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REDUCTION OF GHG EMISSIONS FROM SHIPS

Wind propulsion technologies as a key enabler

Submitted by RINA and IWSA

SUMMARY

Executive summary:	The maritime wind propulsion industry is evolving rapidly with significant strides made in analysis, testing, verification and demonstrator ship deployment that make use of Wind Propulsion Technologies (WPTs). This document highlights much of that progress and summarizes the key themes and papers delivered during a recent event held at IMO.
Strategic direction, if applicable:	3
Output:	3.2
Action to be taken:	Paragraph 39
Related documents:	MEPC 62/INF.34; MEPC 75/INF.26; MEPC 76/6/2, MEPC 76/6/6, MEPC 76/6/7, MEPC 76/6/8, MEPC 76/6/10, MEPC 76/6/31; MEPC 79/INF.21 and MEPC.1/Circ.896

Introduction

1 The Royal Institution of Naval Architects (RINA) and the International Windship Association (IWSA) recently gathered wind propulsion experts and end users on 16-17 February 2023 at IMO Headquarters in London, representing a significant milestone in the journey to develop a wind-powered fleet fit for the 2030's and beyond.

2 The first day was opened with a keynote speech by the IMO Secretariat referring to both the scale of the challenge of decarbonization facing the shipping industry but also outlining the positive initiatives underway in IMO. The Secretariat also highlighted how the potential for wind propulsion aligns with these IMO and industry goals and will be an important technology segment available to reach the goals to be set at MEPC 80.

3 Mr. Gavin Allwright, Secretary General of IWSA, opened the second day with his keynote speech, focusing on the wind propulsion segments' achievements to date. He highlighted that the current use of alternative fuels and renewable energy sources within

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the shipping industry is still relatively scarce. Growing environmental legislation and concerns are driving the need to develop and apply innovative alternative power and propulsion technology for ships. It was noted that the maritime wind propulsion industry is rapidly evolving and expanding and brings with it a clear opportunity to meet ambitious emissions reduction goals. The market for WPTs may currently be considered to be niche, but there are clear signals of increased confidence and a growing number of stakeholders investing heavily in this technology basket.

4 As noted in document MEPC 75/INF.26 (Comoros) and expanded upon in document MEPC 79/INF.21 (Comoros et al.), there are seven categories of wind propulsion technology (rotor sails, kites, hard or rigid sail, soft sail, suction wing, turbines and hull form). Each of these systems has varied properties and adaptations that can make them suitable for all ship types or selected fleet segments but as a whole, wind propulsion solutions are deployable on virtually all ship types across the fleet.

5 Based on public announcements and shipyard orders made to-date, IWSA estimates that by the end of this year up to 49 large ships will be making use of wind as a renewable energy source, with 105 rigs installed and a combined tonnage of over 3.3 million DWT[1].

6 The conference clearly underscored that while many WPTs have moved beyond the conceptual phase, with an increasing number of WPTs in operation on large ships, the need for continued studies and performance verification in this technology field is imperative and ongoing. Uncertainty in investment has decreased as various projects in the last years have provided additional evidence on safety, installations and on the realized fuel savings.

7 However, there is much work still to be done to bring wind propulsion to its full potential. Variability in wind conditions, the uncertainty about trade routing and sometimes even complicated performance prediction analysis, create a lack understanding of the main dynamic functional principles of WPTs leading to reticence and inertia in the decision-making process.

8 The main themes covered in the conference were:

.1 Wind Propulsion Data Analysis;
.2 Transparent WPT Performance/Power Contribution Standards;
.3 CII/EEXI/EEDI Considerations;
.4 Seizing Synergies;
.5 WPT Innovation & Optimization;
.6 WPTs and Weather Routing;
.7 Wind Propulsion and Underwater Radiated Noise Mitigation; and
.8 WPT and Maneuvering and Seakeeping Performance of Ships.

Wind propulsion data analysis

9 There is clearly a growing body of data on WPT performance. As the number of demonstrator ships and in-service ships using WPTs grows so data collection increases. The number of studies conducted by commercial entities and academia is also increasing. However, openly available/public, quality third party validated material is still difficult to find and thus it is taking longer to build trust in realistic performance predictions.

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[1] Projections based on public announcements and yard orders to date, numbers may adjust upwards with additional retrofits or downwards with yard/logistics/covid restrictions.

10 Another key conclusion among presenters and in the panel discussions is that overly optimistic fuel saving estimates must be avoided and that standard approaches are required. These considerations were explored in the MARIN paper on Wind Performance Prediction Methods and Maneuvering (Netherlands) (Appendix 1.10, Eggers and Kisjes 2023) concluding that misaligned information slows down the uptake of wind propulsion in general.

Transparent WPT performance/power contribution standards

11 The wind propulsion community has, however, not yet agreed on common key performance indicators (KPI). Some technologies are described using aerodynamic coefficients, others by alternative calculations around expected fuel savings etc. Percentage fuel saving figures are commonly used or requested, but it is often unclear what is included in these and how reflective these are as they are affected by other operational concerns. This complicates comparing technologies and creates a challenge for developing a level playing field when it comes to technology selection and can delay investment decisions. Several possible KPIs were considered in the RISE (Sweden) presentation (appendix 1.7, Werner 2023) including a standard vocabulary and power rating expression. These considerations will be informing a future ITTC submission on standard wind propulsion KPI's in 2024.

12 It can be difficult for shipowners to make investment decisions where quantifying expected gains defies easy quantification performance of a WPT retrofitted onto a standard ship design. This is often designated by the 'fuel saving' observed, however this percentage is derived from a standard motor ship operational profile where no adjustment has been made for weather-routing, speed variation etc. which help optimise WPT performance. With these challenges in mind, FINOCEAN (Finland) (appendix 1.8, Fakiolas 2023) highlighted the difficulty with concluding charter parties where savings are difficult to assess with sufficient accuracy.

13 As noted in document MEPC 79/INF.21, many previous assessments of WPT solutions have either:

.1 not taken into account the optimization factors that enhance WPT solutions;

.2 solely focused on retrofit WPT without adequate emphasis on new build design optimization for wind-assisted or primary wind ships;

.3 have underestimated the number of ships that can utilize wind systems (i.e. fleet-wide) such as IMO Third and Fourth GHG Studies;

.4 undervalued the size and scaled potential for energy provision from WPT; and

.5 excluded the improvement in materials and support systems, automation and innovative approaches in dealing with air draft and operational constraints (movable, hinged, retractable, modular etc.).

14 Bureau Veritas Solutions Marine & Offshore (France) (Appendix 1.9, Bataille, 2023) are conducting discipline modelling work as part of the collaborative PERFO project to develop a methodology to estimate the true performance of hull/sail combinations.

15 There were several additional performance evaluation papers with SINTEF Ocean (Norway) outlining the validation of their power prediction program with physical model tests (Appendix 1.14, Eide, 2023) and the Cape Horn Engineering (UK) paper demonstrating the potential for CFD to support the adoption of WPTs (Appendix 1.15, Azcueta, 2023).

16 The key projects and groundbreaking scientific work being currently undertaken and described in detail at the conference, shows a strengthening of the industry's ability to accurately predict WPT performance.

CII/EEXI/EEDI

17 The weight of the WPTs and its effect on the displacement should be taken into consideration when assessing the effective energy saving. This is the view of NAOS Ships and Boat Design srl (Italy) (appendix 1.11, Prever, 2023). For EEDI purposes, the correspondent increase of weight shall be considered as a loss of DWT. The same should apply to the amount of permanently added ballast water that should be loaded to cope with IMO Intact Stability criteria because of the presence of sails.

18 Anemoi Marine Technologies (UK), a rotor sail producing OEM and Lloyd's Register China presented on the key features of a wind-ready retrofit of a Kamsarmax bulk carrier. (Appendix 1.2, Contopoulos & Jiang, 2023) Employing 3 rotors on an IMO global route basis at 11.5 knots they were anticipating 14% fuel savings. The parties will release a paper on the full results of the project in due course. Critically this will include details around the effect of the installation on EEDI and CII.

Seizing synergies

19 Recommendations and proposals for collaboration were made throughout the presentations and panel discussions with the intention of accelerating the growth of the wind propulsion market.

20 There is the opportunity for collaboration with other technologies such as hull air lubrication systems and other systems. Wartsila (Finland) outlined the potential synergies in combining WPTs with gate-rudder technology which is being tested in the EU CHEK project. The gate-rudder technology is driven not by the propellor wash but by the ship speed which is maintained by the WPT installation (appendix 1.4, Bulten, 2023).

21 The focus on propellor and WPT interaction was further explored in the North Windship Technologies (UK) paper detailing an analysis of wind power in conjunction with both engine and Fixed Pitch Propellor (FPP) and Controllable Pitch Propellor (CPP) configurations along with two operational modes, constant speed and constant RPMs (appendix 1.5, Reche-Vilanova 2023).

22 Material science and WPTs was the focus of the Hexcel (UK) paper on high performance composites for WPTs being delivered at low cost. The commercial shipping WPT industry has a head start in this area thanks to the learnings and cost reductions extracted by the highly cost-driven wind energy sector (appendix 1.18, James, 2023).

23 Norsepower, a rotor sail producing OEM (Finland) emphasized that the benefits, features and performance predictions of various available technologies should be marketed with realistic expectations and claims for performance and preferably backed by third-party verified measurement results. This is essential for building trust in the marketplace and the alignment of regulation and measured policy initiatives are important elements in the dissemination of WPTs (appendix 1.3, Kuuskoski 2023).

24 Examples of topics discussed during the conference where collaboration and guidelines are needed:

.1 technology provider collaboration to open the market for wind propulsion;
.2 collaboration for developing ship design practices and classification rules;
.3 realistic performance predictions and measurements;
.4 performance prediction methods and tools;
.5 safety related matters; and
.6 highlighting the market potential in communication.

25 Shipowners and charterers have started to share the benefits and costs of wind propulsion installations. This includes the need for charter party agreements developed to cater for common interests which will in turn support financing possibilities.

26 Synergies in energy systems are also an intriguing area of development, and the 'Wind Hunter' presentation from MOL and Ouchi Ocean Consultant Inc. (Japan) gave an overview of the zero-emission ship design that utilizes multiple installations of the 'Wind Challenger' rig on a wind powered tanker that in turn generates hydrogen using excess wind energy and stores that in toluene/MCH in its storage tanks (appendix 1.1, Ouchi, 2023).

WPT innovation & optimization

27 Throughout the conference wind ship and WPT references and case studies were presented to support papers and presentations. These examples of technology installations and ship designs were all highly relevant and many of those are among the 24 large wind installed ships already in operation.

28 This wide spectrum of cases was added to during the conference by three additional papers focused on innovation and optimization. Chantiers de l'Atlantique (France) outlined the findings from their prototype testing on their 'Solid Sail' system and the slated integration of these rigs into zero-emission cruise ship designs (appendix 1.12, Abiven 2023).

29 Knud. E. Hansen Australia brought a novel 'proa' style design with a main hull and outrigger for a 50,000 dwt bulker that is powered with wind and solar propulsion systems (Appendix 1.13, Goh 2023).

30 From an optimization perspective, bound4blue (Spain) delivered a paper on the aerodynamic optimization of their high lift 'eSail' system through a combination of CFD modelling and wind tunnel testing (appendix 1.16, Pascual, 2023).

WPTs and weather routing

31 There were numerous references made to weather/wind routing reflecting its importance in further strengthening the delivered performance of WPT installations and primary wind-powered ships as they benefit greatly from route and speed optimization where they have the freedom to utilize these, far more so than do fully motorized ships.

32 D-ICE Engineering (France) spoke specifically to the benefits of optimizing both speed and route in wind assisted and primary wind ships noting that weather routing can enhance the expected fuel savings from a WPT installation by a factor of two (appendix 1.6, Dupuy, 2023).

Wind propulsion and underwater radiated noise mitigation

33 Underwater Radiated Noises (URN) from ships have significant negative impacts on marine life. It is well established that URN emitted by ships mainly comes from propeller cavitation and to a lesser extent machinery equipment.

