A REVIEW OF WIND-ASSISTED SHIP PROPULSION FOR SUSTAINABLE COMMERCIAL SHIPPING: LATEST DEVELOPMENTS AND FUTURE STAKES

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SUMMARY

With the current global warming crisis and contemporary concerns for sustainability, the transport industry is developing and implementing novel solutions to reduce greenhouse gases. With close to 90% of the world's goods relying on maritime transportation, responsible for 3% of global energy-related carbon dioxide (CO_2) emissions in 2019, there is a vital emphasis on reducing emissions. The latest legislation from the International Maritime Organisation has imposed even tougher sulphur oxide targets. On the other hand, emission intensity for CO_2 will need to be decreased by 70% in 2050, compared to 2008 figures. While operating measures and fuel alternatives are suitable in the short-term to meet these novel regulatory constraints, as the use of fossil fuels tapers off, the long-terms solution appears to reside in wind-assisted ships. Consequently, this study aims to identify viable solutions that could reduce emissions, focussing on three prominent technologies, namely sails, rotors and kites. Furthermore, this review provides guidance on the benefits and risks associated with each technology and recommends guidelines for performance prediction and associated constraints. Ultimately, future stakes in wind-assisted propulsion are highlighted, including the need for full-scale validation, the challenge in assessing environmental and economic impact, and the structural issues associated with wind-assisted propulsion systems.

NOMENCLATURE

ABS	American Bureau of Shipping
BV	Bureau Veritas
CFD	Computational Fluid Dynamics
Class NK	Nippon Kaiji Kyokai
CO_2	Carbon Dioxide
DNV GL	Det Norske Veritas Germanischer Lloyds
DoFs	Degrees of Freedom
EEDI	Energy Efficiency Design Index
GHGs	Greenhouse Gases
IMO	International Maritime Organization
ISO	International Organization for Standardization
LR	Lloyds Register
NOx	Nitrogen Oxides
NP	Norsepower
PPP	Performance Prediction Program
RANS	Reynolds-Averaged Navier Stokes
SOx	Sulphur Oxides
VPP	Velocity Prediction Program
WASP	Wind-Assisted Ship Propulsion

1. INTRODUCTION

Shipping and maritime transportation account for close to 90% of the world's goods transport [1], and was responsible for 3% of greenhouse gases (GHGs) emissions in 2019, a figure forecasted to grow to 15% by 2050 should no actions be taken [2]. Some forecasts are even most pessimistic [3], as depicted in Figure 1. The introduction of increasingly stringent international regulations related to nitrogen oxides (NOx) and sulphur oxides (SOx), as well as CO_2 [4], coupled energy efficiency design index (EEDI), aim to achieve more eco-friendly vessels.

There are however many limitations to the EEDI, including its applicability to new builds only, meaning the majority of the commercial fleet will not be covered until the 2040s [5]. The targets are also not deemed challenging enough, poorly accounting for the developments in electrical technologies and wind-assisted propulsion, and ultimately having only a small impact [6]. Nevertheless, ambitious regulations to achieve a sustainable shipping industry are a strong driver behind reduced emission vessels.

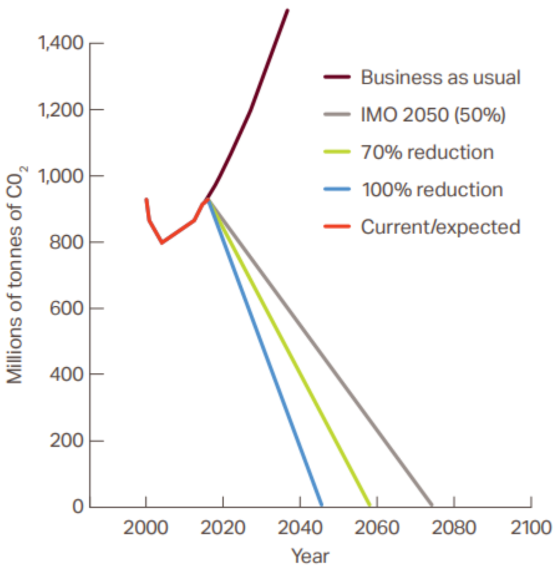


Figure 1: *CO_2 emissions forecast, taken from [3].*

To address the challenge of ship emissions, an array of strategies have been implemented. These can be categorized into operational and technological solutions. Operational measures [7] such as slow steaming (27% fuel saving for 10% speed reduction) and weather routing (2-5% GHGs reduction), while effective, will not be tackled in this paper.

