Analysis on the Development of Wind-assisted Ship Propulsion Technology and Contribution to Emission Reduction

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Abstract. With the issue of peaking carbon dioxide emissions and carbon neutrality increasingly becoming the forefront of international public opinion, changes in the shipping industry are imminent and destined to cause long-term transformation across the entire industry chain, from ship design to maritime operations. Wind energy as a clean energy source has attracted the increasing attention of experts in the shipping field. This paper summarizes the application and development of wind-aided navigation technology for ships represented by rotors, towing kites, wing sails and soft sails, and analyses the constraints of wind-aided navigation technology. The contribution to emission reduction of typical wind-aided navigation methods such as rotors, towing kites, wing sails and soft sails is summarized. Finally, the development suggestions of wind-assisted ship propulsion (WASP) technology are summarized and proposed, which can provide reference for further research and application of this technology.

1. Introduction

The transport of goods in worldwide trade is currently dominated by the shipping industry. Carbon dioxide emissions from maritime trade account for about 2.9% of anthropogenic carbon dioxide emissions. The International Maritime Organization (IMO) estimates that by 2050, greenhouse gas emissions from maritime transport are expected to increase by 90-130% compared to 2008 [¹]. In addition, ocean shipping accounts for 13% and 15% of global emissions of sulphides and ammoniacs as the global fleet still commonly uses diesel engines with heavy fuel oil containing high sulphur content [²]. Therefore, under the increasingly stringent emission regulations, there is an urgent need for the shipping industry to take measures to mitigate its negative impact on the environment and human health.

In 2016, at its 70th session, the IMO Marine Environment Protection Committee (MEPC) adopted an agreement that ships over 5,000 dwt will need to submit annual fuel consumption data and reports on their transport work to IMO from 2019. In 2018, in order to align with the reduction targets set in the UN's 2015 Paris Agreement, the IMO launched its first emissions reduction strategy and set targets to reduce total greenhouse gas emissions from shipping by at least 50% by 2050 and to reduce CO₂ emissions per unit weight of cargo transported by at least 40% by 2030 and 70% by 2050 compared to 2008 levels [³]. In May 2019, MEPC approved the decision to advance the implementation of "Phase 3" of the Energy Efficiency Design Index (EEDI) at its 74th session. This puts forward higher requirements for the energy efficiency of new container ships. In November 2020, the MEPC's 75th
session agreed to develop the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicators (CII), among other short-term measures, to achieve further regulation of carbon emissions from existing ships.

With the tightening of environmental policies, reducing carbon emissions in shipping has become a new focus in recent years. In addition to traditional measures such as improving energy efficiency and using cleaner fuels, wind-assisted ship propulsion (WASP) are gaining attention from researchers. This technology has a wide range of technical configurations for different practical situations and can ideally achieve high economic results, which are expected to achieve the long-term carbon emission reduction plan set by IMO. In this paper, we introduce the technical classification and economic effects of wind-aided navigation technology, analyse the practical examples of using wind-aided navigation technology, show the latest progress and development prospects of this technology, and summarize and analyze the emission reduction contribution of different ways of implementing wind-aided navigation technology for ships, to provide new ideas for energy saving and emission reduction of ship shipping.

2. WASP technology and its application

The earliest wind-powered ships can be date back to 3100 B.C. [4] when the Egyptians used the wind to navigate north and south on the Nile. In the following centuries, both river and sea transport relied on wind, and after the Industrial Revolution in the 19th century, when steam-powered ships greatly increased the flexibility and reliability of cargo and passenger transport, the use of sailing ships was largely restricted to sightseeing, recreation and athletics. The use of wind energy has been on hold in the shipping industry for nearly two centuries due to the need for efficiency.

Under the pressure of global environmental policies, wind propulsion technology is once again on the radar of those working in the shipping industry. With wind power providing auxiliary propulsion for ships, ships can maintain normal sailing speed while reducing engine power, or increase ship speed while maintaining the same engine power. In short, the main benefits of using wind power on board ships are the same as for the general wind energy industry, i.e. reduced consumption of conventional energy and reduced emissions of greenhouse gases and harmful substances.

