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Project full title:	Run Wind Propulsion Technology real life trials on sea going ships in operation>showcase proven concepts>market adoption>green sea transport
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D 5.B
New Wind Propulsion Technology
A Literature Review of Recent Adoptions

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List of symbols and abbreviations

AIS	Automatic Identification System
CIIs	Carbon Intensity Indicators
DNV GL	Det Norske Veritas Germanischer Lloyd
DWT	Deadweight Tonnage
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ships Index
GST 2020	Green Shipping Technology Conference
ICCT	International Council on Clean Transportation
IMO	International Maritime Organization
IRENA	International Renewable Energy Agency
ITF	International Transport Forum
MEPC	Marine Environment Protection Committee
MOL	Mitsui O.S.K. Lines
MRV	Monitoring, Reporting and Verification
SEEMP	Ship Energy Efficiency Management Plan
WASP	Wind Assisted Ship Propulsion

Executive Summary

The international community examines various measures towards the enhancement of the energy efficiency profile of the maritime transport sector. The installation of Wind Assisted Ship Propulsion Technologies (WASP) as opposed to primary wind is one of the various potential ways forward to meeting the emission reduction goals that have been set by the International Maritime Organization. The present report by means of an extensive literature review — it involves scientific articles, industry reports, company newsletters and conference presentations — sheds light on the following areas:

- The potential role of WASP technologies within the decarbonisation of the shipping industry
- WASP technological uptakes within the shipping sector
- Economic and operational impact of WASP technologies

WASP technologies have the potential to play an important role in maritime industry's decarbonisation transition. The growth of the "WASP industry" is likely to have a significant economic and environmental impact within the sector. Academic and industry research show considerable fuel savings that can be achieved by the adoption of Flettner rotors, kites, rigid sails, soft sails, and suction wings under different operating conditions (e.g., routes, speed, weather conditions of various shipping segments). Technology developers, ship owners/operators, classification societies, and Non-Governmental Organisations show a growing interest in the potential that this technology has to offer. The number and diversity of commercial uptakes continues to rise and the experience shows significant energy-efficiency improvement. Nevertheless, the full potential of WASP technology for decarbonizing the whole maritime industry is yet to be realized while a number of researchers expect a higher diffusion to take place.

Despite the appealing character of such technologies, there are certain areas that require further research. As the operations of WASP technology are subject to a number of underlying factors, the profile of its risk and return must be further studied for the purpose of investment appraisal. The introduction of WASP technology is likely to motivate ship owners/operators to innovate their business models for more sustainable business cases. When the status quo in the organization is broken, a greater understanding of change management and transformational leadership must be in place for management to steer the company in alignment of the new visions and strategies. At the moment there is a lack of literature in the above area in shipping. With the collaboration of partners in the WASP Project of Interreg North Sea Region Program of the European Regional Development Fund, the WASP project seeks to expand the knowledge and its diffusion in the following research. To this end, the present report paves the way for future research regarding risks of diffusion, adoption barriers, and institutional drivers, related to the uptake of WASP technologies within the maritime transport industry.

1. Introduction

International shipping accounts for around 2.89% of globally produced CO_2 emissions in 2018, increased from 2.76% in 2012, according to the fourth GHG study of the International Maritime Organization (IMO)(IMO, 2020b); projections about their future increase range from 90% to 130% by 2050 compared to the baseline year of 2008. Container ships, bulk carriers, and oil tankers which represent the largest shares of global fleet — 17.6%, 33.6%, 25.4% in gross tonnage respectively in 2018 (Equasis, 2019) — are the leading pollutants whose main engines consume most marine fuels — 22.5%, 18.7%, 13.4% respectively in 2015 (ICCT, 2017).

The disquieting projections of emission escalation have placed the topic of shipping's decarbonisation on the forefront of the global policy making agenda. Particularly, in October 2016, the IMO's Marine Environment Protection Committee (MEPC) at the 70th session agreed that ships over 5,000 gross tonnage, which account for 85% of CO_2 emissions from international shipping, are required to submit fuel consumption data along with their transport work from 2019 on a yearly basis (IMO, 2016). This is in line with the European Union (EU) Monitoring, Reporting and Verification (MRV) regulation, which was ratified in 2015 for ships calling at EU ports (EUR-Lex, 2015). At the MEPC's 72nd session in April 2018, IMO reached a milestone agreement. In alignment with the emission reduction goals set out in United Nation's 2015 Paris Agreement, IMO agreed to cut GHG emissions by at least 50% by 2050 and CO_2 emissions per transport work by at least 40% by 2030 and 70% by 2050 compared to the 2008 level as well (IMO, 2018).

The IMO emission reduction strategy was followed by multiple efforts made to accelerate or toughen the already set abatement targets. In May 2019, at its 74th session, the MEPC approved the acceleration of Energy Efficiency Design Index (EEDI) "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 tightens the requirements of energy efficiency of newbuild container ships (IMO, 2019). In March 2020, the Clean Shipping Coalition and Pacific Environment tabled a new regulatory proposal to the IMO aiming for a minimum reduction of CO_2 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 (Lloyd's List, 2020a).

In line with the IMO emission reduction strategy, the international community is currently examining various measures and actions so as to enhance the energy efficiency of the maritime transport sector by means of promoting best green practices and technological innovation uptake. Among the various existing options towards this direction, the IMO has started to pay attention to the exploitation of wind assisted propulsion technologies (WASP) due to their capability of fuel consumption and emission reduction (IMO, 2020a). Given the urgency for finding suitable and viable options for the decarbonisation of the shipping sector, the Interreg North Sea Region Program of the European Regional Development Fund initiated the Wind Assisted Ship Propulsion (WASP) project in 2019. The project brings together industry and research institutes to study and validate the performance and commercial viability of wind-assisted propulsion technologies (Interreg North Sea Region, 2019).