34 XP Sea (France) and Semantic TS highlighted that as the world fleet, composed in majority by bulkers, tankers, and container ships, tripled over the last six decades, oceans are getting noisier with an average increase of 20 dB during the same period.

35 While a clear reduction of URN can be achieved through specific design of propeller, propulsion engine and hull design these are costly measures. Ship speed decrease is also a way to reduce cavitation as propulsion power and rpm are reduced but speeds may be too low for commercial operation, whereas wind propulsion is the most silent means to propel a ship. Its contribution to ship propulsion is an opportunity to reduce URN to acceptable levels for marine life, as demonstrated by this study, the first of its kind to be published (appendix 1.19, Cordier, 2023).

WPT and manoeuvring and seakeeping performance of a ship.

36 Attention must be paid to the additional transversal forces and yaw moments connected to a WPT, as it can affect the manoeuvring and seakeeping performance of a ship.

37 Time-domain simulations can be utilised to assess the manoeuvrability of a wind powered ship to support the decision making, from the early design stage, all the way to testing the control systems, design of the Human-Machine Interface (HMI) and developing crew guidelines and training.

38 RISE (Sweden) provided an example of a process where ship design and evaluation were performed in stages where time domain manoeuvring simulations are included together with Velocity Prediction Program (VPP) and Computational Fluid Dynamics (CFD) as other important components (appendix 1.17, Lundback, 2023).

Action requested of the Committee

39 The Committee is invited to note the information provided in this document and its annex and that further technical documents will be submitted at subsequent MEPC meetings.

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ANNEX

RINA/IWSA Wind Propulsion Conference 16-17 Feb. 2023

Appendix 1: Conference Paper Summaries.

1.01 "Wind Hunter" The Zero Emission Cargo Ship Powered by Wind and Hydrogen Energy

Kazuyuki Ouchi[1]*, Kentaro Shima[2] and Keisuke Kimura[2]

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In the year of 2018, IMO (International Maritime Organization) decided that the CO2 emission from merchant ships for the international voyage should decrease by 50% within the year of 2050, furthermore, should achieve Zero CO2 emission from every merchant ship within the early years in the second half of 21st century. In this paper, an idea of perfect Zero CO2 emission ship by capturing and using the ocean wind energy is introduced.

When a sailing ship which has large rigid wing sails, for example Wind Challenger Sail, navigates in a sufficiently windy sea area, the thrusts from sails are strong enough so that they are utilized to not only drive the ship at the proper speed but also rotate a large underwater turbine at significant speed and torque. The turbine generates electricity which is used for the water electrolysis to generate hydrogen onboard. The hydrogen is attached to toluene with chemical reaction and changed in the form of methyl-cyclo-hexane (MCH), which is in liquid form under ambient temperature and pressure. The MCH is stored in the ship's storage tank as a liquid organic hydrogen carrier (LOHC). In the case of weak winds when the sails cannot generate sufficient thrust, the MCH is led to the dehydrogenation device. Using the hydrogen generated by the device, the fuel cell works and supplies electricity to the electric motor propeller for the ship's propulsion and general service onboard. Thus, the ship can navigate at a constant speed regardless of wind speed and direction. Fig.1 shows main components and energy flow of the ship "Wind Hunter".

This sailing ship features large telescopic wing sails, motor/generator commonly used as turbine generator and electric motor propeller, water electrolysis device, hydrogenation device, dehydrogenation device, fuel cell, and storage tanks for the toluene and MCH. The concept of this ship is one of the best candidates for a Zero CO_2 emission ship, because the system is operated by only wind energy and does not require fossil fuels such as oil and gas.

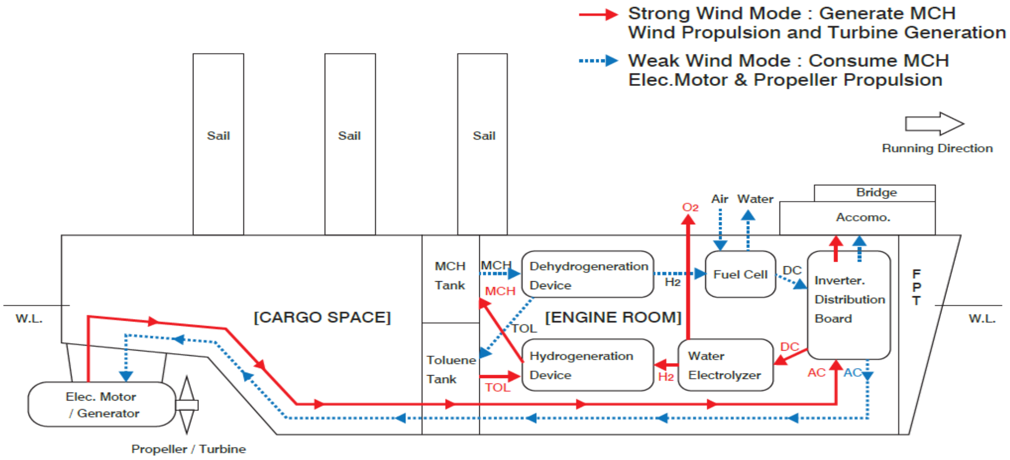

Fig.1 Main Components and Energy Flow of Wind Hunter

1.2 Key Features of *'Wind Ready'* Retrofit of a Kamsarmax Bulk Carrier

Nick Contopoulos and Baiqian Jiang, Anemoi Marine Technologies (AMT), UK and Lloyd's Register Classification Society (China) Co. Ltd

Rotor Sails generate lift, and thrust, for fuel saving in operation by rotation of a vertical cylinder by electric motor. A retrofit to install three Rotor Sails with rail deployment to a Kamsarmax bulk carrier is being executed in two phases:

- **1st Phase retrofit to a *'Wind Ready'* state**: completed in November 2022
- **2nd Phase for Rotor Sail installation**: expected to be completed by Q3,2023

Figure 1: Illustration of Rotor Sails to be installed on Bulk Carrier in 3Q2023 *(Image courtesy of AMT)*

1st Phase Retrofit Lessons for Future Rotor Sail Installation Cases

From practical experience with 1st Phase retrofit the following aspects were described in our RINA Conference paper and deserve special attention for efficient execution of Rotor Sail installations

Definition of Scope of Design and Engineering Scope of Work

Early detailed definition of scope of design and engineering was made on two key retrofit aspects:

- Rotor Sail integration
- Ship regulatory compliance

Significant project scoping effort was made immediately before and, within a short time, after the May 2021 retrofit contract for Rotor Sail retrofit. Original project execution document was developed to define an expected scope of re-examination of ship regulatory compliance aspects.

In addition, ship regulatory compliance scope of work was validated with Flag State and, at same time, expected process for issue of a certificate of exemption on behalf of flag was discussed in expectation that full regulatory compliance for some aspects of Safety of Navigation may not be achievable after installation of Rotor Sails.

Detailed Preparatory Inspection of the Ship and Systems for Rotor Sail Retrofit

Two aspects were especially important for smooth execution of retrofit works at ship repair yard:

- Detailed preparatory inspection of the ship in advance of retrofit including dimension survey of existing structures as well as a 3D scan to identify conflicts of installed Rotor system with existing outfitting.
- Assessment of compatibility of rotor sail control and vessel performance monitoring systems to avoid duplication of data acquisition.

Regulation of Carbon Intensity and Improvement of Energy Efficiency

It may be possible to anticipate an optimal timing of wind assistance retrofits in an energy efficiency improvement plan (*as part of SEEMP III*). In Figure 2 the required Carbon Intensity Indicator *(CII)* for an example Bulk Carrier is shown. It is assumed that CII reduction factors will be applied from 2026 in order to meet IMO 40% carbon intensity reduction target in 2030. Colour shading, and key, shows rating bands for attained carbon intensity.

An idealized illustration of impact of a Rotor Sail retrofit is shown with grey font arrow indicating a reduction in attained carbon intensity on retrofit.

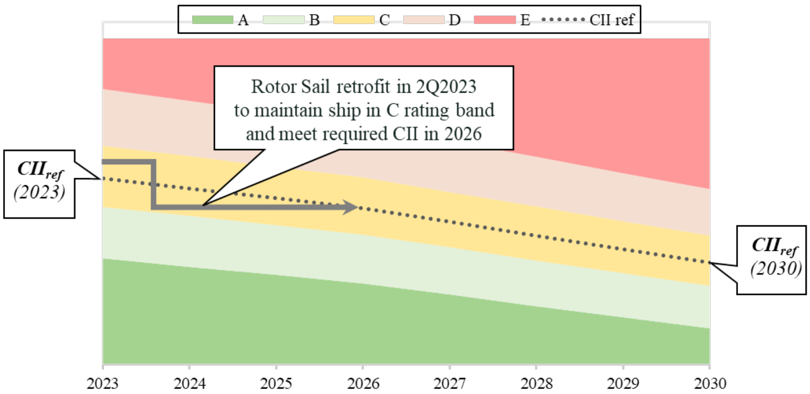

Figure 2: Idealized illustration of Rotor Sail retrofit to maintain ship rating and to meet required CII in 2026

Wind readiness may also be appropriate to consider in order to prepare the ship for later installation of Rotor Sails. In such a case a '*Wind Ready*' retrofit can also be planned based on ship dry-docking schedules and timed so as to ensure that future retrofit of Rotor Sails meets required timing of energy efficiency improvement for ship rating on measurement of attained carbon intensity.

Benefits of Adopting a Two-Phase Retrofit with 1st Phase 'Wind Ready' Retrofit

By adopting two-phase retrofit beneficial possibilities arise including, for example,

- Timing of retrofit phasing to align with scheduled dry-docking as well as Rotor Sail availability for installation.
- Phasing may allow for contracts with similarly phased investment decisions, for example, where a Rotor Sail installation may be phased to align with energy efficiency improvements for regulatory compliance.
- Re-deployment of a Rotor Sail between ships is also a possibility in a scenario where an aged Rotor equipped ship is being sold or scrapped and equipped with residual operational Rotor Sail life.

In Closing

Each Rotor Sail installation will have its own unique, or unusual, characteristics and these differences include for example ship type, ship design, ship configuration, operating profile, and trade. This notwithstanding a possibly obvious, but nevertheless worth stating, remark may be appropriate for closing that prior preparation when considering the wind readiness of a ship is a pre-requisite for a smooth execution of a Rotor Sail installation.

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1.03 Building Trust in Thrust

J. Kuuskoski and **V. Paakkari**, Norsepower Oy Ltd, Finland

This paper discussed the status of the emerging wind propulsion market and describes Norsepower's experiences of entering the shipping market with a modernized Flettner rotor, the Norsepower Rotor Sail^{TM}. Recommendations and proposals for collaboration are made to accelerate the growth of the wind propulsion market. The benefits, features and performance predictions of various available technologies should be marketed with realistic expectations and claims for performance and preferably backed by third-party verified measurement results.

1. Suggested Guidelines for Technology Providers

Examples of topics where collaboration and guidelines are needed:

- Technology provider collaboration to open the market for wind propulsion.
- Collaboration for developing ship design practices and classification rules.
- Realistic performance predictions and measurements.
- Performance prediction methods and tools.
- Safety related matters.
- Highlighting the market potential in communication.

The existing rules and regulations for ship design and operation are in development to accommodate features specific for various wind propulsion technologies. Such work has been ongoing already for several years and will continue as more data is collected from operating installations. There is a strong regulatory push to improve energy efficiency and reduce the emissions of shipping. A well-designed wind propulsion installation saves fuel, reduces emissions and is an economically profitable investment. Sails are very likely enablers for alternative fuels which compete with traditional fossil fuels. Active collaboration of technology providers to promote development of safe and efficient regulations, rules and operational practices is a benefit for the growing wind propulsion market and a great benefit for our planet.