To use wind power for energy saving and emission reduction on modern ships, the shipbuilding industry has developed and tried a series of WASP products, including rotors, towing kites, wing sail, soft sail, suction wing sail, wind turbine, hull sails, etc. Among them, rotors, towing kites, wing sails and soft sails have better energy-saving effects.

2.1. Rotors

The inventor of the Rotor is German engineer Anton Flettner, hence the name Flettner rotor. The principle of its use of wind energy is the Magnus effect, a hydrodynamic phenomenon in which when the induced wind meets a rotating cylinder, one side of the cylinder impedes the flow of gas to slow it down, and the other side promotes the flow of air to accelerate it. According to Bernoulli's theorem, high- and low-pressure regions will be formed around the rotating cylinder at this time, and due to the pressure difference and the presence of the side wind, lift and drag forces will be formed in the vertical and parallel wind directions, respectively. As shown in Fig 1. By mounting the rotors on the deck of the ship and using a drive mechanism to rotate it, then when the ship is sailing into a side wind, the rotors will create a combined force to move the ship forward, achieving a saving in main engine power. In 1924, Anton Flettner fitted two iron cylinders of 3 m diameter and 13 m height on a speedboat [5], as shown in Fig 2. Flettner used a 37kW electric system to turn the cylinders and used this speedboat to cross the North Sea between Britain and Denmark.
The rotor configuration is a proven solution with relatively simple technology, good energy efficiency and it has good compatibility with the wind direction. Despite the technical problems of modifying the ship's deck arrangement and powering the rotor, this technology has attracted a lot of attention from policy makers, academic institutions, shipping and energy companies. Commercial companies such as Anemoi (UK) and Norsepower (Norway) are already providing total solutions for the installation of rotor units on existing and new vessels, and their products have been installed on several vessels and have been tested in practice.

The biggest feature of Anemoi’s rotary sail scheme is its patented track deployment system. This system enables the rotary sail to move on the ship's deck, and the port crane can easily load and unload goods without obstruction, to minimize the impact of the installation of rotary sail on the ship's operation. The 64,000 DWT ultra-large bulk carrier Afros, delivered in January 2018, was fitted with four 16m high, 2m diameter rotor sails manufactured by Anemoi and using the orbital deployment system. Based on data obtained while the vessel was sailing on a regular route from Nantong to Vancouver and back between November 2019 and January 2020, the Afros has an estimated fuel consumption and emissions reduction of 12.5%, or 73 tonnes of fuel oil use and 235 tonnes of CO₂ emissions [6].

Norsepower’s rotor products have been deployed on various vessel types and have proven their technical stability and maturity. 109,647 DWT Maersk Pelican was fitted with two 30m high, 5m diameter rotor sails designed and manufactured by Norsepower in August 2018, and measurements by Lloyd's Register confirm that the vessel saved 8.2% in fuel consumption in the first year of operation. On typical global routes, the rotor equipment has reduced the average fuel consumption of the entire vessel by 7-10% [7].

Norsepower has also designed a pitching device for rotary sails, so that ships equipped with this device can still easily pass through inland river bridges. In January 2021, the two largest rotors made by Norsepower, 35 meters high and 5 meters in diameter, were installed on the dry cargo ship SC connector operating in the North Sea, which is expected to reduce fuel consumption and emissions by 25%.

In summary, the rotor sail is a wind-assisted technology configuration that has become a promising technology path for many technology companies and research institutions, with a number of successful commercial products, due to its ideal energy-saving and emission reduction performance, proven reliability and flexible arrangement.