In view of few existing studies, this report focuses on the wider economic impact that wind assisted ship propulsion (WASP) technologies can have on the shipping industry, in conjunction with all the WASP installations in the WASP project. An analysis of secondary data that was retrieved from a broad range of verifiable sources by means of a review of scientific literature, industry reports, news articles, conference presentations, and commercial companies' websites was conducted and complemented by a content analysis. The report is structured in eight sections. The first introduces the topic under study, while the second focuses on the linkage of shipping's decarbonisation transition and WASP technology. The third section discusses the role of alternative fuels within the industry's decarbonisation efforts and describes the potential of WASP technology as option for the energy efficiency enhancement of the shipping sector. The fourth section provides a detailed overview of current commercial WASP technologies uptake within the maritime industry. The fuel consumption savings achieved by the usage of these technologies is described in section five. Sections six and seven present generic and technology specific considerations respectively. Section 8 concludes this report and sets the way forward.

2. The transition towards decarbonisation

Karlsen et al.(2018) used an agent-based model to explore the transition and associated barriers for the adoption of Flettner rotors in dry bulk shipping. They found that demonstration projects and the implementation of carbon price together could significantly improve the diffusion of the technology. More discussion about the transition and barriers specific to the diffusion of the WASP technology will be featured in future reports of the WASP project. In the following section, a transition model will be used to provide a high-level perspective of the green transition of the maritime industry and challenges/opportunities the WASP technology encounters.

A dynamic transition is defined by Rotmans et al. (2001) as "*a gradual, continuous process of change where the structural character of a society (or a complex sub-system of society) transforms*". During a transition, changes happen in multiple domains such as technology, the economy, institutions, behaviour, culture, ecology, and belief systems, which have a dynamic relationship as they reinforce one another. This multi-domain process can also be observed within the maritime industry. Particularly, technological changes, such as these of WASP, represent only one of the potential pathways towards achieving the desired emission abatement results that have been set by the policy makers. When examining a transition under such framework, the result of the transition is shaped by long-term developments of stocks, and short-term developments of flows. Stocks are properties that change slowly (eg., natural, social-cultural changes) while flows are properties that change relatively quickly (eg., economic changes). As far as the technological and institutional changes go, those can be considered as medium-term. From this dynamic perspective, it could be observed that the current decarbonisation transition is shaped by the medium-term changes in technology and institutions that create impact on economic changes and the result of which will change the natural and socio-cultural landscape. As the changes involve changes on multiple levels across different temporal dimensions, wide-scale promotion, adoption, and acceptance of new technology by transnational institutions such as the IMO, larger ship owners/operators, classification societies, and financiers require more than short-term efforts and demands interdisciplinary research and cross-industry collaborations.

The transition process could be dissected into four phases: predevelopment, take-off, acceleration, and stabilization (Rotmans et al., 2001). The decarbonisation transition of the maritime industry can be placed between the take-off and acceleration phase, as the system starts to witness structural changes in terms of social-cultural, economic, and institutional aspects and a combination of collective learning and diffusion through active involvement of participants in different industries. However, there is an urgency to accelerate the process in view of the various proposals related to the three dimensions of transition: the speed of change, the size of change, and the time-period of change. As a result, an increased diffusion of the WASP technology is likely to be a key factor on the entire transition process due to its potential significant impact on emission reduction. This will be discussed further in the following sections.

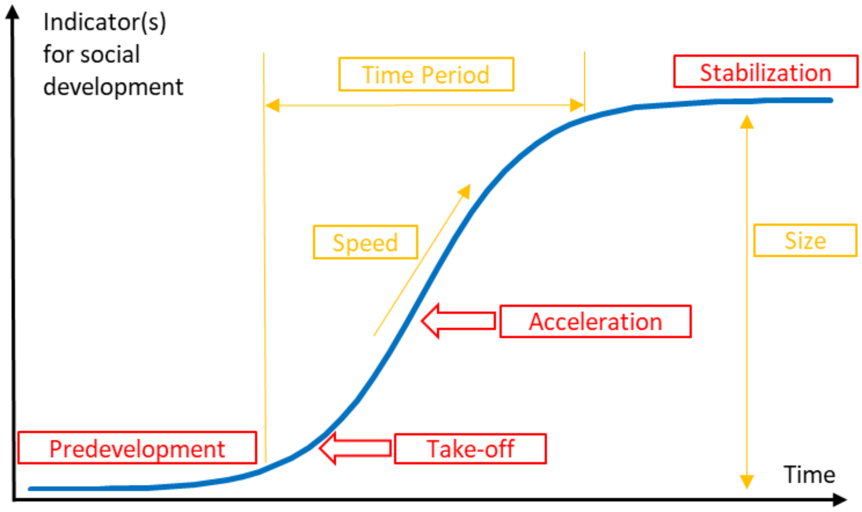

Figure 1: The four phases (red) and three dimensions (orange) of transition (Rotmans et al., 2001)

Technological and institutional changes driven by the WASP technology take place at all three levels: socio-technical landscape, regimes, and niche (Rotmans et al., 2001). Interactions between levels are also observed. In comparison with the incremental changes that usually happen in a regime, niche level actors are generally less constrained and more agile at responding to landscape pressure for radical changes (Mander, 2017). However, niche level innovations face the challenge of competing with existing technologies, rules, practices, and organizational arrangement where stability and inertia reside.