Indeed, the focus is placed on technological advances to provide a long-term sustainable solution [8]. Amongst the various design technologies currently available, wind-assisted ship propulsion (WASP) shows the greatest potential to reduce GHGs, as presented in Table 1.

Table 1: *Effect of design technologies on GHG savings.*

Technology	Potential GHG Savings
WASP	In excess of 30% [7, 9, 10, 11]
Slender Design	Up to 15% [12]
Air Lubrication	Up to 13% [5, 7]
Increased Cargo	Up to 10% [7] (large vessels)
Materials	Up to 10 % [10]
Propeller design	Up to 10% [7]
Bulbous Bow	Up to 7% [6]
Heat Recovery	Up to 6% [14]
Hull Surface	Up to 5% [13]

This paper therefore addresses the current state-of-the-art in wind-assisted propulsion and related performance prediction in order to support the development of sustainable commercial shipping. The remainder of the paper is structured as follows. Section 2 introduces the background and main configurations for wind-assisted shipping. Section 3 tackles the principles and design considerations for sails, rotors and kites respectively. Then, Section 4 addresses the performance prediction. Future stakes are outlines in Section 5, with the key findings of this work summarized in Section 6.

2. WIND-ASSISTED SHIP PROPULSION

Amongst the various wind-assisted options available today, the six rig types originally investigated for wind-assisted ship propulsion in the 1980s [15], and pictured in Figure 2, remain relevant [5]. These are:

- Modern square rig (e.g. DynaRig),
- Rigid/Wing sails,
- Wind turbine,
- Soft sails,
- Rotating cylinders (including Flettner rotors and boundary layer suction devices),
- Kite.

It should be noted that the wind turbine approach is intended to produce electricity to then power the vessel [16], and as such will not fit within the scope of this paper, focused on wind-assisted propulsion options. Moreover, novel theoretical concepts, for instance the *Vindskip* 199 m carriers with an airfoil shaped hull [17], will not be discussed.