2.2. Towing kites
Towing kite boosting solutions provide thrust to a ship by means of lift generated by high altitude winds. Since 2007, Skysails has developed several generations of commercial towing kite products. In 2007, the "Beluga Skysails" was fitted with a towing kite booster and sailed across the Atlantic Ocean from Hamburg, Germany, to Houston, USA, where it took three months to complete live-ship trials. The results of the experiments showed that the ship could save 15-35% fuel consumption depending on the wind conditions [8]. Since then, towing kites has started to gain the attention of shipping
industry practitioners. Currently, Skysails can offer proven towed kite installation solutions for existing and newbuilding vessels with its globally patented SkySails propulsion system consisting of three main components: a towed kite with ropes, a control system for automatic operation and a launch and recovery system [9], as shown in Fig 3.

Figure 3. Skysails towing kite propulsion system

Figure 4. Schematic representation of the structure of the Seawing [11]

The Skysails propulsion unit’s towing kite is "dynamically" regulated, flying ahead of the ship in a Fig eight shape in the air under autopilot control. As a result, the airspeed of the tow kite increases to several times the real wind speed; moreover, the SkySails tow kite works at altitudes of 100 to 500 m, where the wind is stronger and more stable. As a result, SkySails kites can easily generate 5 to 25 times more propulsion per square meter of sail area compared to conventional sail propulsion systems. Technical information provided by SkySails shows that in good wind conditions, towing kites can deliver 2000 kW of propulsion power. With the huge free wind potential on the high seas, the SkySails propulsion unit can halve the fuel consumption of the vessel under ideal conditions. With SkySails propulsion, fuel savings of 10-15% per year can be achieved on average. At the same time, IMO estimates that with SkySails technology alone, up to 100 million tons of carbon emissions could be cut globally each year [10].

In recent years, Airseas, a subsidiary of the Airbus Group, has also introduced their commercial towing kite, the Seawing, which is shown in Fig 4. The traction kite produced by Airseas inherits the safety procedures of the aviation industry and uses the fault hazard analysis method for system safety assessment to ensure the stable operation of the equipment. Sewing’s simple and modular structure allows it to be quickly installed during the berthing of almost all commercial ships in operation today. Airseas claims that its products can achieve a 20% reduction in fuel consumption and emissions [11].

The biggest advantage of this type of equipment is that it takes up almost no deck space, the weight of the complete unit is small and it basically does not interfere with the loading of the ship. The disadvantage is that the solution is useless when the wind is unfavourable or when the ship is fast. The towing kite technology route has been pursued by commercial companies such as SkySails for more than a decade, as well as by newcomers such as Airseas, who have launched proven shelf products backed by the aviation giants’ "downscaling". With simple structures and high performance, towing kite technology is expected to take its place in the wind-aided aviation sector.

2.3. Wing sails

The wing sail is a kind of rigid sail like a wing that uses the Bernoulli effect to generate aerodynamic forces. The airfoil profile causes the air flow to pass through creating a velocity difference and thus a pressure difference, i.e. lift, and the component forces of lift and friction in the direction of navigation constitute the propulsive force, as shown in Fig 5.

This technology was used by Japanese shipowners in the 1980s. In 1980, Japan built the world’s first modern sailing tanker, Shin Aitoku Maru, which displaced 2,400 tons and was equipped with two folding fiber reinforced plastic sails and a low-speed diesel engine for auxiliary power, both of which were used in conjunction. Compared with ordinary ships of the same tonnage, this vessel reduced fuel consumption by approximately 10% to 30% during its lifetime while using the JAMDA rigid sails [12].
In August 1985, the Guangdong Shipping Research Institute installed rigid sails on an 80-ton cargo ship, and the ship's speed increased by 1.41km/h compared with that of an ordinary cargo ship in a class 3 to 4 wind and at medium speed of the main engine. In 1990, the Wuhan Water Transport Engineering Institute and Yueyang Water Transport Company jointly developed the first modern rigid skeleton sail-assisted ship in China, which has a comprehensive energy-saving effect of more than 25% [13].