As the IMO, sovereign States, and transnational institutions continue to face pressure from the socio-technical landscape and niche levels to decarbonize shipping, it can be expected that regime actors will play an increasingly enabling role for the uptake of WASP technology. As the diffusion of WASP technology grows steadily on the niche level, an accumulated amount of momentum will be transmitted to socio-technical landscape and regimes levels, creating a positive feedback loop that further accelerates the process (Rotmans et al., 2001). Referring to Jacobsson & Lauber (2006)'s key conditions for the formative stage of a new industry, i.e., institutional changes, market formation, advocacy coalitions, and the entry of other organizations, the same conditions are already present for WASP technology and actively engaged by a broad range of participants (Allwright, 2018). If the example of German wind and solar industry described in Jacobsson & Lauber (2006) could be used as a reference[1], we expect that, with adequate support from regimes and alterations in the regulatory environment, the "WASP industry" will continue to grow and create substantial economic and environmental impact.

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[1] With the initial reliance on domestic coal mining and the subsequent plutonium shift, German government's support for renewables started in a "limited and ambivalent support" fashion. However, the formation of the renewable industry continued on the "fertile ground" cultivated by a community of enthusiastic participants who set the groundwork and vision needed for the following rapid development from the late 1980s.

3. WASP Technology and alternative fuels

The discussion of potential ways towards the decarbonisation of the maritime industry is mainly placed on the uptake of alternative fuels such as hydrogen, methanol, ammonia, and biofuel. In spite of the appealing character of the uptake of alternative fuels within shipping, it is important to look at the complete life cycle of those fuels from production to utilization. Although ships' "tank to propeller" emission could be significantly lower with the usage of alternative fuels, many applications of hydrogen, methanol, and ammonia induce high "well to tank" emissions comparable to conventional heavy fuel oil and marine gas oil. In other words, there is a risk of emissions being transferred upstream. Moreover, it needs to be stressed that recent research has not yet arrived at a conclusion about alternative fuels' impact on total life cycle emissions and costs (Balcombe et al., 2019; DNV GL, 2019a; IRENA, 2019). It is estimated[2] that an investment of USD 1 – 1.4 trillion into new fuel over 20 years is required for land-based investments (87%) and ship related investments (13%) in order to meet the current IMO 2050 goal (Global Maritime Forum, 2020).

In view of the extensive capital and extensive cross-value chain collaboration requirements so as to achieve meaningful emission abatement results through the usage of alternative fuels, there has been growing interest in exploiting renewable energy to replace part of the propulsive power ships obtain from its motor engine. The importance of adopting a variety of abatement measures and the potential of wind power are evident in Bouman et al. (2017). They concluded that, after reviewing 22 technological and operational practices, none of those alone is sufficient to reduce the required amount of CO2 to meet the IMO 2050 target, but a combination of measures could achieve 75% reduction. Therefore, sole reliance/focus on alternative fuel is suboptimal. The same study also showed that, among various options, wind assisted technology is one of the top eight measures whose third quantile of CO2 reduction potential falls above 20%. This is in line with other existing literature, which identifies wind propulsion technology as a potential strong option to increase the energy efficiency profile of the maritime transport industry as indicated in Table 1 (Balcombe et al., 2019; Bouman et al., 2017; DNV GL, 2019a; Frontier Economics, 2019b; ITF, 2018; T. Smith et al., 2016).

Research	Key strengths and advantages of wind assistance technology
T. Smith et al. (2016)	**10 - 40%** improvement in the EEOI (along with improved block coefficient)
Bouman et al. (2017)	**1 - 50%** CO_2 emission reduction (ranked third in alternative fuels and energy)
ITF (2018)	**1 - 32%** CO_2 emission reduction; applications could be combined
Balcombe et. al. (2019)	**2 - 60%** fuel saving; particularly suitable for high seas shipping
DNV GL (2019)	No infrastructure required; proven technology from long-term development
Frontier Economics (2019)	High cost-effectiveness (negative marginal abatement cost)

Table 1: Review of recent studies on different abatement options in shipping

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[2] The research assumed ammonia being the primary alternative fuel adopted as it has cost and storage advantages over hydrogen and cost advantage over methanol.

4. Development of wasp technology

This section presents the current development of WASP technologies given the appealing character of such innovation as a promising emission abatement solution. A variety of WASP technologies are available on the market with each having its distinct characteristics. Nelissen et al. (2016) presented a taxonomy by screening for technologies aimed for commercial shipping and are developed by developers with more certain commercial presence which are as follows and illustrated in Figure 2-7:

Rotors (Figure 2): These are rotating cylinders installed on deck that generate forward thrust from the Magnus Effect as the cylinders create low and high pressure. In 2018, under one of the subprojects in the EU sponsored project MariGreen, University of Applied Sciences Emden/Leer conducted a study on-board and verified the performance of a retrofitted Flettner rotor developed by EcoFlettner (MariGreen, 2019). Finnish developer Norsepower is currently active in this area and backed by major energy companies (TradeWinds, 2019). Anemoi is a developer active in providing movable rotors on vessels (Dry Bulk Magazine, 2018).

Figure 2: Rotor – Flettner rotor (Norsepower, n.d.)

Towing kites (Figure 3): They 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. Airseas, a spin-off of Airbus Group, is currently developing their own automated products.

Figure 3: Towing kite – Airseas ("Airseas K Line," n.d.)

In Nelissen et al. (2016), suction wings are considered either under the category of rotors or sails. As suction wings have a significant role in the WASP project and are adopted by key external project partners, they will be discussed separately.

Suction wings (Figure 4): eConowind's Ventifoil and eConowind unit are non-rotating wings with vents and internal fans that generate force with boundary layer suction. 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.

Figure 4: Suction Wings (eConowind, n.d.)