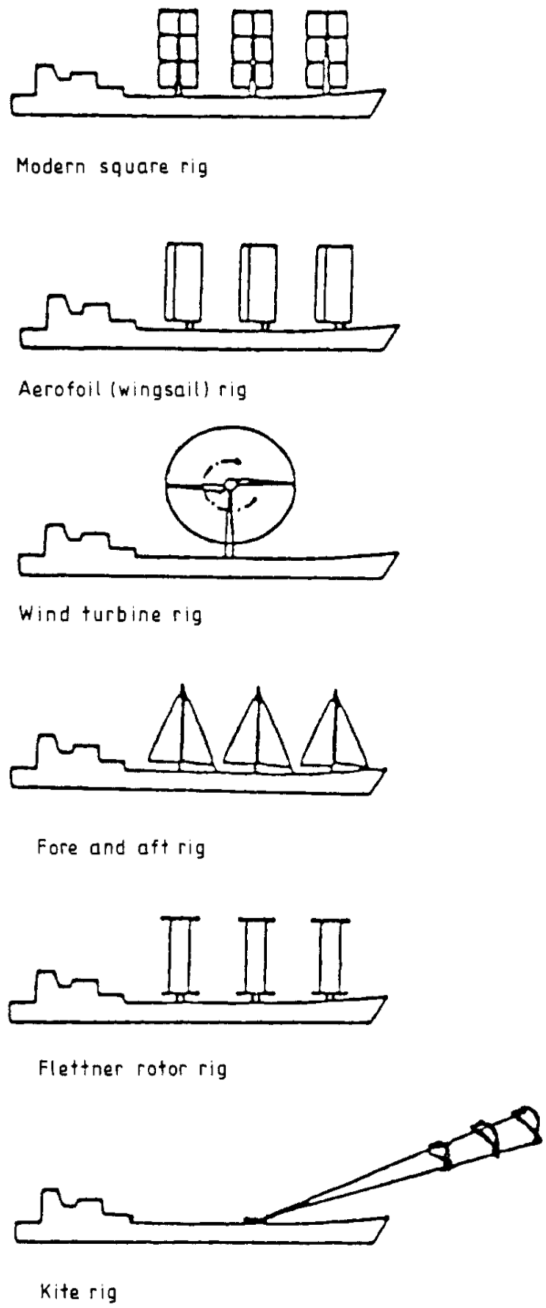


Figure 2: *Main configurations proposed for wind-assisted ships in the 1980s, taken from [15].*

Over the past decade, most configurations have gone from concepts to now being commercially operational, as shown in Figure 3 (based on data edited from [18]). This highlights the ever-growing demand and implementation of wind-assisted commercial vessels. Furthermore, Figure 3 reveals that, for large vessels (greater than 10,000 DWT), sails, rotors and kites are currently the most common configurations. This justifies the particular focus of this paper on these three configurations.

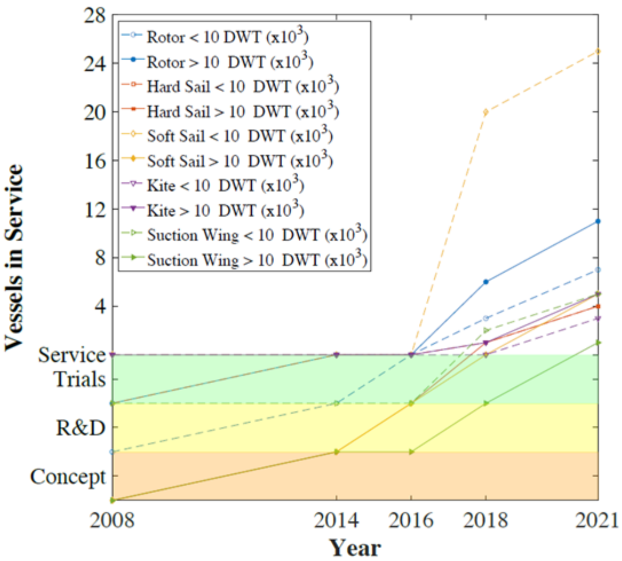


Figure 3: *Development in wind-assisted technologies since 2008.*

3. PRIMARY TECHNOLOGIES

3.1 SAILS

Sailing has historically been central to the development of civilisations and trade, with evidence of sailing vessels dating back as far as the VI[th] millennia BC [19]. It remained the primary mode of maritime propulsion before being phased out with the development of engine, providing greater power and guaranteed speeds. Since then, sailing has become vastly more complex with yachts being developed to compete in races. This has leads to significant research into the design and performance of sails and sailing yachts, which now proves vital to refine the design and optimize the performance of WASP configurations [20].

Here, the term sails encapsulates soft sails, but also rigid wings, whether using airfoil [21] or the increasingly popular circular arcs section [22, 23, 24, 25]. From a fluid dynamics point of view, a significant distinction needs to be made between sails where the flow remains attached, and those experiencing separated flow. Low camber sails at low angles of attack feature largely attached flow. This can easily be modelled using inviscid codes, and has successfully been implemented since the 1960s [26, 27] and employed in the America's Cup [28]. On the other hand, wings experiencing separated flow regions cannot be analysed with such low order methods. Consequently, either experiments or CFD must be employed. For the latter, it was not until the 1990s that the use of Reynolds-averaged Navier-Stokes CFD could be applied to such sails [29].

Rigid sails and wings have been shown to generate greater lift coefficients than soft sails. In all cases, a greater aspect ratio is associated with better performance, but this leads to a raise in the vertical centre of effort, and thus a larger heeling moment. To reduce the negative effect on stability while maintaining a high sail area and therefore power, multi-masted configurations are considered, with some designs having up to nine masts, as depicted in Figure 4.