At the same time, the operation of wing sails on ships faced various difficulties, including the vulnerability of the structure to damage, hindering the operation of the deck, and less available wind direction, and the shipping industry gradually stopped the development of this direction after the 1980s. In recent years, with the tightening of environmental protection policies and the advancement of automation technology, material technology and manufacturing process, this development direction has been restarted by the maritime research institutions of many countries. On November 13, 2018, the world's first 308,000 DWT Very Large Crude Oil Carrier (VLCC) No. 80 "Kaili" built by China Grand Ship Group with wing sail installation was successfully delivered. The vessel was successfully delivered, as shown in Fig 6, which is the representative of wing sail boost VLCC. The sails are 39.68 m high and 14.8 m wide, with a maximum outside diameter of 5.3 m for the slewing base and 4.5 m for the middle cylinder of the base [14]. At least 5% fuel can be saved when sailing at 12 knots under full load condition and BF scale 5. When the wind comes from the best angle, 16% fuel will be saved.

The eConowind-unit developed by Conoship is a new foldable, fully automated wind assisted propulsion module that is easy to install on all types of vessels. The entire module is based on a standard 40-foot container, as shown in Fig 7, enabling quick installation and removal on the vessel and very easy placement in the container during bad weather. eConowind-unit is a fully automated unit, with the wing sail automatically unfolding and automatically adjusting to the optimum position for maximum thrust in favourable wind directions. The sail uses the same thrust generation mechanism as the wing sail, but features a suction device on the tail of the suction sail that continuously draws in the fluid boundary layer, reducing or even avoiding flow separation and thus greatly increasing the lift coefficient. This technology was first used in aviation to solve the problem of insufficient lift of the airfoil at large angles of attack and low velocity flow, with the disadvantage that the suction device requires additional energy.

The fuel consumption and CO\textsubscript{2} emissions of a ship using this wing sail device can be reduced by 10-20%, depending on the sailing area, speed and ship size, while maintaining the same speed [15].
Figure 7. The eConowind-unit that can be stored in a container

Figure 8. Wing sail combined with solar technology on the Eco Marine Power

Standardization, light weight, intelligence will become the key direction of future research and development of wing sails. For example, the sail blade is changed from metal to non-metal such as carbon fiber material, and the overall structure is a mixture of metal and non-metal, which will greatly reduce the weight of the booster system. Some researchers have also explored the possibility of combining wing sails with solar technology \(^\text{[16]}\), as shown in Fig 8. This technical route of wing sails still needs more reliable experimental data after installation on real ships to prove its energy-saving performance and reliability.

2.4. Soft Sails

The Dynarig sail, a modified version of the traditional square sail developed by Prof. Poulos, consists of a cantilevered mast, a sail beam and sails that are independent of each other and can be stowed independently. When in use, the sails are spread together to form a continuous sail surface. In terms of aerodynamic performance, Dynarig sails are excellent, safe and reliable in operation, but the disadvantage is that Dynarig sails are costlier and more complex in structure. The practical application of this technology on commercial vessels is limited due to deck layout requirements and is currently used mainly on large sailing yachts, as shown in Fig 9.

In July 2019, the French owner company Neoline placed an order for 2+2 sail-powered ro-ro vessels, which are 136 m long and 24.2 m wide and whose concept is shown in Fig 10, and she can carry up to 478 cars and reach a speed of 11 knots. With a total sail area of up to 4,200 square meters, her sail attitude can be automatically calculated and adjusted according to the direction of advance and wind direction. The vessel also comes with its own 4,000kW diesel motor power system, but this system will only be activated for outbound and inbound calls and in emergencies \(^\text{[17]}\). Neoline hopes to save 80-90\% in fuel consumption and reduce carbon emissions with these sail-powered new ro-ro vessels to provide transportation services.
Although some ship owners have already decided to rely on soft sails to achieve their ambitious carbon zero plans, this technology route will be difficult to accommodate with existing large ocean-going vessel designs due to its high maintenance and operating costs and deck space requirements, and until new soft sail design configurations become available, it is difficult to expect to see large-scale adoption of this technology route.