Rigid sails/wingsails (Figure 5): foils that could be adjusted to produce aerodynamic forces. Japanese ship owners had already applied the technology in 1980s. One example is the "Wind Challenger Project" from MOL, Oshima Shipbuilding, and University of Tokyo (MOL, 2019).

Figure 5: Rigid sail/wingsail (University of Tokyo, n.d.)

Soft sails (Figure 6): These are traditional sails with modern features. One example is Dynarig which is currently used on large sailing yachts (DNV GL, 2019a).

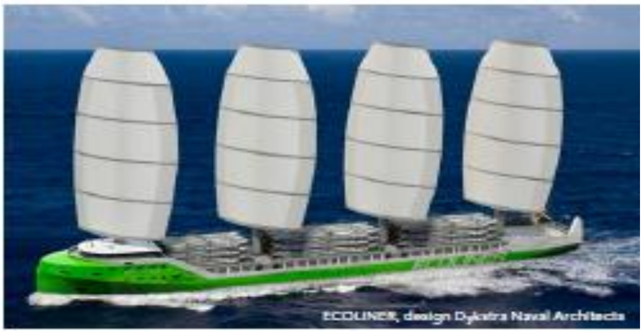

Figure 6: Soft sail – Dynarig (DNV GL, 2019a)

Wind turbines (Figure 7): turbines that generate electricity and/or thrust by the blades.

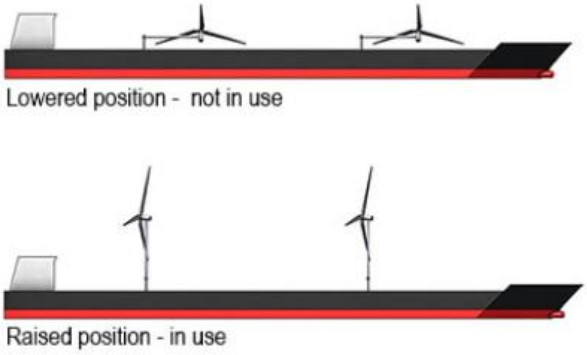

Figure 7: Wind turbine (PROPit, n.d.)

Hull sails (Figure 8): These are hulls that use relative wind with its symmetrical hull foils that generate aerodynamic lifts.

Figure 8: Hull sail – Vindskip (Lade, n.d.)

The installation of WASP technologies does not take place at the same pace for each technology, mainly, due to their varying benefits, costs, restrictions, technical requirements, and the fit to the ships. At the moment it appears that rotors, kites, and suction wings are most popular as these have been installed on 13 commercial ships since 2008. Table 2 provides a detailed summary of the commercial uptakes of the WASP technology. The table mainly covers commercial transport ships that exceed 5,000 gross tonnage as those account for about 85% of CO2 emissions from international shipping (IMO, 2016). Some smaller commercial ships are also included as the installations of the WASP technology are recent and their gross tonnage is close to 5,000. 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 (Equasis, 2019) and are the leading pollutants, whose main engines consume most marine fuels, 22.5%, 18.7%, 13.4% respectively in 2015 (ICCT, 2017). This report does not investigate the cases of private yachts and small exhibition ships, as they account for a small portion of emissions.

Ship Name	Ship Type	DWT	Specific Technology Characteristics	Ship Built Year[c]	Installation Year
Flettner Rotor			**Number 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	9,700	2/3[b]/18	1999	2014
Viking Grace[a]	Passenger	6,107	1/4/24	2013	2018
Fehn Pollux[a]	General Cargo	4,250	1/3/18	1997	2018
Maersk Pelican[a]	Tanker	109,647	2/5/30	2008	2018
Afros[d]	Bulk Carrier	64,000	4/-/- (movable)	2018	2018
Copenhagen[e]	Ferry	5,088	1/5/30	2012	2020
Annika Braren[f]	General Cargo	5,100	1/18/3	2020	Oct 2020 expected
SC Connector[g]	Ro-Ro	8,843	2/35/5	1997	Q4 2020 expected
Kite			**Dimension of the kite (m^2)**		
Michael A.[h]	General Cargo	4,884	160	1994	2008
BBC Skysails[i]	General Cargo	9,832	320[i]	2008	2008[j]
Theseus[i]	General Cargo	3,667	160[g]	2009	2009[h]
Aghia Marina[i]	Bulk Carrier	28,522	320[i]	1994	2012[j]
Ville de Bordeaux[k,l]	Ro-Ro	5,200	500	2004	Nov 2020 expected
TBA[k]	Bulk Carrier	TBA (Capesize)	1,000	TBA	2021 expected
Suction Wing			**Number of wings/height (m)**		
Ankie[m]	General Cargo	3,600	2/10	2007	2020
Frisian Sea[n]	General Cargo	6,477	2/TBA	2013	Sep 2020 expected
Rigid sails/wing sails			**Number of foils/height (m)/width (m)**		
New Vitality[o,p]	Tanker	306,751	2/32/15	2018	2018
TBA[q]	Tanker	TBA (VLCC)	TBA	2022	2022 expected

Table 2: Recent WASP adoptions of commercial ships (a: (Comer et al., 2019); b:(Norsepower, n.d.); c: marinetraffic.com; d:(Dry Bulk Magazine, 2018); e:(Press - Scandlines, n.d.); f:("Eco-Flettner Für Das Neue Frachtschiff 'Annika Braren,'" 2020); g:(Norsepower Unveils First Tiltable Rotor Sail Installation with Sea-Cargo Agreement - Norsepower Rotor Sails, n.d.); h:(Aguiar Delgado, 2016); i: (Nelissen et al., 2016); j: (Novotny, 2016); k:(Reinhard, 2020); l: (Lloyd's List, 2020b); m: (The Maritime Executive, 2020); n:(Boomsma Shipping, n.d.); o: (G. Peng, personal communication, May 13, 2020); p: (Peng, 2019), q: (China Merchants Orders VLCC with Sails, 2020)