Figure 4: *University of Tokyo Wind Challenger, taken from [30].*

As multiple masts is an uncommon configuration on racing yachts, new research investigating the interaction between wings have been conducted specifically for wind-assisted ships. This is for instance the case of Bordogna [24] who conducted experiments with two wings (and rotors), and Macklin [21], who investigated the interaction between two foils numerically. However, there remains research questions when looking at higher number of wings interacting with each other, that are yet unanswered in the literature. Furthermore, current research has mostly focussed on wings behind each other, when new concepts such as that of *Neoline* feature two rows of two masts, equipped with two sails each (a main and a jib).

3.2 ROTATING CYLINDERS

Rotating cylinders comprise two main technologies, namely Flettner rotors and boundary layer suction devices (e.g. *Ventifoil*), with the former being of primary focus in the literature and this paper. Flettner rotors were developed in the 1920s as an alternative to sails. It comprises a vertical spinning rotor which employs the Magnus effect to generate thrust [31]. The concept was first demonstrated in 1926 when a vessel fitted with two Flettner rotors, depicted in Figure 5, crossed the Atlantic [32]. On the other hand, the boundary layer suction devices are a relatively recent development compared to the Flettner rotor. The first use of such sysrem to propel a vessel occurred in the 1980s with *Turbosail*. These devices also utilise the Magnus effect to produce thrust, this time through the use of a suction fan.

Rotors benefit from a higher aspect ratio, albeit with the same stability drawback as sails. However, the tip vortex losses can be alleviated with the use of a top plate, or Thom disc [33]. Rotors also benefit from their ability to be adjusted to match the direction of the wind by simply changing the rotational speed. This helps the device utilise the wind in both legs of a trip which is not always possible for some other wind-assisted propulsion methods [34]. Additionally, rotors are available in numerous dimensions and configurations. The training required is also minimal, consisting of mainly monitoring the system. These reasons make rotors ideal for retrofitting on a range of vessels. It may also explain why, at present, rotors are the most common configuration on vessels above 10,000 DWT, as previously shown in Figure 3.

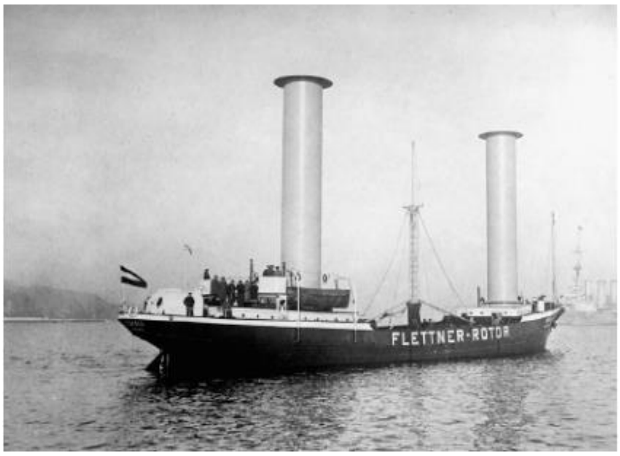


Figure 5: *Original Flettner rotor ship, taken from [35].*

However, Flettner rotors do suffer from added drag, which can result in an increase in engine power and therefore fuel consumption when the rotors are not operable, for instance close to the wind. This has prompted new developments to mitigate this drag penalty, with the apparition of folding rotor. Nevertheless, not all vessels will have the deck space available for this mechanism to be effective. Another disadvantage is the incompatibility rotors have with container ships due to a lack of deck space. These crafts are particularly important as they are responsible for the majority of emissions due their high speeds [36]. Conversely, rotors are compatible most ship type [37]. New containerized rotor units may also prove a useful solution for container ships, although the overall size and thus power would be limited. Lastly, sails tend to have a higher fuel saving potential (of up to 30%) whereas rotors have an average fuel saving of 8% but a maximum potential of around 20% [7].