2. Collaboration for Developing Ship Design Practices and Classification Rules

A working group focused on developing approved solutions for complying with regulations and developing standards would facilitate the application of wind propulsion on ships. Current requirement for exemption applications consume time from many parties and present a repeating process dealing with almost identical issues. Such a working group could include flag states, classification societies and wind propulsion suppliers.

3. Realistic Performance Predictions and Measurements

The overall fuel saving potential of wind propulsion is vast and can be further increased by integration with the power plant and propulsion control systems as well as technologies such as route planning and voyage optimization. When discussing the fuel savings and emission reduction potential of wind propulsion, there are couple of important aspects that should be addressed.

The first one is the use of transparent performance indicators. Recent developments such as the workshops organized by SSPA on common Key Performance Indicators, WiSP & WiSP2 joint development projects, revised EEDI/EEXI calculation guidelines are steps to right direction. However, it must be stressed, that in the end, the wind propulsion providers are responsible for indicating the performance of their systems in a transparent and reliable way.

Second, trust is created by realistic performance predictions. Over optimistic fuel saving estimates must be avoided. Misleading information slows down the uptake of wind propulsion in general. Wind propulsion has enough potential even without exaggeration.

4. Safety Related Matters

Safety is the highest priority in shipping. Ship owners, captains and crews as well as ship designers and shipyards must be convinced of the safety of the wind propulsion systems they work with. Also, other parties, such as pilots, port and terminal authorities, flag states which might not be working with sails on a daily basis must be confident of safety aspects. Wind propulsion suppliers are responsible for designing their products and operational instructions to comply with high safety standards.

Active involvement of technology providers together with operators and regulatory authorities is a crucial component in ensuring safe operations of wind assisted ships. Norsepower is committed to ensuring the safety of our product and improving the safety of the wind propulsion industry.

Training and operational support for superintendents, ship officers and crews will become increasingly important as more wind propulsion installations are installed on ships. Crew rotation and new employees need training to familiarize themselves with the relatively new technology of wind propulsion. Introducing modern sail technology in the training programs for seagoing personnel will also be necessary. Wind propulsion suppliers have a supporting role to provide and assist with training programs by providing material and opportunities for visiting training sites.

5. Conclusions

Wind propulsion suppliers have the main responsibility to communicate the features, benefits, technical and economical aspects relevant for customers and other stakeholders in the value chain. Ship owners and charterers have new issues to discuss when contracts including wind propulsion systems are negotiated. How to agree the potential sharing of investments, operating costs and benefits. There are already charter contracts in place where the financial impact of wind propulsion installation is considered. It will take time before such terms become more common and widely accepted for use in charter contracts. However, the recognition of all parties in the shipping industry of how wind propulsion benefits their business, and the planet, is the key to successfully installing thousands of wind propulsion applications on ships.

Norsepower urges the shipping industry stakeholders to embrace new technology and applications with an open and collaborative mind set.

1.04 Synergies of wind-propulsion and Gate-Rudder™ technology

Norbert Bulten, Wärtsilä, The Netherlands

To reduce vessel GHG-emissions, new developments are observed based on both hydrodynamics and aerodynamics. Implementation of wind-propulsion is getting full attention, where the energy of the free available wind is harvested to propel the vessel. On hydrodynamic side a novel Gate-Rudder concept is introduced (as shown in the picture below), which works as an energy saving device. In addition, the Gate-Rudder improves the vessel course-keeping capability.
In general wind-propulsion comes with a certain amount of side-force, which increases the demands on the vessel rudder-system. Conventional rudder concepts flourish when the propeller loading increases and the velocity downstream of the propeller increases. The successful application of wind-propulsion will reduce the propeller loading and therefore the effectiveness of the conventional rudder will diminish.

The Gate-Rudder working principle is based on the actual vessel speed to a much larger extend and therefore the course-keeping capability remains at constant level, independent of the propeller loading. Detailed Computational Fluid Dynamics (CFD) simulations have provided the underlying data to confirm this phenomenon. Due to better course-keeping capability, the vessel leeway will be smaller compared to conventional rudder systems and therefore the utilisation of the wind-propulsion will become more effective.

Another aspect which needs to be considered in a holistic design concept based on wind-propulsion is the actual layout of the propeller and drive-line. The common layout is a Fixed Pitch Propeller driven by a 2-stroke Diesel-Engine. Due to significant reduction of the propeller loading, the actual operating point shifts far away from the initial design point, resulting in non-optimal hydrodynamic efficiency and engine fuel-consumption. To have a larger versatility, a Controllable-Pitch Propeller can be installed to keep good hydrodynamic efficiency at favourable engine fuel-consumption operating points.

Further hydrodynamic optimization can be found when the design RPM of the (large) propeller is reduced. In case of 2-stroke engines this design RPM is dictated by the engine design however. When considering 4-stroke engines with gearbox, the selection of optimal propeller RPM is a matter of designing the right gearbox-ratio to couple the engine RPM with the optimal propeller RPM. When considering a gearbox in the drive-line configuration, various concepts come into sight, like twin-in-single-out gearbox concepts and hybrid solutions with Power-Take-In/Power-Take-Out (PTI/PTO). With two main engines, there is more flexibility to run on the optimal number of cylinders (small engine only, large engine only, both engines), which is typical for bulkers and tankers, when sailing either loaded or in ballast. With Power-Take-In available electric energy, for example from solar power, can be utilised. In addition, battery stored power can be used for peak-shaving.

Given the variation in weather and thus in the contribution of wind-propulsion, a flexible propulsion concept needs to be considered to get the maximum reduction of GHG and fuel-consumption.

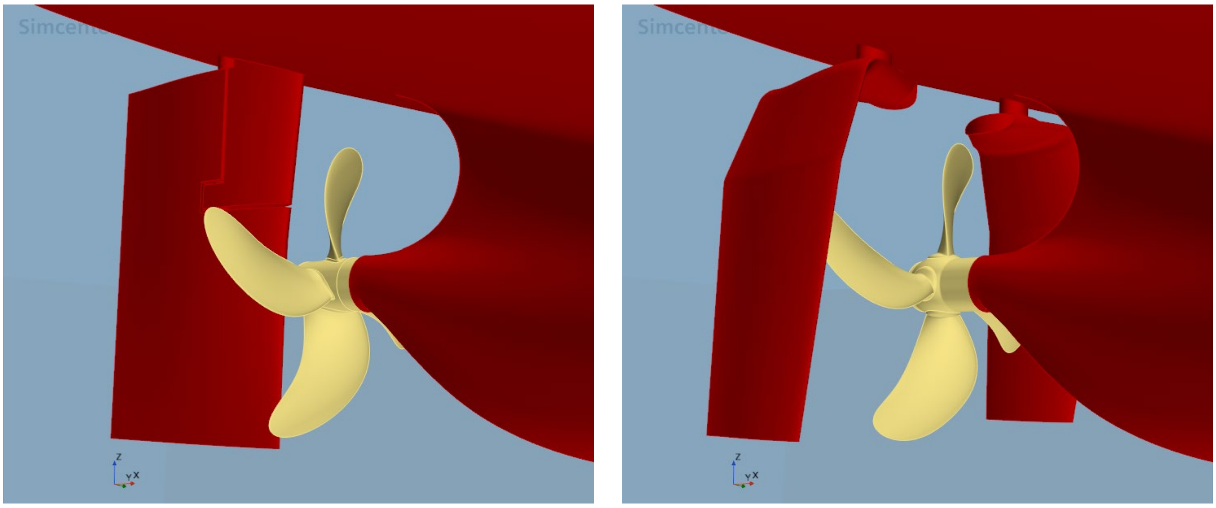

Figure 1: comparison of conventional rudder and Gate-Rudder™ technology

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1.05 Preliminary Study on the Propeller and Engine Performance Variation of Commercial Ships with Wind Propulsion Systems

Martina Reche-Vilanova, North Windship Technologies (UK)

Most Wind Propulsion Systems (WPS) will operate in a hybrid mode alongside actual main propulsion units. This interaction significantly affects the propeller and engine operating conditions and thus, their performance. As seen in our study, wind propulsion systems unload the propeller and engine, leading to a beneficial increase in propeller efficiency and a detrimental rise in the main engine specific fuel oil consumption (SFOC). However, propeller gains outweigh engine losses, resulting in extra savings. Thus, not only does WPS save fuel and pollutant emissions by reducing the required engine power but using the entire propulsive system more efficiently.

1.06 About the Benefit of Optimizing Both Speed and Route in Wind-Assisted Ships Multi-Objective Weather Routing

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Context

Optimizing ship navigation with regards to meteorological and oceanographic forecasts is a crucial issue for the marine industry. Different approaches have been proposed, but a few are general enough to solve all applications and therefore compute route optimization for sailing, motor, and hybrid-propelled ships. This is a topic of interest as wind propulsion is being pushed on the shipping industry by the IMO regulations, to reduce its carbon footprint.

Various algorithms are available in the state-of-the-art and an important characteristic is the number of control variables considered for the optimization. In this study, we compare and analyse different optimization strategies, amounts of wind assistance, and service speeds. We quantify the added value in terms of fuel savings of the simultaneous optimization of route and speed and how it is enhanced by wind propulsion.

Study

We considered 4 scenarios of optimization depending on whether the route and/or the speed is optimized:

- GCR - CS : Great Circle Route and Constant Speed
- GCR - OS : Great Circle Route and Optimized Speed
- OR - CS : Optimized Route and Constant Speed
- OR - OS : Optimized Route and Optimized Speed

For every scenario, we computed a set of departure dates from 01.01.2016 to 01.01.2020, with a weekly frequency. To evaluate the sensibility to wind propulsion, we considered three generic Ro-Ro vessels: with mechanical propulsion only, with the addition of 4 suction wings, and with 6 suction wings (based on Malavard's model). We considered three voyage durations to evaluate the impact of service speed.

The chosen route was a transatlantic, from Europe to Caribbean, and we used wind and waves from the reanalysis dataset ERA5 of the European Center for Medium-Range Weather Forecast.

Main Results

In Figure 1 we present the benefits in terms of consumption of each optimization scenario (compared to the GCR-CS one), depending on ship kind and service speed.

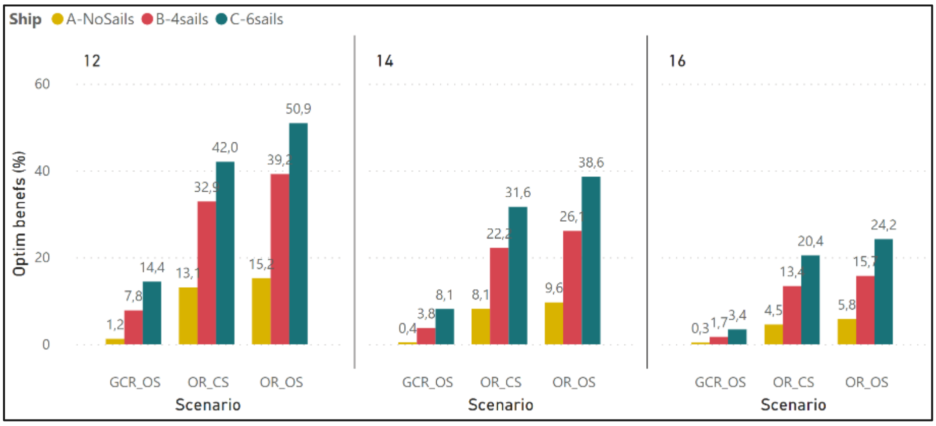


Figure 1: Optimization benefits for each scenario compared to GCR-CS, depending on ship and service speed.

The main result that has been highlighted is that the more we have wind assistance, the more we have an added value at considering two control variables in the optimization. This is an important result because a lot of methods only consider one control variable. While the shortfall of considering one control variable is not that important for motor ships, it is for wind-assisted ships.

For a motor ship at a 14kt of service speed, the relative savings associated with speed, route, and combined speed and route optimization are respectively 0.4%, 8.1% and 9.6%. For the 4-sails hybrid ship, these benefits are respectively 3.8%, 22.2% and 26.1%, and for the 6-sails hybrid ship, 8.1%, 31.6% and 38.6%.