3. Constraints of WASP technology

Wind speed and wind direction are the two main factors of fuel savings in the existing literature and in commonly used computational models. In general, it can be shown that, all other factors being equal, the higher the wind speed, the greater the energy output of the wind-assisted technology and thus the greater the fuel savings. This is obvious because wind-assisted devices all use wind energy to generate thrust for the ship. However, wave heights are usually higher at higher wind speeds and this has a negative impact on the navigation of the ship. When modelling ship performance using wind-assisted navigation, more sophisticated models that consider lateral forces and yaw moments should be used to obtain more accurate fuel consumption predictions.

Routing factors also affect the performance of wind-assisted devices, and related studies have used climate data, AIS data, and shortest paths for route reconstruction and concluded that fuel savings from wind-assisted technology increased from 14-36% to 28-53% when route optimization was used to obtain more wind energy for ships with wind-assisted devices [19]. While the sailing route affects the level of wind energy utilized by wind-assisted devices, the compatibility of wind-assisted technology with commercial operations is also considered during route optimization.

Climatic factors must be considered in the study, and seasonal differences in fuel savings were observed from simulations of the Argentine-UK route, where rotor sails performed better in winter and wing sails performed better in summer. Higher wind speeds in the northern hemisphere in winter allowed the rotor to save more fuel. In a related study, the direction of the voyage was also found to cause fuel savings differences. The typical westerly winds in the Atlantic Ocean resulted in a significant difference in fuel savings between Baltimore to William Shaven (36%) and William Shaven to Baltimore (14%) [19].

It has also been found that long-distance voyages show less variability in fuel savings performance than short-distance voyages, and that ocean voyages are more likely to save more fuel because wind speeds tend to be higher in open water. Related studies have shown that most effective in saving fuel and reducing emissions off the west coast of Europe, the South China Sea, the Indian Ocean and the Arabian Sea, while the same WASP devices are performed less well off the Mediterranean Sea and the west coast of Africa [20].

Operational limitations of wind aids to navigation remain another issue. Since the crew is responsible for the operation of the equipment while the vessel is underway, they are subject to greater workload and risk, and may require additional training to effectively use and maintain the wind aids to navigation. In addition, it may be difficult to maintain operational efficiency and levels as the vessel's crew is regularly replaced. Informed decision making by the skipper is required to decide whether to change the speed and course of the vessel to go downwind and thus save fuel, which the fully automated system is not capable of doing for the time being.

To achieve the best economic benefits in the operation of a ship using wind-aided navigation technology, it is most important to take a systems analysis approach rather than to analyse individual factors in isolation. For example, the route determines the wind speed and wave height that a ship encounters in a given season; the shipowner not only wants to maximize fuel savings, but also to reduce navigational irregularities. Table 1 summarizes the typical environmental, ship and commercial factors that have an impact on the operational efficiency of wind aids to navigation [21].

| Influence factors | Environment factors | Ship factors | Commercial factors |
|-------------------|---------------------|--------------|--------------------|
| 1 Air velocity    | Route optimization  | Trade route  |
| 2 Wave            | The captain’s command of the source | Travel time |
| 3 Seasonal climate change | Crew training | Port demand |
4. Contribution of WASP technology for emission reduction

At present, as the wind-aided navigation technology gradually receives the attention of shipping industry practitioners and researchers of related institutions, the relevant experimental data gradually become more and more abundant. The fuel saving and emission reduction data of wind-aided navigation devices are shown in Table 2 and Table 3, after summarizing the simulation analysis research data, the fuel saving and emission reduction data of existing deployed wind-aided navigation devices on real ships, the public technical indexes of relevant commercial companies, and the reports of relevant research papers.