Table 2 mainly illustrates the commercial uptakes of WASP technologies until 2018. Since then, these have accelerated together with the involvement of multiple market players and are as follows:

- In January 2018, four moveable Flettner rotors developed by Anemoi were installed on Blue Planet's ultramax vessel Afros which marked the first installation of Flettner rotors on geared dry bulk vessels (Dry Bulk Magazine, 2018).
- Maersk Tankers reported 8.2% fuel saving from September 2018 to September 2019 on its Long Range 2 product tanker Maersk Pelican after the installation of two Flettner rotors from Norsepower (Maersk Tankers, 2019).
- Van Dam shipping's Ankie was retrofitted with two suction wings from eConowind in January 2020 (The Maritime Executive, 2020).
- Airbus Group is scheduled to install one 500 m^2 kite from Airseas on Louis Dreyfus Armateurs' Ro-Ro vessel Ville de Bordeaux in November 2020. Japanese ship owner "K" LINE also agreed to install one 1,000 m^2 kite on one capsize bulk carrier by end of 2021, according to Airseas. "K" LINE also indicated 50 possible installations conditional on a successful first delivery (Lloyd's List, 2020b; Nor-Shipping, 2019; Reinhard, 2020).
- Danish ferry operator Scandlines has installed one Flettner rotor from Norsepower on ferry Copenhagen in May 2020 (Pressekontakt et al., n.d.).
- Boomsma Shipping has scheduled an installation of two eConowind Flatrack unit of suction wings in October 2020 (Boomsma Shipping, n.d.).
- In September 2020, we have learned that Tharsis Sea-River Shipping has also expressed interest in participating in the WASP project by means of a suction-wings installation on one of its ships.

Overall, the industry has been witnessing a steady increase in the number of WASP technological installations, diversification of available WASP technologies, as well as an increase in the diversification of ship type, size, and ship owners that adopt them. This is a positive sign as the market expands and the collective learning of the "WASP industry" is likely to speed up and contribute to a positive feedback loop.

5. Economic impact - fuel saving

As shipping is an energy intensive industry and fuel costs account for a large share of a ship's operating cost and total costs (T. Notteboom, 2011; T. E. Notteboom & Vernimmen, 2009; Ronen, 2011), ship owners/operators are generally informed and concerned about fuel consumption (Jafarzadeh & Utne, 2014). The uptake of WASP technology has the potential to improve ships' efficiency as it reduces the propulsive power required from the fossil fuel-consuming main engine by introducing propulsive power generated from wind power so that a ship could maintain the same speed for reduced engine power or increase ship speed for the same engine power (Argyros, 2015). As mentioned in Stopford, (2009), different operating models in shipping (eg., voyage charter, time charter, bare boar charter) result in different cost distributions. In voyage charter, owners bear the cost of fuel while in time charter and bare boat charter charterers bear the cost of fuel. This has an impact on the decision making for WASP adoption because it is usually owners who decide on and fund ship modifications. This topic will be discussed further in the future reports in the WASP project. Here the focus is on the fuel-saving potential of the WASP technology.

An improved fuel efficiency does not only increase the expected profitability of the asset but also provides an operational hedge against volatile fuel costs. This can be seen for instance in other transport industries. Particularly, Treanor et al. (2014) and Berghöfer & Lucey (2014) 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 financial hedge with derivatives. Figure 9 shows that marine fuel in two major bunker ports Rotterdam and Singapore has been traded in the range between USD 100 and USD 600 per tonne in the last five years from February 2015 to February 2020. Hence, WASP technology can also act as a hedging instrument that helps ship owners/operators reduce their exposure to the volatility of bunker prices and reduce the number of bunker calls, making the ships more flexible.

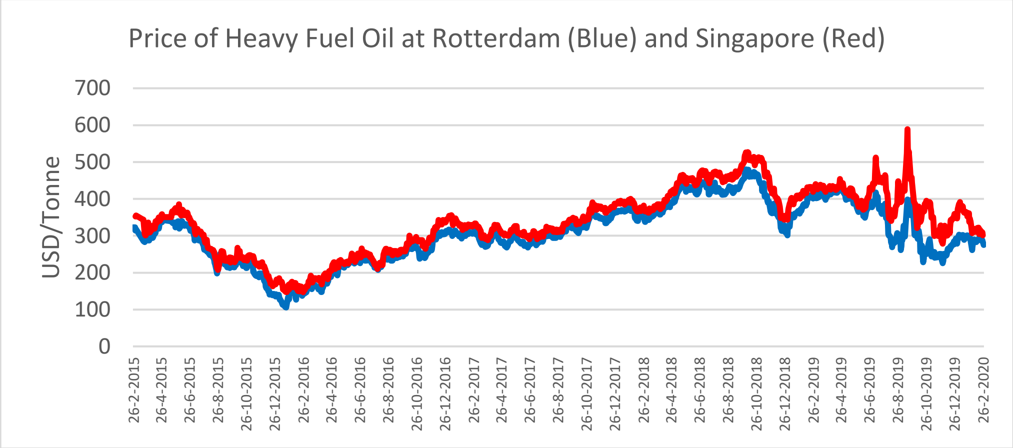

Figure 9: Heavy Fuel Oil Price from February 2015 to February 2020 (Reuters, accessed on 2 March 2020)

Articles and statements of WASP technology developers, centre their focus on the amount of fuel-saving that can be achieved. This caters to the interests of ship owners/operators. As observed on the GST

2020 Wind Propulsion Forum in Copenhagen, ship owners who have already adopted WASP technology clearly pointed out the importance of legitimate economic benefit from their investment. In other words, emission reduction alone is unlikely to convince ship owners and justify an investment in WASP technology due to the capital investment required and operational risks involved, such as technical uncertainty, counterpart issues, and port operations. An economic case has to be made so the potential financial upside compensates the costs and risks.