Another interesting result was the understanding of algorithm behavior related to the control variable considered in the optimization. First, the savings associated with speed optimization are due to ship speed monitoring: acceleration in good weather conditions and deceleration in bad weather conditions. Besides, we saw that the definition of such good and bad weather conditions evolves with the amount of wind assistance. Then, we showed that the important savings achieved with route optimization are due to the capacity of the algorithm to find routes that face favorable weather conditions. Finally, optimizing both route and speed leads to added savings compared to previous steps of optimization thanks to the combination of both strategies, and slightly improved apparent wind conditions.

Moreover, as statistical weather routing is used for wind-assisted ships performance evaluation, this study shows how much we must use optimization strategies with two control variables in such cases. The added value in terms of percentages may be decisive for the viability of the projects.

1.07 Technical Key Performance Indicators for Wind-Powered Ships

S Werner, RISE Maritime, Sweden

The maritime wind propulsion industry is evolving rapidly, and many new wind propulsion technologies (WPTs) emerge on the market. The different technologies have their specific strengths and weaknesses, which need to be assessed and quantified when selecting a WPT for a particular application. The wind propulsion community has, however, not yet agreed on common key performance indicators (KPI). Some technologies are described using aerodynamic coefficients, others by e.g. expected fuel savings. Percentage saving figures are commonly used, but it is often unclear what is included in the comparison. This complicates comparing technologies, puts the level playing field at risk, and delays investment decisions.

Before this background the Interreg North Sea region project WASP, the International Wind Ship Association (IWSA), and the International Towing Tank Conference (ITTC) have joined forces to develop and propose KPIs for wind-assisted ships. As part of this effort, several focus group meetings were held during the autumn of 2022. These online workshops were open to all stakeholders from the wind propulsion community and aimed at sharing ideas and discussing implications of various KPI alternatives. Figure 1 summarises and groups the participants.

In the full paper (Werner, 2023) we present several possible KPIs. Their advantages and drawbacks are discussed based on the industry workshops, written communication with industry representatives as well as with the authors own experience of wind propulsion applications for commercial ships.

ITTC will publish new Guidelines regarding power prediction for wind assisted ships in 2024. The present work has been conducted in close co-operation with *30th ITTC Specialist Committee for Wind Assisted and Wind Powered Ships*, and the outcome will influence new industry standard ITTC Guidelines.

Recommended KPIs for Performance expectation and business case input

A Power Saving Potential (PSP) is derived by comparing the power requirement for a ship with WPT against the same ship without WPT on the same route and same speed. This can be done with a matrix multiplication of a weather matrix or by voyage simulations, in both cases using hind-cast weather covering all year around weather conditions. The power prediction should include the power consumption by the WPT if active, the drag from idling device if non-tiltable, and the operability range. The PSP is the ideal performance, assuming 100% operability within the operation range. The real saving may be lower due real-life practicalities such as repairs, logistics etc. It can also be higher, of smart routing and energy management is used onboard.

The PSP can be derived using methods and input of different confidence levels. Table 5 presents a system of KPIs for different confidence levels. An overview description of the corresponding power modelling methods are presented in Table 6. The details should be given in for example the coming ITTC's Guidelines.

Table 1. Recommended KPIs for Performance expectation and business case input

KPI	Unit	Usage	Power modelling*)	Weather modelling
Rated WPU power	kW	General comparing, scanning the market	Stand-alone WPU power	EEDI
PSP-I	kW	Early idea	Level I	EEDI or the ship's intended route
PSP-II	kW	Early business case assessment	Level II	The ship's intended route
PSP-III	kW	Business case & Performance expectation	Level III	The ship's intended route
ESP-IV	kW	Advanced Business case & Performance expectation	Level IV	The ship's intended route (incl. possible weather routeing, speed optimisation)

*) See details in Werner (2023).

References: Werner, S., Key Performance Indicators for Wind-Powered Ships, in the proceedings of RINA Wind Propulsion Conference 2023

1.08 Empirical Methods for Developing WASP Performance Indicators and Heuristics-Based Decision Making Under Uncertainty

K M Fakiolas, Naval Architect & Marine Engineer, CEO Finocean Ltd, Finland

Wind-assisted ship propulsion is recently perceived positively by Ship Operators as one of a potentially promising energy saving and emission reduction investment choice, however the variability in wind conditions, the uncertainty about trade routing and sometimes even complicated performance prediction analysis, create a lack understanding of the main dynamic functional principles of WASP leading to reluctance in decision making.

Ship Operators need to have independent indicators of empirical nature to use at hand for achieving a fast technical and business evaluation on the 'ship-systems-trade' WASP applicability so that a common understanding is established on expectations about performance and target settings. Scientific methods are heuristic in nature, with heuristics defining primarily simplifying, incomplete, underdetermined, and fallible problem-solving rules that can nevertheless serve certain goals in certain contexts better than truth-preserving algorithms. In other words, Heuristic is a simple procedure that helps find adequate, though often imperfect, answers to difficult questions,

This paper provides below first set of heuristic, empirical performance indicators can be identified to the service of decision makers sourcing from the fundamental working principles of wind-assisted ship propulsion, related to the ship type, WASP system type, the wind conditions and routing, those being:

- *The most available ocean winds at a given route, present a Weibull probability distribution mostly concentrated around an average intensity range (BF2-BF6, i.e.,6-20 knots), statistically potential to blow almost equally from any direction, with 1-2% higher propensity as head or tail winds***.**
- *The most Useable wind intensities for the cargo shipping fleet exist within BF 4-6, occurring abt 53% of the time.*
- *For 70-80% of the sailing time, the useable winds will be coming from 0° - 90°, with close-haul to headwinds (0° - 45°) occurring by abt 50-60% of the time in major long-haul cargo ship trade voyages.*
- *The most important functional properties of a wind propulsion system are: 1) the* C_L/C_D *ratio achieved in close haul/beamy wind ranges, and 2) the accuracy with which a wind sensing system can provide every time the optimal* C_L/C_D *setting.*
- *Any given WASP system is expected to operate within a passive capacity factor range of up to 10% on basis of global trade routes wind statistics and for typical cargo ship speeds of 11-16 knots. Systematic route optimization, integrated power management, improved WASP and ship designs, wind-harvest purposed operational measures and improved accuracy of wind measurements can provide for better values, even up to or exceeding 20%.*
- *A conservative, empirical average anticipated wind-assist propulsion power contribution during global trade routes can be calculated by the simplified generic formula* ***P≈0.03NbAVs****, with values selected appropriately as per mechanical sail type.*

The analysis done above also indicate that it is meaningful for wind propulsion system developers and engineers to focus on optimizing their aerodynamic device to be able to demonstrate superior performance within the narrow 0° - 45° close-haul window, by striving to elevate as high as possible the C_L and reduce as much as possible the C_D, and for the Operators to find means to increase wind energy harvesting in this particular operational window.
It is also demonstrated that every different wind propulsion system type needs different operational optimization techniques, so apples-to-apples comparison is meaningless to be done on stand-alone wind propulsion unit performance comparison basis, but on full ship profile-trade basis.

1.09 PERFO: Methodology benchmark for Wind Assisted Propulsion Ship Performance Estimation

J Bataille, C Blayo and P Sergent Bureau Veritas Solutions Marine & Offshore, France

Recently, the maritime sector has seen a significant development of Wind-Assisted Ship Propulsion (WASP) to act towards reducing the global emissions induced by goods transportation at sea. The installation of a WASP onboard a vessel decreases the required propeller thrust but introduces significant side forces, modifying the attitude of the vessel and adding drift-induced resistance. Hence, it is unsuitable to account for the gains as a simple reduction of effective power. To overcome this difficulty, Power Prediction Programs (PPP) account for the hull's hydrodynamic response to the transverse force generated by the WASP and estimate the couple of drift and rudder angles.

The PERFO project develops a methodology to assess the wind-assisted vessel's performance on its operating route. It is based on two existing PPP solvers: xWASP, a state-of-the-art open-source solver, quickly applicable using semi- empirical formulations; and SEECAT, an advanced in-house tool, provided with loads from CFD modelling.

PERFO is a collaborative project between the French Oceanographic centre Ifremer, the naval architecture firm Stirling Design International and the engineering office Bureau Veritas Solutions M&O. The open-source benchmark vessel ONRT has been used as a study case.

The extensive methodology developed here aims at helping the shipbroker at any step of its WASP project progress. Extensive means as accurately as possible without mobilizing unnecessarily expensive computational resources. The accuracy of the performances delivered by a PPP tool mainly comes from the assessment of the loads acting on the vessel, provided as input data. Here, xWASP as a state-of-the-art tool, using fully empirical rapid methods is compared to the in-house SEECAT advanced solver provided with loads from CFD modelling. Both approaches allow for characterizing the vessel's response in terms of drift and rudder angles. They have been compared: qualitatively through forces polar curves of wind side force and added resistance in leeway and quantitatively in terms of performance gain averaged over a standard operating route.

The main assumptions done in this study are:
- The forward speed is fixed and constant;
- The load balance is solved in static;
- Only horizontal planar motion is considered (the heel effect is ignored);
- Calm water hypothesis is made (no wave taken into account);
- The propeller efficiency modified by the load taken by the sail is ignored.

Based on this first reference case, the following conclusions can already be drawn:
- While working on Wind Assisted Ship performance predictions, accounting for the deadworks is not negligible;
- The empirical method Blendermann used for estimating the deadworks aerodynamic loads allows a satisfying approximation at early-stage study;
- Concerning the response to side forces, the manoeuvrability coefficients calculated empirically are a very rough approach. Manoeuvrability coefficients from sea trials or CFD modelling would be more accurate.
- The resistance estimated using the Holtrop-Mennen method is reasonable for an early-stage estimation. However, it is only applicable to "traditional" hulls. In the case of a modern hull, it would be recommended to at least perform one point of CFD resistance calculation to calibrate the Holtrop-Mennen results;
- Accounting for wind profile degradation is the first stage of a more global ship-to-sail interactions model. Further developments on that topic are currently being undertaken and could not be disclosed within that paper.

These conclusions are intended to be consolidated through further work within the PERFO project and thanks to other more realistic study cases.

1.10 WISP2 Project on Wind Propulsion Performance Prediction Methods and Manoeuvring

A S Kisjes, Maritime Research Institute Netherlands, The Netherlands
R Eggers, Maritime Research Institute Netherlands, The Netherlands

The number of ships equipped with wind propulsion, and the number of credible suppliers of wind propulsion systems are rapidly increasing. It appears that the shipping industry is increasingly seeing the need for design changes in view of the climate crisis and simply due to more strict regulations on greenhouse gas emission performance of ships. The uncertainty in investment has decreased as various projects in the last years provided evidence on the realised savings.

Nevertheless, there is much work still to be done to bring wind propulsion to its full potential. In 2019 MARIN and ABS started the WiSP JIP (Wind Ship Propulsion Joint Industry Project), followed up by WiSP2 which is to be concluded in 2023. The first WiSP project started on the premise that the increased uptake of wind propulsion was hindered by a lack of verified performance data as well as a lack of appropriate standards, rules and regulations. This was one of the main "barriers" as identified by the report by Nelissen et al, for the European Committee. At the conclusion of the first WiSP project, there was already an increase in reports from ships actually sailing with wind propulsion. The project itself contributed to the improvement of the EEDI & EEXI guidelines for wind propulsion. However, knowledge and standards on prediction methods, certainly on more substantial contributions of wind propulsion, as well as better rules and regulations still appear to be needed.