3.3. KITES

Although kites are believed to have existed since circa 500 BC, record of their use for propulsion only dates back to the 1820s. The concept of kite powered ships did not actually appear attractive at the time, and was only brought back a few decades ago. A distinction is made between static and dynamic flight for kites [38]. A static flight would be a much more passive system, where the kite acts primarily as a drag generating device, and thus only contributing to the ship's propulsion when sailing close to dead-downwind. Conversely, a dynamic flight would operate in an eight-shape pattern, with a very different kite design allowing lift. As such, a wider range of sailing angles can be achieved, and far greater performance attained [39].

Kites offer significant advantages compared to sails and rotors. Firstly, the ease of installation and ability to be fitted, or retrofitted, to virtually all ships, is substantial. They also offers virtually no reduction in deck space. In addition, because of the atmospheric boundary layer, greater wind speeds are present higher above the water. Kites are able to operate further up from sea level, and thus benefit from these higher wind speeds, which is a squared terms in the lift generation equation. Lastly, the heeling arm generated by a kite is extremely small in comparison to sails and rotors, thereby alleviating the significant stability concerns of the other methods.

However, the technology being more recent and thus less established, coupled with the more restricted wind angles it can operate at, are drawbacks of the kites. The impact on power may also be limited, with research showing a single rotor being more effective than a kite [40]; this will be further evidence in Figure 7 in Section 4.2

4. PERFORMANCE PREDICTION

4.1 HISTORICAL DEVELOPMENTS

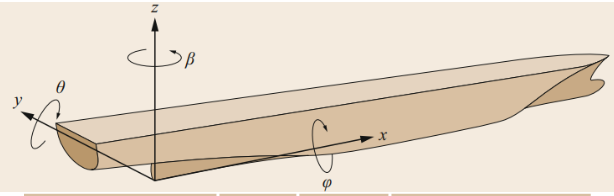
The use of velocity prediction programs (VPPs) is another example of performance racing sailing technology cascading down into wind propulsion [20, 41]. Following the pioneering work of the 1930s on yacht performance [42], significant progress was made in the 1970s [43], with numerous developments since the 1990s [44] leading to today's static VPPs [45], but also dynamic ones, accounting for manoeuvres [46, 47].

More recently, VPPs or performance prediction programs (PPPS) as they are more often referred to for wind-assisted ships, have been used to support the optimisation of sails [48], hulls [49] and hydrofoils [50, 51], as well as maximise the performance of both wind-assisted ships [52, 53] and fully wind-powered ships [54]. Similar performance optimisation strategies are employed; for instance, the established use of depowering in yachts [55] has now been applied to wind powered cargo ships [56], albeit with different constraints for the allowable heel angle, much smaller compared to yachts.

4.2 GUIDELINES FOR WASP PERFORMANCE PREDICTION

The performance prediction fundamentally relies on achieving equilibrium for the degrees of freedom (DoFs) considered, out of the 6 DoFs depicted in Figure 6. PPPs for wind-assisted ships typically consider either:

- 3 DoFs (surge, sway, roll);
- 4 DoFs (surge, sway, roll, yaw);
- 6 DoFs.



Degree of freedom	Name	Symbol	Sign convention
Linear velocity along the *x*-axis	Surge	x	Positive forward
Linear velocity along the *y*-axis	Sway	y	Positive to port
Linear velocity along the *z*-axis	Heave	z	Positive upwards
Angular motion around the *x*-axis	Roll	φ	Positive to starboard
Angular motion around the *y*-axis	Pitch	θ	Positive bow down
Angular motion around the *z*-axis	Yaw	β	Positive to port

Figure 6: *The 6 degrees of freedom, taken from [37].*

A 4 DoFs PPP is most commonly adopted to yield a reliable performance prediction that allows to accurately ascertain the savings and economic impact of the configuration evaluated. Establishing the constrains on the various degrees of freedom however remains a challenge. The most variation is seen in the critical value of the maximum heel angle, with values as low as 2° [39], recommendations for less than 4° [57], the use of 5° [56], 8° [11] and as high as 10° [58]. Guidelines for constraints applied to the performance prediction of wind-assisted ships are therefore suggested in Table 2.