As the commercial adoptions of WASP technologies start to ramp up, academic research on the commercial viability has also been increasing in the past decade. The majority of studies conduct ship-wise simulations of ships' fuel consumption in steps, as described in Tristan Smith et al. (2013):

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

The aim of this process is to model the wind power contribution towards ship propulsion. Despite the similarities in the process that is 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 non-route-based simulation (De Marco et al., 2016; Leloup et al., 2016; Naaijen et al., 2006; Ran et al., 2013). It uses models to capture a range of parameters of modelled technologies, ships, and weather conditions based on assumptions or historical data found in literature or data bases. The objective is to calculate, under each scenario, how much energy output could be generated by the WASP technology. The net energy output is then compared with the propulsive power required by the modelled ships to ascertained the energy saving. Simply put, the simulation aims to compare the fuel consumption of a referenced ship with and without a WASP technology installed.
2. The second approach is route-based simulation, which in addition to the first approach, reconstructs specific route from ships' Automatic Identification System (AIS) data and takes into account wind and wave condition along the voyage of each route (Bentin et al., 2016; Comer et al., 2019; Lu & Ringsberg, 2019; Ouchi et al., 2013; Tristan Smith et al., 2013; Traut et al., 2014).
3. The third approach does not rely on simulation but 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 (DNV GL, 2019) and comparing the amount of fuel consumption.

The results of the studies consistently showed that WASP technologies have the potential to help ships save considerable amount of fuel under different conditions as is illustrated in Tables 3 - 5. It is important to note that different studies choose different parameters in their models such as the technology specification (e.g., number, dimensions, technical specifications), ships (e.g., type and size of the ships, speed), wind conditions, and routes. The table aims to include studies done on common commercial ships that make up the majority of the worldwide tonnage. Studies done on concept ships are not included because special designs of concept ships make the interpretation of data and comparisons between studies particularly challenging. A representative example is seen in the Sail project (Schwarz-Röhr et al., 2015) which found that WASP technology could lead to about 46% fuel saving with four Flettner rotors and about 10 – 40% fuel saving with 3-mast Dynarig.

As shown in the parametric study of Lu & Ringsberg, (2019), for ships fitting a Flettner rotor, the diameter, height, rotating speed, installed location, and average voyage speed all have an impact on the resulting fuel saving. Therefore, a direct comparison of results between different studies is not meaningful. In addition to the amount of potential fuel saving, the studies revealed a number of generic considerations and technology-specific considerations, which have direct and significant impact on the economics of WASP technology.

Study	**Dimensions of the Technology**	**Ship Type**	**Route**	**Fuel Saving Found**
Tristan Smith et al. (2013)	Unspecified	10K dwt Chemical Tanker	Buenos Aires - Western Approaches	20% - 50%
Traut et al. (2014)	1 Flettner rotor: height (h) = 0 35 m, diameter (d) = 5 m	7k dwt Ro-Ro 8k dwt Product Tanker 6k dwt General Cargo 50k dwt Bulk Carrier 30k dwt Container Ship	Dunkirk - Dover London - Milford Haven Varberg - Gillingham Tubarao - Grimsby Yantian - Felixstowe	4% 14% 21% 5% 2%
Nelissen et al. (2016)	2 Flettner rotors: h = 22 m, d = 3 m 3 Flettner rotors: h = 48 m, d = 6 m 2 Flettner rotors: h = 24 m, d = 3.5 m 2 Flettner rotors: h = 48 m, d = 6 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% - 7% 9% - 13% 5% - 7% 17% - 23%
Bentin et al. (2016)	1 Flettner rotors: h = 25 m, d = 4 m	17k dwt General Cargo	Baltimore - Wilhelmshaven	14% - 36%
De Marco et al. (2016)	2 Flettner rotors: h = 28 m, d = 4 m	75k dwt Product Tanker	N.A.	Up to 30%
Comer et al. (2019)	4 Flettner rotors: h = 27 m, d = 4 m 2 Flettner rotors: h = 18 m, d = 4 m 1 Flettner rotor: h = 24 m, d = 4 m 1 Flettner rotor: h = 18 m, d = 3 m 2 Flettner rotors: h = 30 m, d = 5 m	10k dwt General Cargo/Ro-Lo 10k dwt Ro-Ro 6k dwt (2.8k pax) Passenger 4k dwt General Cargo 110k dwt Tanker	Porto - Montevideo; Eemshaven - Porto Rotterdam - Middlesbrough Stockholm - Turku Livormo – Mostaganem; Huelva - Alexandria Sklkda – Singapore; Yeosu - Spain	8.3% - 47% 1.6% - 9.0% 0.4% - 2.8% 1.0% - 6.6% 1.8% - 4.7%
Lu & Ringsberg (2019)	1 Flettner rotor: h = 18 m, d = 3 m	Aframax Tanker	Cape Lopez - Point Tupper Angra dos Reis - Rotterdam	8.9% 6.5%
DNV GL (2019)	1 Flettner rotor: h = 18 m, d = 3 m	4k dwt General Cargo	Unspecified	10% - 20%