The present paper discusses the performance prediction methods as explored in a follow-up, WiSP2. However, we will extend beyond "just" the steady condition, to manoeuvring & seakeeping. Compliance to the manoeuvring standards is not trivial for many ships. In many cases, their course keeping ability is also an indication of the possibility to handle large side forces and yawing moments that are inevitable with wind propulsion. In this paper we will discuss replication of earlier seakeeping and manoeuvring tests in the WindLab project, as well as a broader exploration of wind conditions with the MARIN Ferry used as case vessel equipped with 4 Flettner rotors. The results of this work are used to show some scenarios of how the IMO manoeuvring standards may be interpreted. The results directly show, for two ship design cases, in which conditions it may be a challenge to comply, and where not. Also, other ship behaviour such as the maximum heel angle during a turn is evaluated, as in certain wind conditions these heel angles increase significantly.

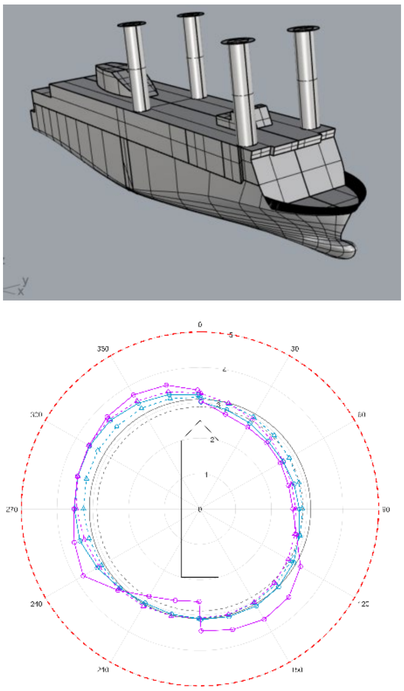


Figure 1: MARIN Ferry and tactical diameter in turning circle for various approach wind angles and types of modelling

Anton Kisjes holds the position of Project Manager at the Maritime Research Institute Netherlands.
Rogier Eggers holds the position of Senior Project Manager and knowledge co-ordinator of Ships Manoeuvring at the Maritime Research Institute Netherlands.

Footnotes:

[1] Nelissen, Dagmar, Michael Traut, Jonathan Koehler, Wengang Mao, Jasper Faber, and Saliha Ahdour. 2017. "Study on the Analysis of Market Potentials and Market Barriers for Wind Propulsion Technologies for Ships." Delft: CE Delft.

[1] International Maritime Organization. 2021. "2021 Guidance on Treatment of Innovative Energy Efficiency Technologies for Calculation and Verification of the Attained EEDI and EEXI." MEPC.1/Circ.896

[1] International Maritime Organization. 2002. "Standards for Ship Manoeuvrability." Resolution MSC 137(76)

[1] Eggers, R., and A.S. Kisjes. 2019. "Seakeeping and Manoeuvring for Wind Assisted Ships." In International Conference on Wind Propulsion. London, United Kingdom: Royal Institution of Naval Architects

[1] Ferrari, V, H vd Boom, AS Kisjes, and FHHA Quadvlieg. 2020. "Heel Angles in Turn and Passenger Safety." In Sustainable and Safe Passenger Ships. Athens, Greece.

1.11 WASP Assessment from a Ship Designer Point of View

Roberto Prever, NAOS Ships and Boat Design srl., Italy

1) The weight of the WAPS and its effect on the displacement shall be taken into consideration when assessing the effective energy saving. For EEDI purposes, the correspondent increase of weight shall be considered as a loss of DWT. The same should apply to the amount of permanently added ballast water that should be loaded to cope with IMO Intact Stability criteria because of the presence of sails.

2) The energy saving shall be considered on the whole range of wind direction as equiprobable – neglecting 50% of the unfavorable wind direction is anti-scientific, and will over-reward WAPS with poor upwind efficiency, which will not be the case in real life operations.

3) If the equiprobability of wind direction is considered, high efficiency of the wind device is necessary for fast ships, where the apparent wind is mostly in a narrow range of angles around the bow.

1.12 Wind Propulsion Towards Zero-Emission Cruise Vessels

N Abiven, **V Vautier**, **F Cany**, **J B Fabre**, and **L Rouxel-Duval**, Chantiers de l'Atlantique, France

1. Overview and Motivation

Wind propulsion for ships has gained new momentum due to the stringent GHG reduction requirements set up by the International Maritime Organization and furthermore within the European Green Deal. Indeed, wind propulsion is a key enabler in this decarbonizing journey as it is one of the very few single solutions enabling energy saving beyond 10%, but still limited with current wind propulsion solutions and wind-assisted vessel applications.

In this challenging context, Chantiers de l'Atlantique (CdA), the largest shipyard in Europe and a leader in energy and environment efficiencies through its dedicated Ecorizon® R&D Programme (started 2008), has considered from the very beginning wind propulsion as a key technology to be developed. Wind-propulsion has not been used for the last 100 years in modern shipping, due to strong drawbacks such as safety, crew-intensive solution, limited fabric sail lifespan, inherent wind versatility compared to low-cost steam/internal combustion engine powered vessels. Thus, to overcome these drawbacks and allow large deployment of such solution a well as significant energy saving even on large ships, CdA has considered several "must-have" requirements (i.e., safety, automation, cost/power-efficiency, durability and scalability for large vessels) in its wind propulsion specifications.

Based on these key stringent success requirements, CdA has made a thorough analysis of potential wind propulsion solutions. State of the art conducted with renowned Dijkstra naval architect team (designer of numerous Dynarig sailing mega-yachts) has shown that no existing/potential solution would fit these key success requirements and has pushed CdA in 2008 to develop in-house an innovative wind propulsion solution, i.e., Solid Sail solution. This rather unique and unconventional solution is based on large flat sail composite panels hinged together which deform under wind pressure thus generating aerodynamic thrust and mounted on a free-standing 74m canting aerorig.

This solution is safe, automated, cost/power-efficient, sturdy, durable and overcomes both current wind powering limitations (i.e., ship size and energy saving) offered by other current solutions.

Indeed, together with relevant ship architectures such as CdA large sailing cruise ship concept design (named Silenseas®), this innovative wind propulsion system is suited for full wind-powering of medium/large ships, thus allowing very large energy savings and GHG reduction emissions up to 90% compared to similar conventional ships. Achieving such GHG emission reduction level with one single solution is rather unique for shipping, thus confirming CdA R&D long term investment to develop such technology.

2. Methodology and Main Results

Since the first idea of giant sails for cruise ship coming all the way back from 2009 (see Eoseas concept), CdA has conducted a thorough solution development, demonstration and validation scheme making use of extensive numerical modelling analyses and experimental tests to assess the solution relevance and performances as well as a design to weight and cost approach. Such methodology has addressed four main areas:

- Aerodynamic thrust assessment for Solid Sail as well as at ship level, through use of Fluid-Structure Interaction and/or experimental testing, to monitor, predict and control sail deformation under wind pressure,
- Transient operation assessment of the full Solid Sail rig in all service conditions (hoisting and lowering the sails, sailing, tackling, gybing, rig tilting…) with actuator and automation operation and validation, through aerodynamic cinematic/structure simulation and/or experimental testing,
- Novel wind-powered ship architecture development and assessment to ensure large wind powering contribution to the overall ship powering, taking into account the peculiar impact of wind thrust to the ship equilibriums and behavior (i.e., ship heeling and drift), (through use of hydrodynamic and energy performance simulations and/or experimental testing),
- Manufacturing process development/optimization of the large sail composite panels and the outstanding composite mast (30-180mm thick, 74m high, 2m chord).

The Solid Sail detail solution validation itself made use of four successive steps, such as:

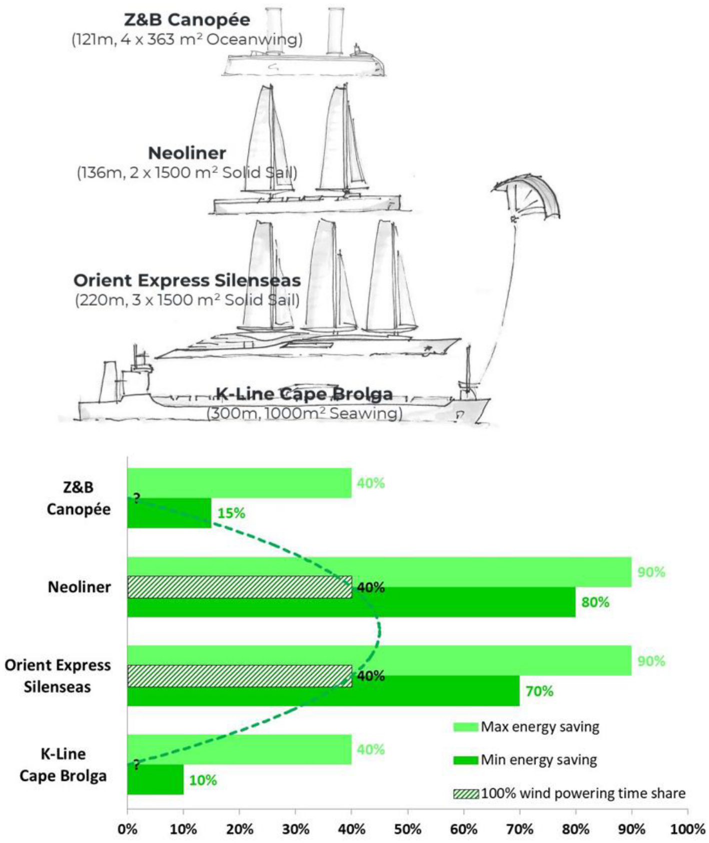
- 1st-generation 15sqm SolidSail 1:10-scale prototype in 2016 (“Silenseas Project” supported by the French Environment and Energy Management Agency) to evaluate the behaviour of the sail in real conditions, optimize the scantling of the Glass Reinforced Polyester (GRP) panels as well as the cinematic of the various parts of the sails,
- 2nd-generation 150sqm Solid Sail 1:2-scale prototype in 2017 (“Solid Sail 2.0 Project” supported by the Bretagne Region), which allowed good correlation between the calculation and the real-life constraints measured in the sails, as well as outfitting improvements,
  After large sea trial validation, an extended version of the 2nd-generation sail prototype was installed in 2018 on Le Ponant (an 88m sailing cruise ship) for one-year operation and 2 Atlantic crossings. This sail proved its sturdiness as well as its ease of use and allowed better anticipation of all scale effects that could affect the full-size product (1000-1500 sqm objective).
- 3rd-generation 50sqm 1:5-scale onshore prototype of the whole wind propulsion system including a Solid Sail jib version and a 360° rotating self-supported aerorig in 2019 (“Jib Sea” project supported by the Bretagne Region, and “LeanShips Project” supported by Horizon 2020 R&D Programme),
- Full-scale onshore demonstrator, with all expected features (tilting feature, sensors and automation system…), in 2022-2023 in two successive steps: first a 500sqm main sail with a 40m mast, and this year 2023 the full 1500sqm sail area and 74m high mast (under progress). All handling procedures have been tested in the first version (automation of sails and rig, vibration loads, emergency procedures, fatigue tests...). Feedbacks of these last fatigue tests showed an expected Solid Sail service life span of 25 to 30 years versus 1 to 2 years only for a premium classic sail. In parallel, Solid Sail received in March 2022 an Approval in Principle (AiP) from Bureau Veritas (BV), based on BV Rule Note for WIND PROPULSION SYSTEMS (WPS) – NR 206.

After 7-year intensive tests and demonstrations, Solid Sail solution now achieves a 5-6 Technology Readiness Level (TRL), with aerodynamic performance close to membrane racing sails, tremendous energy saving and GHG emission reduction potentials (as shown in Figure 1 below) and major weight and cost savings achieved compared to the 1st-generation design (e.g., overall Solid Sail solution rig cost by 1.5-fold). Additional technical optimization and pre-manufacturing activities are foreseen to reduce further this solution cost, improve its Return of Investment ratio much below 15 years (based on current Marine Gas Oil fuel price) and ease future market uptake.

3. Conclusions and Way Forward

CdA development, simulation and assessments of its Solid Sail wind powering solution and related hybrid wind-powered ship architecture demonstrate the great potential contribution of hybrid wind-powered vessels with respect to the challenging International Maritime Organization (IMO) and European Green Deal decarbonizing objectives. Solutions developed here make wind-powered vessels possible with energy saving much beyond current wind-assisted vessels, thus providing a key leverage for future zero-emission shipping.

