is the safety of wind installations. However, evidence on this subject is still limited, and future studies should focus on a structured safety assessment of each wind technologies. This could be complemented by an empirical review of the reliability and durability of the WASP technologies. The investigation of these proposed research directions will add more transparency regarding the WPT's implications on the shipping industry.

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