Table 3: Review of fuel-saving performance of rotors

Study	**Dimensions of the Technology**	**Ship Type**	**Route**	**Fuel Saving Found**
Naaijen et al. (2006)	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%
Ran et al. (2013)	1 kite: a = 640 m2, l = 600 m	73k dwt Tanker	N.A.	40%
Traut et al. (2014)	1 kite: a = 500 m^2, l = 350 m	7k dwt RoRo	Dunkirk - Dover	3%
		8k dwt Product Tanker	London - Milford Haven	24%
		6k dwt General Cargo	Varberg - Gillingham	32%
		50k dwt Bulk Carrier	Tubarao - Grimsby	6%
		30k dwt Container Ship	Yantian - Felixstowe	1%
Nelissen et al. (2016)	1 kite: a = 400 m^2, l = 350m	5k dwt Tanker	Worldwide trades of each ship type according to AIS data	9% - 15%
		90k dwt Tanker		3% - 4%
		7k dwt Bulk Carrier		9% - 14%
		90k dwt Bulk Carrier		5% - 9%
		1k TEU Container Ship		2% - 4%
		5k TEU Container Ship		1% - 2%
Leloup et al. (2016)	1 kite: a = 320 m^2, l = 300m	50k dwt Tanker	N.A.	10% - 50%

Table 4: Review of fuel-saving performance of kites

Study	Dimensions of the Technology	Ship Type	Route	Fuel Saving Found
Tristan Smith et al. (2013)	1 Dynarig	10K dwt Chemical Tanker	Buenos Aires - Western Approaches	15% - 35%
Lu & Ringsberg (2019)	1 Dynarig: area = 1,000 m^2	Aframax Tanker	Cape Lopez - Point Tupper Angra dos Reis - Rotterdam	5.6% 4.2%

Table 5: Review of fuel-saving performance of soft sails

Study	Dimensions of the Technology	Ship Type	Route	Fuel Saving Found
Ouchi et al. (2013)	9 wingsails: height (h) = 50 m, width (w) = 20 m	180k dwt Bulk Carrier	Yokohama - Seattle	20% - 30%
Tristan Smith et al. (2013)	Unspecified	10K dwt Chemical Tanker	Buenos Aires - Western Approaches	20% - 60%
Nelissen et al. (2016)	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%
Lu & Ringsberg (2019)	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 wingsails

Study	Dimensions of the Technology	Ship Type	Route	Fuel Saving Found
Nelissen et al. (2016)	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%

Table 5: Review of fuel-saving performance of wind turbines

6. Fuel-saving considerations

The speed and direction of wind are two major factors that determine the fuel saving in the models of all the studies examined in section five. 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 resulting in higher fuel savings. This is not unexpected as WASP technologies utilize wind power to produce thrust for ships (Bentin et al., 2016; Leloup et al., 2016; Naaijen et al., 2006; Nelissen et al., 2016; Ouchi et al., 2013; Ran et al., 2013; Tristan Smith et al., 2013).

Optimal routes of ships fitted with WASP technologies could differ from the optimal route for ships without WASP technologies. On the other hand, wave height, which has a negative impact on ships' performance, are often higher where wind speed is higher (Tristan Smith et al., 2013). When modelling 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 (Tillig & Ringsberg, 2019). Many of the studies use reconstructed routes from AIS data and/or shortest paths (Lu & Ringsberg, 2019; Nelissen et al., 2016; Traut et al., 2014). Bentin et al. (2016) has shown that when a route-optimizing tool is utilized, fuel saving of WASP technologies is increased from 14 - 36 % to 28 – 53%. Tristan Smith et al. (2013) showed 5% - 10% more fuel saving could be achieved when the ship is free to deviate from the Great Circle route to utilize optimal wind and wave, while Ouchi et al. (2013) observed a 30% fuel saving on a wind-optimal route compared to 22% on the Great Circle.

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 (Naaijen et al., 2006; Tristan Smith et al., 2013). In cases where a route is optimized for WASP technologies to achieve a lower fuel consumption, the trip duration and irregularity of the trip duration may deteriorate when trying to maximize the most favourable wind, resulting in a suboptimal economic result (Naaijen et al., 2006). 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 crew on-board 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 the WASP technology effectively. The change of the crew takes place on a regular basis and thus the level of operational efficiency could be difficult to maintain (Nelissen et al., 2016). An automatic system could play a significantly role in reducing the risks associated with crew demand.

As the ship master is in charge of the navigation of the ship, a fully automated system may not allow the flexibility of a competent ship master with good sailing skills to achieve an optimal result (Argyros, 2015). At times, it might be beneficial to changing ship's speed and course to maximize fuel saving to catch favourable wind, which demands good decision making of the ship master.

Trade patterns have a significant impact on the fuel saving potential of WASP technologies, as wind and ocean current in different geographic locations affect ships' performance. It is important to match the right technology to the right trade pattern. Rehmatulla et al. (2017) show that for dry bulk carriers ranging from 0 – 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. Comer et al. (2019) 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 (Lu & Ringsberg, 2019; Nelissen et al., 2016; Traut et al., 2014).

Seasonal differences in fuel savings are observed in the simulation of (Tristan Smith et al., 2013) for the Argentina-UK trade line where Flettner rotors perform better in the winter and a wingsail performs better in the summer period. Comer et al. (2019) shows that in the winter of Northern Hemisphere the wind speed is higher and enables Flettner rotors to achieve more fuel saving. In Bentin et al. (2016), Tristan Smith et al. (2013), and Traut et al. (2014), direction of the voyage is found to cause a difference in fuel saving. The dominant west – east wind direction present in the Atlantic ocean resulted in significant difference in fuel saving between Baltimore to Wilhelmshaven (36%) and Wilhelmshaven to Baltimore (14%) (Bentin et al., 2016). Longer-haul voyages are found to have a lower variability of fuel saving than short ones (Traut et al., 2014), and are more likely to enable more fuel saving as wind speed tends to be higher in more open ocean (Nelissen et al., 2016). Research focusing on application of the WASP technology in North Sea is currently lacking. The WASP project fills this gap and will verify the potential of the WASP technology in North Sea by measuring the performance of each installation.