Table 2: *Guidelines for constraints applied to PPPs for wind-assisted ships.*

Degree of Freedom	Recommended Range
Surge	n/a
Sway	± 5°
Heave	Negligible
Roll	± 4°
Pitch	± 0.5°
Yaw	± 20°

In its simplest form, a 3 DoFs empirical PPP for wind-assisted ships can be developed using the resistance prediction theory of Holtrop and Mennen [59] for the hydrodynamic model. Additionally, the theory inherent to the aerodynamic model is readily available for both yachts [51, 60] and wind-assisted ships [11, 39]. The drive force generated can be subtracted from that provided by the engine, thus leading to a lower engine power and therefore fuel consumption and pollutant emissions for a given speed. The balance of the sail side force created by the wind-assisted system, and the underwater side force, will yield the leeway angle. This is the angle of attack the vessel must adopt in order to generate an equal and opposite side force to that of the wind-assisted configuration. Lastly, the side force applied at the location of the centre of effort results in a heeling moment. To achieve equilibrium, the vessel will roll until a heel angle leading to an equal righting moment is provided.

This would be representative of an early design PPP, allowing for a fast an inexpensive design optimisation. At this stage, it is commonly acknowledged that the performance is not a fully accurate value. Yet, it is appropriate for the purpose of comparative performance prediction [61]. At a later stage of the design, a more advanced PPP may be developed [58], often relying on both hydrodynamic tank testing [57] and aerodynamic wind tunnel testing [24], or CFD [21, 62]. This is crucial to the estimation of fuel savings and comparing the various systems available. The meta-analysis of Neilssen et al. [63] yielded the results presented in Figure 7 for a range of vessel types and cargo sizes, fitted with either a rotor, rigid sail or kite.

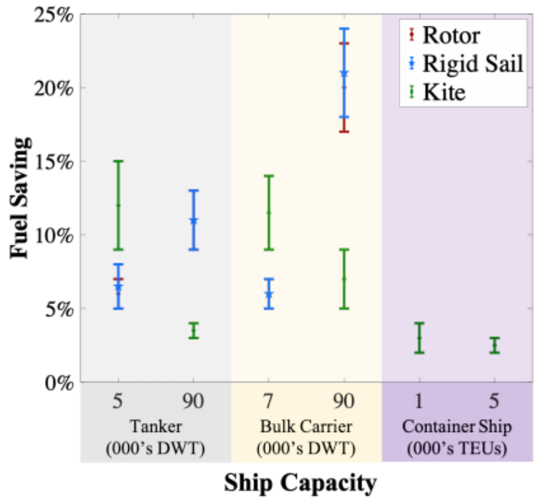


Figure 7: *Potential fuel savings thanks to wind-assisted ship propulsion.*

5. FUTURE STAKES

5.1 PERFORMANCE VALIDATION

The development of aerodynamic coefficients, whether numerically or experimentally remains an area of primary focus. However, the multi-masted configurations, prompted by benefits such as better stability, is driving further work on the interaction between multiples wings and rotors [21, 24, 62], to help support performance prediction.

While such prediction are now well-developed, validation data remain very scarce, not always fully relevant, and ultimately yield a much higher uncertainty compared to that found on yachts [58, 60]. Indeed, as few vessels are currently in service, it will take time for data to be gathered for the array of wind-assisted systems available. Additionally, delays are expected between the acquisition of the data and its availability in the public domain. Because of the industrial interest in the performance prediction, some, if not most of the data, may never be made publically available. It therefore appears critical, and most beneficial from an environmental point of view, to ensure synergies between academia and industry. In the meantime, free-sailing scaled models, such as the *Wallenius Oceanbird*, can provide valuable insights and contribute to the refinement of PPPs [64].

5.2 ENVIRONMENTAL AND ECONOMIC IMPACT

Despite the statistical data on wind strength and direction available as part of the EEDI regulation, weather remains impossible to predict, and as such the benefits of wind-assisted ships remain difficult to precisely ascertain [65]. A comparison of the estimated propulsion savings for a *Maersk Pelican* fitted with a rotor is presented in Figure 8. This shows the output from the PPP of Reche-Villanova et al. [58], the Norsepower (NP) estimation, and sea trial data, highlighting the challenges remaining to predict performance, as well as environmental and economic impact.