Table 2. Data on fuel savings from emission reductions from existing commercial wind aids to navigation on actual vessels [6, 7, 9, 14, 15]

| Ship’s name | Performance parameters | Ship type | Routes | Emission reduction and fuel saving targets |
|-------------|------------------------|-----------|--------|------------------------------------------|
| Afros       | 4 rotor sails 16m×2m    | 64000DWT Ultra Large Bulk Carrier | Nantong to Vancouver | 12.5% |
| Axios       | 4 rotor sails 25.4m×3.5m | 82,000DWT Kamsarmax bulk carrier | Kamara jar to Paranagua | 12% |
| Estraden    | 2 rotor sails 18m×3m    | 9000 DWT Cargo Ship | Netherlands to United Kingdom | 6.1% |
| Timberwolf  | 2 rotor sails 30m×5m    | 110,000DWT tanker | Tanjung Pelepas to Ain Sukhna | 8.2% |
| SC Connector| 2 rotor sails 35m×5m    | 8843DWT Ro-Ro vessel | Risavika to Aarhus | 25% |
| Michael     | SKS160 Kite System     | 3560DWT Cargo Ship | Indeterminate | 10-15% |
| eConowind unit | 2 wing sails 13.3m×2.44m | Modular arrangement | Indeterminate | 10%-20% |
| Kaili       | 2 wing sails 39.68m×14.8m | 308000DWT Tanker | Indeterminate | 5-16% |

An examination of related research shows that rotors and towing kites are currently the two technology with the highest number of live-ship deployments and the most theoretical research attention. The fuel-saving capability of rotor sails is less sensitive to course and weather conditions, while towing kites offer fuel-saving performance advantages over conventional sail types due to their ability to capture stronger winds at higher altitudes and to produce smaller cross-tilt moments due to their lower traction points. In terms of scalability, rotor sails are more advantageous in that they can be raised in height and diameter or increased in number as the size of the ship increases, and the power contribution is expected to increase linearly with the number of spinners. Although towed kites are less scalable, their advantage of not taking up too much deck space makes them still particularly attractive to container ships.

Since the actual operational performance of each wind-aided navigation device depends on many factors, and the amount of available literature has not found a clear technical configuration with outstanding performance. Therefore, in order to construct a system for predicting and evaluating the performance of WASP technology based on the effects of wind speed and direction, trade patterns, geographical area, seasonal effects, long and short range, ship operation generalizations and limitations, and route optimization, more real ship deployments and simulation experiments must be conducted.
Table 3. Experimental data on fuel savings from emission reduction of wind-aided navigation devices under numerical simulation for different technology lines [21-24]

| Performance parameters | Ship type | Routes | Emission reduction and fuel saving targets |
|------------------------|-----------|--------|------------------------------------------|
| 1 Turret sail          | 8k DWT product tanker | London-Milford Haven | 14% |
| (height × diameter):  35m×5m | 6k DWT general cargo ship | Varberg-Gillingham | 21% |
|                        | 50k DWT bulk carrier | Tubarao-Grimsby | 5% |
|                        | 30k DWT container ship | Yantian-Felixstowe | 2% |
| 2 rotor sails          | 5k DWT tanker | | 5.7% |
| (height × diameter):  22m×3m | 90k DWT tanker | Typical global trade routes by ship type based on AIS data | 9-13% |
| 3 rotor sails          | 7k DWT bulk carrier | | 5.7% |
| (height × diameter):  48m×6m | 7k DWT bulk carrier | | 17-23% |
| 2 rotor sails          | 90k DWT bulk carrier | | 9-14% |
| (height × diameter):  24m×3.5m | 7k DWT Ro-Ro vessel | Dunkirk-Dover | 3% |
| 2 rotor sails          | 90k DWT bulk carrier | | 9-14% |
| (height × diameter):  48m×6m | 8k DWT product tanker | Typical global trade routes by ship type based on AIS data | 5-9% |
| Kite towing (area × rope length): | 6k DWT groceries | London-Milford Haven | 24% |
| 500m²×350m             | 50k DWT bulk carrier | Varberg-Gillingham | 32% |
|                        | 5k DWT tanker | Tubarao-Grimsby | 6% |
|                        | 90k DWT tanker | | 6-9% |
|                        | 7k DWT bulk carrier | | 3-4% |
| Kite towing (area × rope length): | 90k DWT bulk carrier | Typical global trade routes by ship type based on AIS data | 2-4% |
| 400m²×350m             | 1k TEU container ship | | |
|                        | 5k TEU container ship | | 1.2% |
|                        | 5k DWT tanker | | 5.8% |
| 3-seater wing sail     | 90k DWT tanker | Typical global trade routes by ship type based on AIS data | 9-13% |
| (height × width):     | 50m×17m | | 5.7% |
| 5-seater wing sail     | 7k DWT bulk carrier | Cape Lopez-Point-Tupper | 8.8% |
| (height × width):     | 25m×9m | Angra dos Reis-Rotterdam | 6.1% |
| 3-seater wing sail     | 1 wing sail (height × width): | Cape Lopez-Cape Tapper | 5.6% |
| (height × width):     | 50m×20m | | 4.2% |
| One Dynarig type soft | Aframax tanker | Angra dos Reis-Rotterdam | |
| sail (area):          | Aframax tanker | | |
| (1000m²)              | | | |