Indeed CdA Solid Sail technology and Silenseas® wind-powered concept ship have recently convinced both ACCOR and NEOLINE ship owners to use these solutions for their future Orient Express Silenseas cruise vessel and Neoliner ro-ro to be delivered in 2026 and 2025 respectively. This wind-powering global solution will allow both ships to sail under wind-powering only on a 40%-time share, thus enabling major energy savings and GHG reductions (i.e., -70 to -90%, depending on wind conditions and routes) as shown in Figure 1 below.



Sources: CdA, published data

Figure 1. Solid Sail wind-propulsion performances compared to other wind-assistance solutions.

1.13 Novel Platforms for Optimising Renewable Energy Powered Ships

K Goh, Knud E. Hansen A/S, Australia

1. Summary

The concept of a 50,000 DWT bulk carrier that uses wind and solar propulsion as the main source of propulsion is presented. The concept uses a proa form with main hull and outrigger. The unique form allows the vessel to maximise wind and solar energy harvesting. The development of the calculation model for sailing economics is presented and trialled with several Windship variants to show the benefits of operating cost and CO2 emissions over a conventional motor ship.

2. Proa Windship Concept

On a proa, cargo is loaded entirely into the leeward main hull, which is also close to the centre of buoyancy. There will be very little change in righting moment regardless of the cargo load. Stability is provided by the weighted amah and outrigger structure to windward, not buoyancy to leeward. The righting moment remains consistent, meaning stress, scantlings and sail area will also remain consistent when laden and unladen. This is conducive to an efficient structure through a widely varying displacement compared to other multi-hulls.

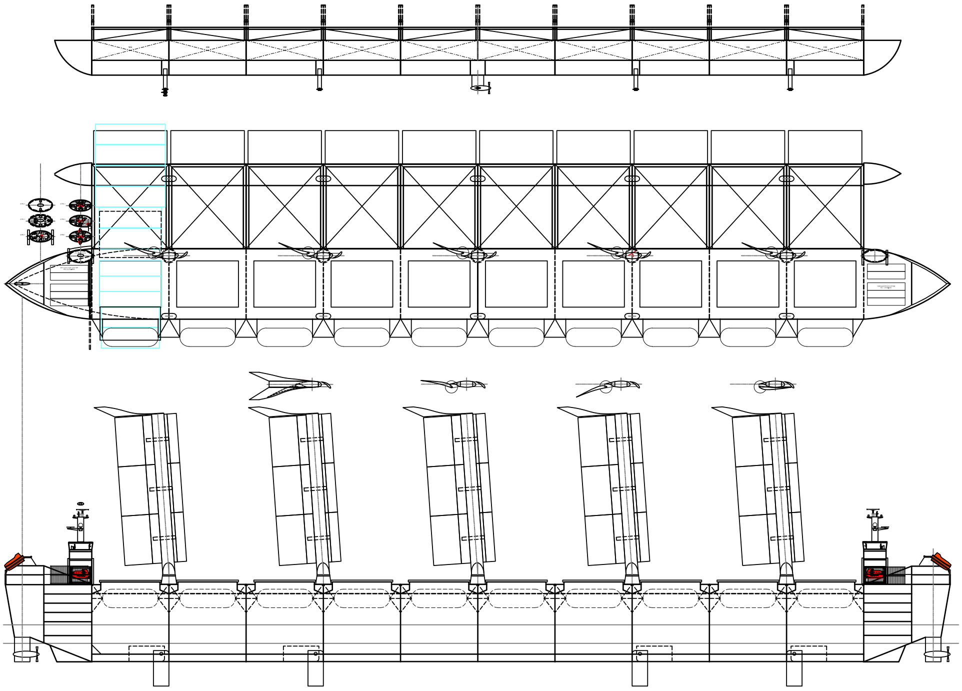


Figure 1. Proa Windship general arrangement

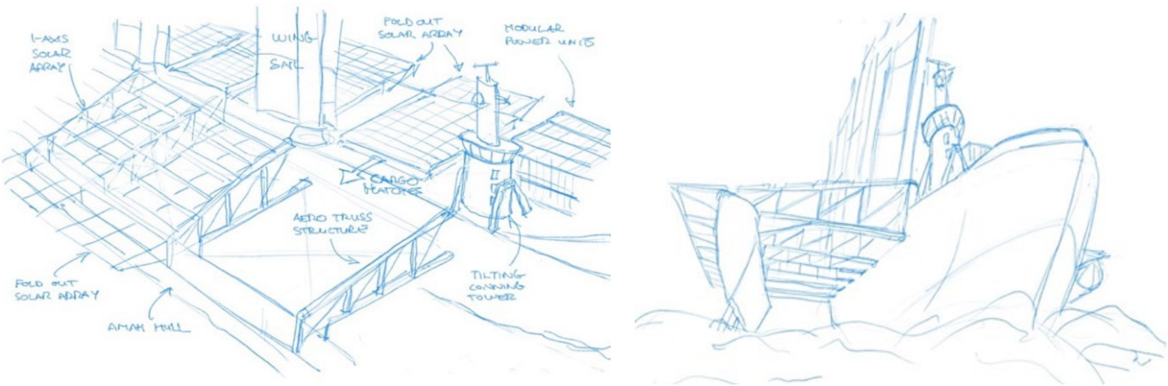


Figure 2. Proa Windship – Novel design aspects & sailing heeled

The additional stability afforded by the proa configuration enables the main hull length-to-beam to be increased beyond the normal range of 5-7. The longer hull supports a larger solar array to harvest more energy and more space for locating the sailing rig and reduce the wind shadowing effect of one mast on another.

With a heeled sailing attitude, CFD analysis has shown a great potential for reduced powering. At 15 knots and a 5° heel the overall resistance is reduced by 25%. At 10° the amah hull is out of the water, and the resistance is reduced by 60%. Added resistance in waves is also expected to be reduced considerably with a narrower hull having less frontal area and a longer hull pitching less in heavy seas where a wind powered ship will spend much of its time.

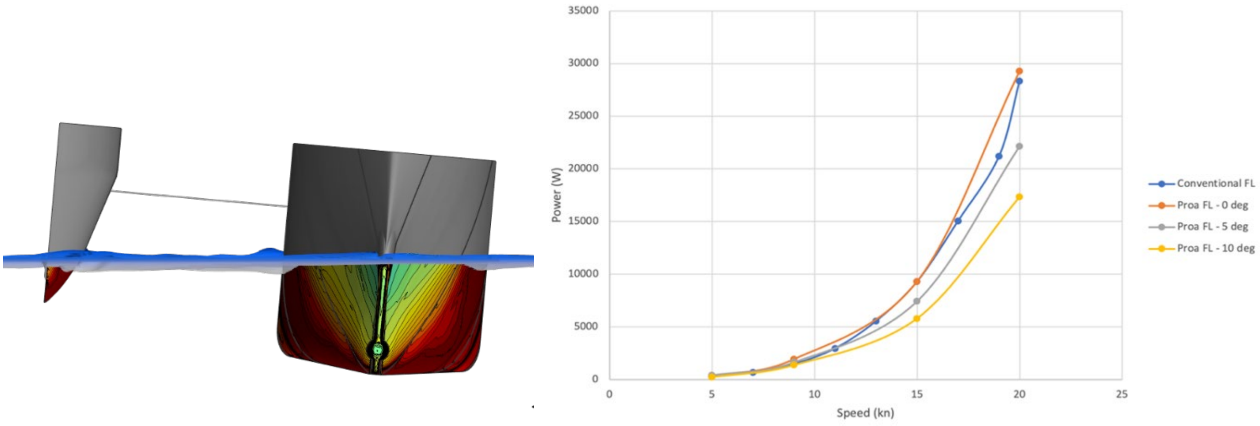


Figure 3. Hull pressure at 15 knots & 5 degree heel

The propellers shall also operate as hydro generators when the vessel speed is favourable. Model testing of the Windship with a conventional hull demonstrates that in a favourable reach (wind from the beam), the bulker vessel could sail at nearly 20 knots in a wind of 15 m/s. At these higher speeds resistance is halved for the proa hull sailing with amah free of the water.

3. Techno-Economic Modelling

The calculation model developed is able calculate sailing performance by wind and auxiliary propulsion systems for any chosen sailing route and thereby also inform the fuel consumption based on generally accepted efficiencies and performance metrics. Three Windship variants were tested against a conventional vessel. Two variants had different amounts of solar power, and the third variant was unmanned and utilised modular gensets for propulsion instead of a typical 2-stroke engine.

Trial results from the calculation model over several typical Atlantic, Pacific and Indian Ocean trade routes show an average vessel speed of 11 knots is optimum for the lowest operating cost for a

Handymax bulker. Windier routes provide greater savings. The total operating cost of a Windship is almost always lower than a conventional motorship except on highly equatorial routes with lower average wind speeds, in which case there is a Windship cost penalty however it is small.

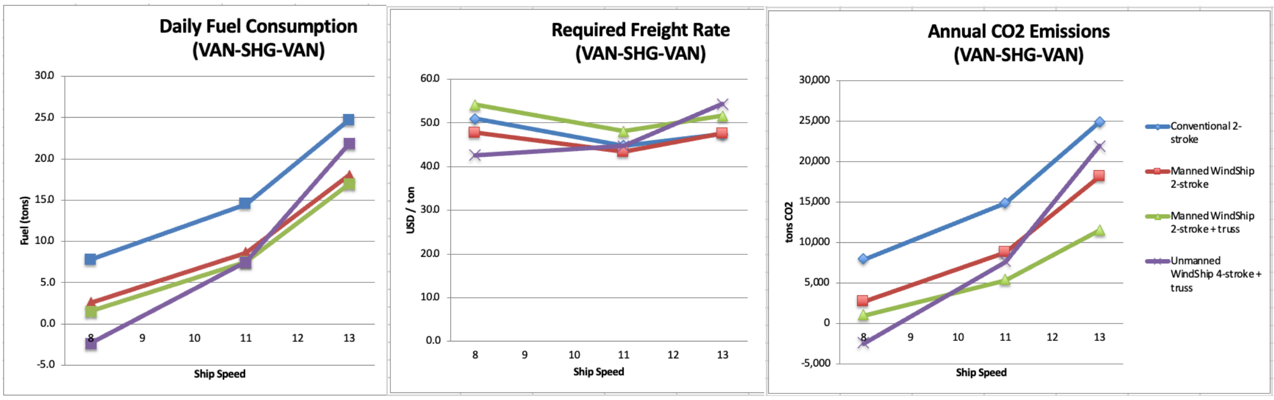


Figure 4. Windship & conventional vessel performance on Vancouver-Shanghai route

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1.14 Validation of Performance Prediction Program Against Cyber-Physical Model Tests

K Eide, **A Östman** and **A Alterskjær,** SINTEF Ocean, Norway

The presented paper describes a validation of a numerical performance prediction program against cyber-physical model tests for a ship equipped with four Flettner rotor wind propulsion devices. The performance prediction program solves the motion of the vessel in three degrees of freedom (surge, sway and yaw), where the applied manoeuvring coefficients, resistance curve, wind propulsor model and propeller characteristics, can be obtained experimentally using model tests or numerically by CFD simulations or by other faster numerical tools.

The SINTEF Ocean bulk carrier (SOBC-1) was chosen in the validation study due to recently performed cyber– physical model tests, where the effect of the wind propulsors was included using a novel hybrid testing technique. In the experiments, the SOBC-1 model was running at self-propulsion, where propulsion was delivered from four numerically modelled Flettner rotors based on published CFD simulations results, in addition to a single screw conventional propeller. The forces generated by the wind propulsors were applied to the model using a system of wires, connecting the model to actuators, providing forces in 5 degrees of freedom according to prescribed wind conditions and measured vessel kinematics.