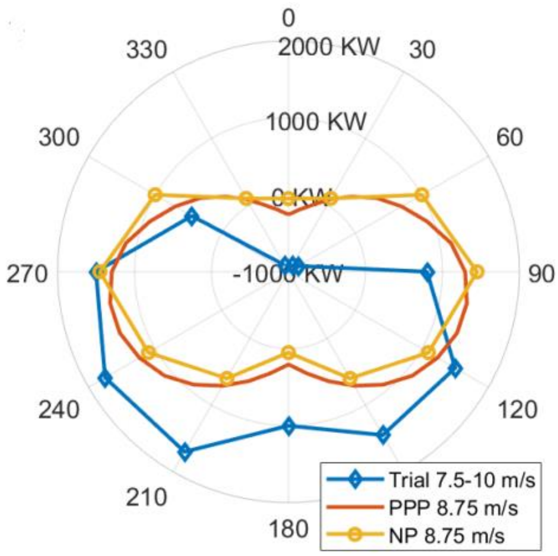


Figure 8: *Comparison between PPP, company (Norsepower) estimate and sea trials, taken from [58].*

With reliable wind data, the power savings estimate can then confidently be converted into reductions in emissions, and the economic impact quantified. This is a vital financial consideration to assess return on investment for wind-assisted ships. Oils prices are also known to have an effect on interest in more sustainable propulsion options, but their volatility is unpredictable. An argument could therefore be made for non-negligible financial incentives to support WASP, making it more financially attractive.

5.3 STRUCTURAL DESIGN AND OPTIMIZATION

The growth of wind-assisted technology has also prompted classification society have developed new rules and regulations intended at wind-assisted ships and their structure. Class NK first released a *Guidelines for Wind-Assisted Propulsion Systems for Ships* in 2019 [66], shortly followed by DNV GL's standard for *Wind-Assisted Propulsion Systems* also in 2019 [67]. In 2020, ABS detailed its requirements for *Wind-Assisted Propulsion System Installation* [68], while the *Rules for Sail Assisted Ships* [69] developed by LR identified basic structural requirements for the masts, posts and supporting structures. More recently, in 2021, BV's *Wind Propulsion Systems* [70] grants additional classification to vessels equipped with wind-assisted propulsion systems, divided between standing parts only (WPS1) and standing and running parts (WPS2). The design combines environmental (wind, sea-state and snow and ice), operating (sailing and out of operation) and system (intact and accidental) conditions. The interface between the ship and rigging is also considered, with a focus on local ship reinforcement as well as global hull girder strength. Indeed, longitudinal strength requirement can be far greater than the conventional wave global loads (peak and trough landing) due to the compressive forces exerted by the rigging. There is, therefore, a need for the vessel-tailored support towers to be fully integrated to the ships structure [71].

With the forecasted growth for wind propulsion, and as greater design experience and sea trial/operation data becomes available, it is expected the scope of the inherent structural regulations will be extended and refined. Moreover, as in many areas, wind-assisted technologies can benefit from the knowledge acquired in sailing yachts structures [72], which features detailed regulations for rig loads and attachments [73, 74], for which the same level of depth remains to be attained on wind-assisted propulsion systems.

6. CONCLUSIONS

Wind-assisted ship propulsion appears as an undeniable part of the future of maritime transportation, offering the greatest long-term potential for emission reduction, as highlighted in this paper. Furthermore, several vessels, utilizing an array of wind-assisted propulsion systems, are already in service, with significant new projects in developments.

The main considerations for sails, rotors and kites have been reviewed. The theory underpinning performance prediction programs was presented, with recommendation on the applicable constraints for all degrees of freedom. The validation of such performance predictions however remains an area of future work, with greater sea trial data available in the public domain being necessary. This constitutes one of the future stakes for wind-assisted ship propulsion, as is the accurate quantification of environmental and economic impact, and the currently under-considered structural implications.

7. ACKNOWLEDGEMENTS

The authors would like to express their thanks to the Institution of Mechanical Engineers (IMechE) for the funding awarded to this research by the Educational Awards Committee.

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