5. Conclusion

With the issue of carbon emission reduction increasingly at the forefront of international opinion, changes in the shipping industry are imminent and destined to cause transformation of the entire industry chain, from ship design to maritime operations. WASP technology is an excellent option for shipowners to adapt to the transition. Numerous studies in academia and industry have quantified the technical potential for fuel savings from wind energy and have examined the impact of wind speed and direction, trade patterns, geographic regions, seasonal effects and route optimization. The results consistently show that WASP technology has a large potential to improve the energy efficiency of ships, save energy and reduce emissions. This paper draws the following conclusions through analysis and summary:

(1) Wind energy is a renewable and clean energy source, and there are relatively mature wind energy utilization technologies and markets on land. As an auxiliary technology to improve the energy efficiency of ships, wind navigation technology has a variety of configurations and technical routes,
with significant energy saving effects, and many companies have launched commercial products, which have a broad application market and development space.

(2) It is necessary to be seen that the number of actual ships currently deployed with wind-aided navigation equipment is still very small, and the relevant technology, data and experience need to be further tested in practice; as more ships are fitted with wind-aided navigation devices, the impact of wind-aided navigation technology will gradually become greater, which will drive competition and improvements in different technical configurations, leading to cost reductions and efficiency improvements.

(3) The constraints on wind-aided navigation technologies for ships are multiple and these factors will have a significant impact in terms of the form of wind utilization and its compatibility with ship operations, so that different technologies have different performance characteristics under different practical conditions and a diversity of WASP solutions need to be developed according to practical needs.

(4) Future emphasis should be placed on the techno-economic assessment of wind-aided navigation technologies and the safety assessment of wind energy application equipment. More research should be conducted to establish the risk-reward relationship of wind energy applications and to explore how wind energy technologies can contribute to hedging the capital risk of ship owners and operators. There is currently limited research on the safety assessment of wind energy applications, and in the future a structured safety assessment for each wind energy technology configuration should be considered.