7. Technology-specific considerations

Flettner rotors contribute more to fuel savings achieved, while Dynarig (soft sail) save less according to the studies by Lu & Ringsberg (2019), Nelissen et al. (2016), and Tristan Smith et al. (2013) that provided direct comparisons between technologies. However, it is worth noting that the studies used different specifications of ships and technologies so the results may only serve as a reference. As studies that provide direct comparisons are scarce, more research, like the WASP project will serve as an important way to find out more about the performance between different technologies. Traut et al. (2014) found that the power output of kites is more volatile than Flettner rotors, as by nature, Flettner rotors generate propulsive power over a wider range of wind directions; hence, Flettner rotors' performance is less sensitive to geographic locations and weather conditions. Similar result is found in Nelissen et al. (2016).

On the other hand, kites have a number of advantages over Flettner rotors as they can catch stronger wind at a higher altitude, they are safer for the ship due to lower impact on the roll heeling moment, and they take little deck space (Naaijen et al., 2006). However, the impact on the roll heeling moment shall be studied further on real-life installations on actual sailing conditions. Such research will be done in the WASP project with the collaboration of ship owners. On the other hand, it was found that when the kite flies higher, it contributes more thrust to the ship and helps save more fuel (Naaijen et al., 2006) compared to flying at a lower altitude. In terms of scalability, both Flettner rotors and wingsails have the potential to scale up with ship size. Although kites may have less scalability, the fact that they do not take much deck space make them particularly attractive for container ships (Nelissen et al., 2016).

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 tail wind, while Flettner rotors thrive on sideway winds ((De Marco et al., 2016; Leloup et al., 2016; Lu & Ringsberg, 2019; Nelissen et al., 2016; Ran et al., 2013; Traut et al., 2014). 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, power demand of the ship has a greater effect on the fuel consumption than the contribution of rotors/wingsails (Lu & Ringsberg, 2019; Nelissen et al., 2016; Tristan Smith et al., 2013). Kites not only generate more savings in absolute term under lower speed, but also generate more or equal absolute savings as the apparent tailwind is likely to be stronger (Nelissen et al., 2016; Ran et al., 2013). As suction wings is relatively new to the market, more research shall be done to better understand its performance under different conditions. It plays a key role in the WASP project and will be thoroughly studied.

8. Concluding remarks

The global maritime community is currently investigating various measures in order to meet the decarbonisation targets that have been set by policy makers. Although under less spotlight than alternative fuel, WASP technology is increasingly available and proven to be an integral piece in this transition process that requires a variety of abatement measures to work in conjunction. In addition to niche actors that have been driving the development of WASP technology since day one, an increasing number of regime actors such as regulatory authorities, classification societies, and large international ship owners have joined the "WASP industry". This growth has the potential to lead to more uptakes and an accelerated decarbonisation transition.

WASP technology has come a long way in terms of its development and commercial adoptions. An uncertainty remains over just how much longer it takes to make a larger economic and environmental impact. Rotmans et al. (2001) noted 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 1970s to continued growth phase 2000s appears to confirm this requirement of at least one generation's effort (Jacobsson & Lauber, 2006). If we consider 2008 the start of recent uptake of new WASP technology, it seems we are now at around the mid-point of this transition and the acceleration has begun thanks to a cluster of dedicated industry and academic participants. From now there is clearly much more potential to be realized before the WASP technology reaches the diffusion level suggested in Nelissen et al. (2016) (3,700 - 10,700 ships in 2030) and Frontier Economics (2019a) (37,000 – 40,000 ships by 2050).

The sense of urgency is growing in the maritime industry, as discussion intensifies to bring more long and short-term changes, such as the implementation of Energy Efficiency Existing Ships Index (EEXI) and Ship Energy Efficiency Management Plan and Carbon Intensity Indicators (SEEMP & CIIs) (Lloyd's Register, 2020). The WASP technology is a strong option for policy makers to support and ship owners to adapt for the transition. A good amount of research in academia and industry have quantified ship-wise fuel saving potential and studied the impact from variability in wind speed/directions, trade patterns, geographical areas, seasonal effect, long/short-haul voyage, ship's operation profile/limits, and route optimization. The result consistently showed that WASP technology has significant potential to make ships more energy-efficient. To achieve the most desirable fuel consumption reduction in the most favourable way to ship owners/operators, a range of factors mentioned in the previous sections must be taken into consideration.

As the uptake continues to increase in both number and diversity, the economic impact of WASP technology will be made even more transparent going forward. A promising pipeline in the next 12 to 24 months will increase the pace of the development of the WASP industry. Since different technology has distinct performance characteristics under different conditions, a one-size-fits-all solution is unlikely to exist. In other words, before seeing mass uptakes, the majority of ship owners/operators will likely demand more information and seek to learn the experience of market players that have adopted WASP technology. Therefore, at the core of the WASP project, it is crucial to produce more verified third-party research teamed with actual commercial uptakes, thus more legitimacy could be generated and a broader audience could gain more insight into the risks and opportunities of WASP technology. In addition, more research shall be done to establish the risk and return relationship of WASP technology and how it could contribute to the operational hedge of ship owners/operators. A higher management perspective on the organizational transformation and business models is also a future area of research. Along with the ambition to shed light on above topics, the WASP project will also place an emphasis on the technologies' performance in the North Sea region and provide one of the first studies on suction wings at sea. The objective is to further the green transition of maritime transportation in North Sea and help verify new WASP technology.

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