In the present validation, the computed ship speed, drift angles and rudder angles can be directly compared against the model test results. The drift-angle induced added resistance of the vessel is indirectly compared by evaluating the propulsion point of the single screw propeller and compared against measured RPM, torque and power during model tests. The validation is conducted for a set of true wind directions ranging from 30 to 150 degrees, while true wind speed varies from 10 to 20 m/s. The results show a good correlation between model tests and simulations, capturing the essential physical effects of operating at different points of sail. This validates both the numerical models applied for the calculation of hydrodynamic effects, as well as the methodology of the program.

A performance prediction program is an essential tool when evaluating the effects of equipping a vessel with wind propulsion devices. As a ship owner must balance installation cost versus potential performance gains, an analysis needs to be conducted for a wide variety of conditions the ship may encounter during the many voyages it completes throughout its life. This validation study suggests that quicker numerical methods can produce reliable results, which is highly advantageous when analysing a vast set of environmental and operational conditions.

Further refinements to the numerical models are expected to provide a tool with increasing accuracy and flexibility for future performance assessments of wind-assisted ships.

1.15 Performance Prediction of Wind Propulsion Technologies via CFD

Dr Rodrigo Azcueta, Cape Horn Engineering, UK

Dr Rodrigo Azcueta from Cape Horn Engineering presented a paper at the RINA Wind Propulsion Conference on 16-17 February 2023 at the IMO headquarters in London. He presented examples of services provided by the company for performance prediction of all type of vessels using CFD, such as for resistance, propulsion, seakeeping, and manoeuvring simulations. Furthermore, he presented the extensive research programme carried out using the SINTEC Ocean bulk carrier benchmark (SOBC-1) with comparison to towing tank results.

For the SOBC-1 benchmark, open water propeller simulations, resistance tests at model and full scale, propulsion tests with virtual disk and with rotating propeller, and finally 6 DOF simulations for motor-sailing conditions were presented and discussed.

Furthermore, the importance of verification and validation practices for EEXI/EEDI calculations, in particular when introducing ESDs and WASP devices to improve vessel performance, were highlighted. The requirement of demonstrating the qualification of the CFD solution by performing numerical uncertainty analysis following the ITTC and IACS recommendations was described. Finally, an investigation into the uses of Machine Learning with CFD for wing trim optimisation was presented.

All simulations presented were performed with the commercial CFD package STAR_CCM+ from Siemens Digital Industries in the latest version from mid-2022.

For the open water propeller simulations several strategies to set up the simulations were implemented and compared among each other and with cavitation tunnel results from SINTEF Ocean. The comparison of the simulated results to the experimental ones shows discrepancies of less than 2% on average.

For the towing resistance at model scale a perfect correlation (0.05% difference) with the measured total resistance in the tank was obtained with the k-epsilon model. Values for dynamic sinkage and trim are also well predicted. At full scale a correlation with the towing tank extrapolated results of between 0.6 to 3.7% was obtained, depending on the turbulence model used. Similarly, for the self-propulsion simulations, either with a simplified virtual disk model or with the actual rotating propeller, the agreement with SINTEF Ocean extrapolated results were withing 5%. However, in those cases there is always the uncertainty in the procedure that each towing tank uses for extrapolating the resistance to full scale.

Azcueta also presented results of Verification and Validation of recent projects for the calculation of the EEXI power curve, showing that a low level of numerical uncertainty of around 1% and correlation factors between simulation and sea trials of less than 3% are achievable. Furthermore, extracts of their Best Practice Guidelines and Demonstration of Qualification documents which are required by the ITTC and IACS were presented.

One of the main takeaways from the presentation was the introduction of Cape Horn Engineering's latest workflow to directly assess the performance of different WASP devices with 6 Degrees-of-

Freedom simulations. The 6 DOF simulations are basically all-in-one, simultaneous hydrodynamic and aerodynamic simulations where, together with the propeller, the thrust is generated by wings or any other WASP device on deck. The wind conditions above the water surface are modelled with an accurate wind profile, considering wind gradient. This results in a variable apparent wind speed and direction at different heights, due to the combination of an advancing ship and a wind velocity that varies with height. The wind forces on the WASP device, and on the hull and superstructure, induce drift and heel angles, and the rudder angle is adjusted during the simulation to balance the yaw moment of the whole system. The virtual disk model of the propeller adjusts the RPM to balance the drag and thrust forces. Thus, the vessel is motor-sailing and balanced in all six degrees-of-freedom. This type of simulations is much more accurate than running separate force models, for the hull and for the wings, and balancing the results with a Velocity Prediction Program. Thus, they can either be used to validate a VPP, or to directly compare different WASP technologies.

Finally, Azcueta presented the application of the 6 DOF simulations to three vessels. The first one is MV Regal, a well-known benchmark vessel for validation of CFD a ship scale. In this case, either two solid wings or two Flettner rotors were modelled and compared with the cases without any devices on deck. The second vessel is the SINTEF Ocean Bulk Carrier. In this case, two solid wings were modelled on deck and results also compared with the cases without the wings. Initially the wings were trimmed estimating the optimal sheeting angles. Following that a Machine Learning model of the wings' interactions was used to find the optimum trim angles. After repeating the 6 DOF simulations the power savings improved by an extra 4% (the initial estimate was quite close to optimum). The last case presented was for an industry client; Humphreys Yacht Design with their patented FastRigs from the company Smart Green Shipping. Six FastRigs were modelled on deck of an existing Panamax bulk carrier and were analysed for six different wind strengths and directions. These simulations were compared with the cases with the exact same wind conditions but without the wings. The maximum power saving at 20 knots wind from the side was 54% and the average over the six conditions was 29%. It can be argued that optimising the wing trim angles, installing a variable pitch propeller and a hybrid power plant, the average power savings of 29% would increase even further.

There is little doubt that these levels of power savings are achievable, due to the nature of these type of simulations which considers all of the most important physical phenomena and interactions. It also directly compares the cases with and without the wings, and coming from an independent third-party subcontractor removes any bias. Figure 1 below shows the power savings in Watts and as percentages.

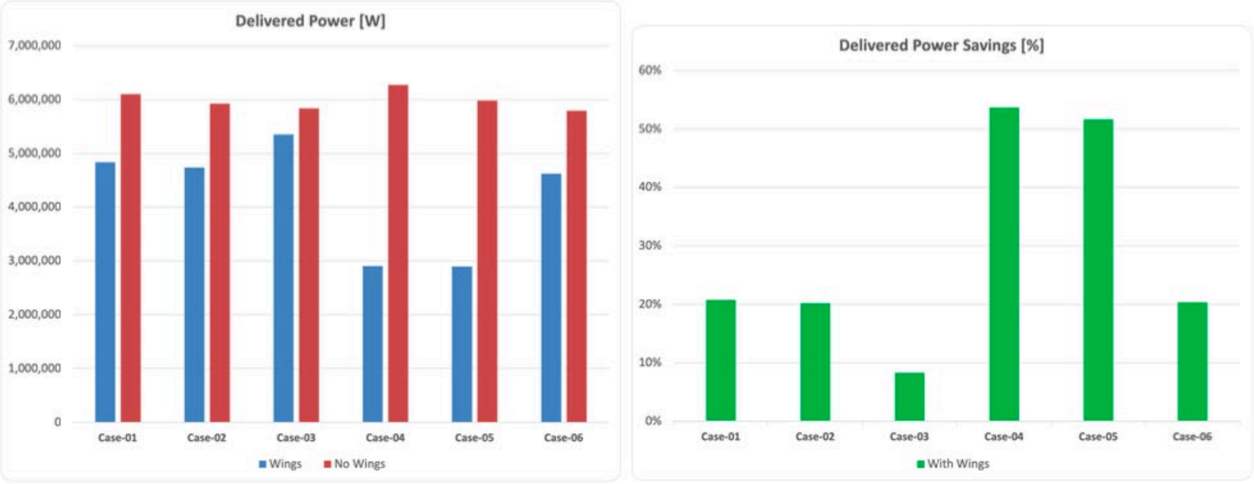


Figure 1: Delivered Power and Power Savings

1.16 Aerodynamic optimization of the eSAIL, bound4blue's suction sail for wind-assisted vessel propulsion

A Llopis Pascual, **G Bailardi**, **B Charrier** and **D Ferrer Desclaux,** Bound 4 Blue S.L., Spain

bound4blue is a European WAPS (Wind-Assisted Propulsion System) provider which has developed the eSAIL, an autonomous suction sail that combines the positive features of a conventional wingsail (simple operation, excellent capacity to sail upwind) but takes profit of active boundary layer control techniques (based on suction) to prevent flow detachment (stall), achieving extraordinarily high values of lift coefficients 6 to 7 times higher than those obtained with regular sails, resulting in smaller size and lower weight sails for equivalent savings. bound4blue offers a portfolio with different eSAIL sizes, so that it is suitable for the different types and sizes of merchant vessels. Full-scale eSAIL installations have already been executed on 2 vessels, 3 additional installations are ongoing, and additional full-scale realizations are in preparation.

R&D and constant improvement are part of the DNA of bound4blue and its team. This paper summarizes the results obtained thanks to the work and effort of the aerodynamics' department team.

Origin/Concept

In the early 1980's, Captain Jacque-Yves Cousteau, oceanographer, and explorer, wanted to build a new ship to replace the *Calypso*. The Cousteau Foundation mobilized a Research Team under the direction of Prof. Lucien Malavard and PhD. Bertrand Charrier to propose wind assisted propulsion systems. The outcome of their extensive research led to the creation of Turbovoile, a suction sail that used active boundary layer control to delay stall and therefore achieve extraordinarily high values of lift.

bound4blue's eSAIL

Taking the lessons learnt from the development of the Turbovoile, bound4blue set out to improve the performance of the suction sail. The culmination of this work is the eSAIL: a fully autonomous suction sail delivering an increase of lift-to-power ratio of up to 20% when compared to the Turbovoile.

Technology Improvement

To achieve this increase in performance, bound4blue has conducted extensive work to develop the necessary tools for aerodynamic optimisation of the eSAIL and their validation. Numerical tools such as CFD allow the exploration of the design space. The first step was to validate the CFD modelling techniques using experimental data of the Turbovoile. The best conditions/hypothesis was selected as the one where the physical quantities are well predicted but stall angle is underpredicted. This means that the CFD results could be considered as "conservative" and could realistically have higher lift coefficient values. This was followed by a 2D parametric study of the suction sail to explore the design space and identify the configuration which provides the best lift-to-power ratio. The best configuration is then used as the basis for a parametric study in 3D, where additional parameters can be studied: fan modelling, winglet effects and local disturbances caused by mechanical and manufacturing limitations.

To provide additional validation points and to confirm the findings of the parametric studies, a wind tunnel test campaign was conducted in September 2022. The data obtained from the wind tunnel testing campaign was used to validate the CFD modelling technique in two ways: comparison of the lift curve slope and a comparison of the pressure distributions. The comparison of the lift curve slope shows a very good match for the linear section of the curve and varying results in stall angle.

This can be attributed to CFD underpredicting stall angle as seen during the early CFD studies. A comparison of the pressure distribution showed an excellent match.

The strong match between all data provides a high confidence in the CFD tools developed and therefore, confidence in predicting the performance of the eSAIL. As such, the paper includes the performance of the eSAIL in the form of two plots: coefficient of lift versus coefficient of aspiration and aerodynamic polar, coefficient of lift versus coefficient of drag. A comparison of the eSAIL and Turbovoile performance, shows that the eSAIL delivers up to a 20% increase in lift compared to the same power. Including lift coefficients of up to 8.2 for a coefficient of aspiration of 0.9.

Detailed studies for each eSAIL installation

The high confidence in the numerical modelling techniques means that it is now possible to add complexity to understand the effects of realistic conditions on the performance, instead of idealised conditions. Examples include: installation height, the effect of the atmospheric boundary layer, sail to sail interaction and ship-sail interaction.