References

[1] Faber, J, Hanayama S, Zhang S, Pereda P, Comer B, Hauerhof E, van der Loeff W.S, Smith T, Zhang Y.& Kosaka H 2020 Reduction of GHG Emissions from Ships—Fourth IMO GHG Study 2020—Final Report J.IMO MEPC, 75, 15.
[2] Seddiek I S, Ammar N R 2021 Harnessing wind energy on merchant ships: case study Flettner rotors onboard bulk carriers J. Environmental Science and Pollution Research 1-13.
[3] International Maritime Organization 2018 UN Body Adopts Climate Change Strategy for Shipping. Available online: https://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx (accessed on 23 August 2021).
[4] Bowen R L 1960 Egypt's earliest sailing ships J. Antiquity 34 117-31.
[5] Nuttall P, Kaitu'u J 2016 The Magnus Effect and the Flettner Rotor: Potential Application for Future Oceanic Shipping J The Journal of Pacific Studies 36 161-82.
[6] Anemoi 2021 Anemoi Rotor Sail technology is inspired by history to produce a solution that works for the future. Available online: https://www.anemoimarine.com/rotor-sail-technology/ (accessed on 23 August 2021).
[7] Norsepower Bringing sailing back to shipping Available online: https://www.norsepower.com/tankers (accessed on 23 August 2021).
[8] Kleiner K 2007 The shipping forecast J. Nature. 449 272-3.
[9] SkySails SkySails Marine wind power for shipping. Available online: https://skysails-marine.com/index.html (accessed on 23 August 2021).
[10] SkySails SkySails propulsion system turn wind into profit. Available online: https://skysails-group.com/pdfassets/SkySailsMarine_Brochure_EN.pdf (accessed on 23 August 2021).
[11] Airseas Airseas to power with wind. Available online: https://www.airseas.com (accessed on 23 August 2021).
[12] OUCHI K 2011 Huge Hard Wing Sails for the Propulsor of Next Generation Sailing Vessel In Proceedings of 2nd International Symposium on Marine Propulsors (SMP'11, Hamburg Germany) 6 pp 387-91.
[13] Zhang R 1993 Potential for energy conservation in coastal sail aids in China J. Ship Engineering 6 4-8.
[14] Li C, Wang H, Sun P 2020 Numerical Investigation of a Two-Element Wingsail for Ship Auxiliary Propulsion J. Journal of Marine Science and Engineering 8 333.
[15] ECONOWIND-UNIT Wind assisted ship propulsion autonomous 40 ft containerized unit with two foldable venti foils. Available online: https://www.conoship.com/portfolio-item/econowind-unit/ (accessed on 23 August 2021).

[16] Eco Marine Power Sail Assisted Shipping with Solar Power. Available online: https://www.ecomarinepower.com/en/aquarius-eco-ship (accessed on 23 August 2021).

[17] Neoline The Neoline Solution. Available online: https://www.neoline.eu/en/the-neoline-solution/ (accessed on 23 August 2021).

[18] Tillig F, Ringsberg J W, Psaraftis H N, & Zis T 2020 Reduced environmental impact of marine transport through speed reduction and wind assisted propulsion J. Transportation Research Part D: Transport and Environment 83 102380.

[19] Smith T W P, Newton P, Win G & Grech La Rosa A 2013 Analysis techniques for evaluating the fuel savings associated with wind assistance J. Low Carbon Shipping Conference (London) pp 10

[20] Comer B, Chen C, Stolz D & Rutherford D 2019 Rotors and bubbles: Route-based assessment of innovative technologies to reduce ship fuel consumption and emissions J. ICCT working paper 11 6

[21] Chou T, Kosmas V, Acciaro M, Acciaro M & Renken K 2021 A Comeback of Wind Power in Shipping: An Economic and Operational Review on the Wind-Assisted Ship Propulsion Technology J. Sustainability 13 1880.

[22] Traut M, Gilbert P, Walsh C, Bows A, Filippone A, Stansby P & Wood R 2014 Propulsive power contribution of a kite and a Flettner rotor on selected shipping routes J. Applied Energy 11 3 362-72.

[23] Nelissen D, Traut M, Koehler J, Mao W, Faber J & Ahdour S 2016 Study on the analysis of market potentials and market barriers for wind propulsion technologies for ships J. CE Delft

[24] Lu R, Ringsberg J W 2020 Ship energy performance study of three wind-assisted ship propulsion technologies including a parametric study of the Flettner rotor technology J. Ships and Offshore Structures 15 249-58.