The paper shows an example of a detailed study: the installation of two eSAILs on the Eems Traveller (Amasus). A study of the sail-to-sail interference at different apparent wind angles means the control algorithm can be customised to maximise the savings. Historical ship data is used to define the operating conditions that the eSAILs will experience and can therefore optimise the savings for these realistic conditions.

Future work and conclusions

The next steps in this development work are to continue adding complexity to the model and to conduct further wind tunnel test campaigns: extending the CL vs Ca curve to very high values of Ca and to provide validation data for sail-to-sail interaction.

The eSAIL achieves an increase in lift coefficient of 20% for the same power usage when compared to the Turbovoile and can achieve a lift coefficient up to 8.2 These results are considered “conservative” as CFD is shown to underpredict the stall angle, and therefore maximum lift coefficient.

With the tools developed, bound4blue is able to predict the conditions experienced by the eSAIL on each ship and therefore provide a custom control algorithm to maximise the savings offered by the efficient wind propeller.

1.17 Manoeuvre simulations in design process of wind powered vessel

Kontos S., Lundbäck O., Kjellberg M., Wilske E., Werner S., RISE Research Institutes of Sweden, Sweden

Wind propulsion systems (WPS) are one of the most promising technologies for ship propulsion that can radically reduce greenhouse gas emissions. However, attention must be paid to the additional transversal forces and yaw moments connected to a wind propulsion system, as it can affect the manoeuvring and seakeeping performance of a ship.

Time-domain simulations can be utilised to assess the manoeuvrability of a wind powered vessel to support the decision making, from the early design stage, all the way to testing the control systems, design of Human Machine Interface (HMI) and developing crew guidelines and training. It has been demonstrated that tools like SSPA’s/Rise maritime´s six degree of freedom inhouse code, SEAMAN-Winds can give highly valuable insights into how to obtain a viable design of a wind propelled or wind assisted ship. It was also described how this kind of simulation tool make way for introducing human in the design loop to achieve a ship design that is a good working environment for the crew. A few examples of this are given below.

1. To optimise and evaluate design of human-machine interface (HMI)

2. For design and evaluation of automation to help the crew manoeuvring and utilising wind propulsion systems for benefit of the manoeuvring and safety of the ship.

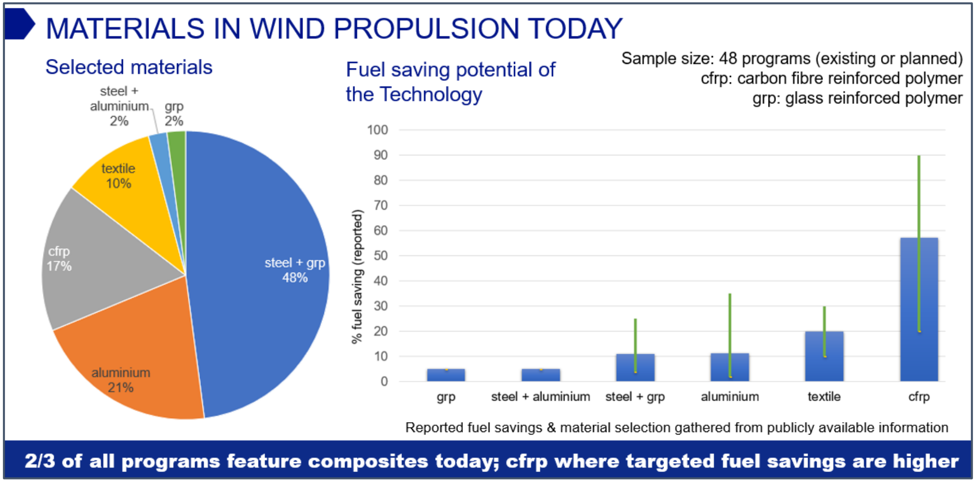
The work presented also gave example of a process where ship design and evaluation were performed in stages where time domain manoeuvring simulations is included together with Velocity Prediction Program (VPP) and Computational Fluid Dynamics (CFD) as other important components.

1.18 High Performance Composite Materials for Wind Propulsion Technologies: Challenges & Opportunities

Thomas James, Hexcel Corporation

About the author: Thomas James holds the current position of Marine Business Development Manager at Hexcel, a world-leading manufacturer of high-performance composite materials. He is responsible for development of strategy and new business opportunities within the marine industry. Having originally qualified as a Naval Architect, his previous experience includes engineering and design roles within the marine composites sector, composite structural engineering for an America's Cup yacht racing team, followed by research and commercial roles within the advanced composites materials industry. Tom is a Chartered Engineer and has been a RINA member since 1998.

This paper provides an overview of the structural design considerations for the most significant wind propulsion technologies in use or under consideration today: Soft sailed rigs, wing sails, rotor sails, suction sails and kites. The material selection process is outlined, and an explanation of the benefits of high-performance composites is provided. A study of currently active or planned wind propulsion technologies shows that approximately two-thirds utilise composite materials, with carbon fibre reinforced polymer (CFRP) already playing a significant role - especially in high power systems where they are an enabling technology. This paper looks in detail at some of the experiences of other highly industrialised and commoditised composite market segments which may provide useful input for wind propulsion manufacturers seeking to evaluate composite material solutions, such as automotive, aerospace and wind energy.



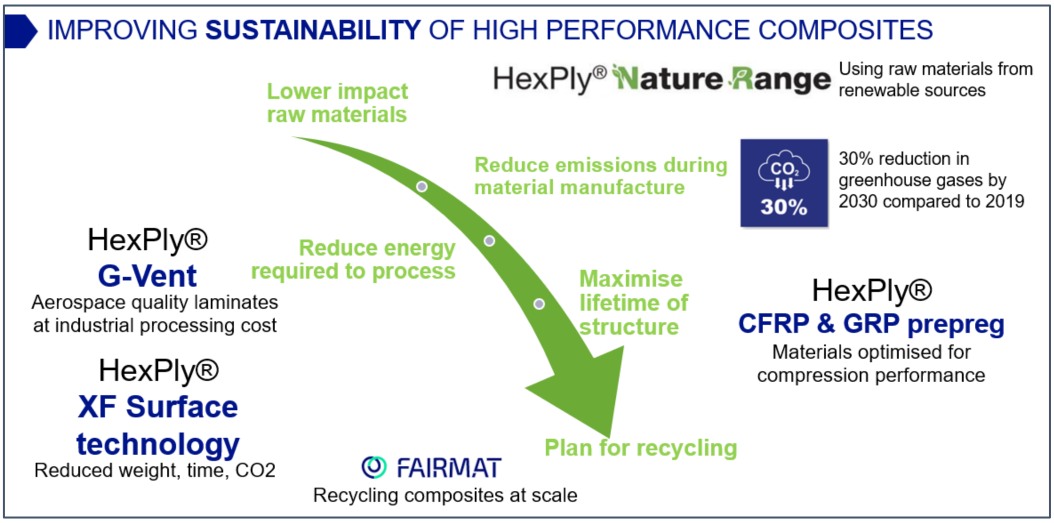
MATERIALS IN WIND PROPULSION TODAY

Sample size: 48 programs (existing or planned)
cfrp: carbon fibre reinforced polymer
grp: glass reinforced polymer

Reported fuel savings & material selection gathered from publicly available information

2/3 of all programs feature composites today; cfrp where targeted fuel savings are higher

Notwithstanding the importance considering the Life Cycles Analysis (LCA) of the ship as an entire system – and the huge benefits that a wind propulsion technology can offer in this regard - the paper outlines what Hexcel and others in the composites material supply market) are doing to improve the sustainability of their products.



We conclude that fundamentally, composite materials are a good fit for the marine industry. They can be moulded into complex shapes, they are lightweight, and they do not corrode in seawater. Wind propulsion can benefit from more than 30 years of material development for wind energy in its quest to accelerate technology adoption.

1.19 Wind Propulsion and Underwater Radiated Noises Mitigation

Pierre Cordier (XP Sea) and **Claire Noël** (Semantic TS)

From various scientific studies, we know that vessels' Underwater Radiated Noises (URN) have significant negative impacts on marine life. As the world fleet, composed in majority by bulkers, tankers, and container vessels, tripled over the last six decades, oceans are getting noisier with an average increase of 20 dB along during the same period.

Since a few years, part of the maritime industry is working to mitigate URN, and most maritime organizations are preparing future rules to protect marine life from noises. The IMO MEPC.1/Circ.833 "Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life" is showing the way to all parties involved in ship design and operation.

It is well established that URN emitted by vessels mainly come from propellers' cavitation and machinery equipment to a lesser extent.

Noise mitigation measures have been applied for many years on specialized units like research vessels, certain navy ships and cruise vessels for other reasons than marine life protection. Machinery equipment are usually isolated which reduces noise radiations through the hull to the sea. These measures are also applied to certain cargo vessels with less stringent requirements. Cavitation can be limited by specific design of propeller, propulsion engine and hull design. These measures are usually costly and not affordable for the major part of commercial vessels' shipowners. Some vessels are retrofitted to improve their propulsion efficiency or reduce their drag to reach CII and EEXI carbon intensity and rating levels. But this does not necessarily reduce propeller cavitation and URN.

Several studies show a clear reduction of URN with ship speed decrease as propulsion power and rpm are reduced. Slow steaming is therefore the cheapest and most efficient way of reducing URN as propeller cavitation disappears below a rpm specific to each vessel. However, this speed limit may be too low for shipping time constraints.

When a noisy vessel crosses an area where marine mammals live, their communication distance is reduced or disturbed. As this disturbance is repeated frequently along shipping routes, it compromises their lives. In this study, we therefore measure the communication distance reduction due to the proximity of a vessel from one individual or group of cetaceans.

Wind propulsion is the most silent means to propel a vessel. Its contribution to ship propulsion is an opportunity to reduce URN to acceptable levels for marine life, as demonstrated by our study, the first of its kind to be published.

For most wind propulsion technologies, and under favourable wind conditions and directions, when a ship fitted with WASP accelerates from slow speed by increasing the propeller thrust, the wind propulsion thrust increases as well. At a certain ship speed, the wind thrust reaches its maximum level and then, above that speed which we call the “Optimum Ship Speed” (OSS), the wind thrust drops quickly.

Our study considers a standard general cargo vessel fitted with a WASP system bringing 40% thrust contribution at the OSS, which is 12 knots in our case.

We then compare two cases: Case A with the vessel using 100% conventional propulsion (as if there was no wind) and Case B with 40% wind thrust contribution, both at the speed of 12 knots. Case A vessel is running with a propeller rotating at 105 rpm whereas Case B vessel is at 68 rpm.

As we know URN levels for different rpm values, we can compare the URN in both cases. URN levels are given for several frequency ranges. We focus the comparison on the frequency of 100 Hz where URN levels are high and as this frequency hits the communication frequency broadband of most marine mammals.

The results show that the URN level is reduced by 14 dB from Case A to Case B. This important reduction is due to the change of propeller regime from cavitation to no-cavitation. In Case B, the remaining noises are mostly emitted by the machinery equipment which are usually correctly isolated from the hull for crew comfort criteria.

It is to be noted that without wind propulsion contribution, the reduction of rpm reduces the ship speed from 12 kts to about 9 kts in calm weather conditions.

In terms of communication distance between two individuals, which is vital for marine mammals’ social life, the impact of the URN generated by one Case A vessel is equivalent to 25 Case B vessels. Starting with a communication distance of 40 km in a standard ambient noise level, our simulation shows that in Case A, it is reduced by 36 km, and in Case B by 8 km only. Therefore, the disturbance is 28 km less with 40% wind propulsion which is considerable for these animals.

Fishes and invertebrates are also impacted by URN in other respects. The disturbance reduction shown in this study for marine mammals would also be applicable to these species with other criteria. We are convinced that wind propulsion is a major solution to mitigate disturbance due to URN. And the effect should be significant even for smaller wind thrust contributions (30%, 20%, …).

For the way forward, we plan to collect more data on existing vessels without WASP, vessels retrofitted with WASP and new vessels designed for wind propulsion. Then we will proceed with several simulations to give a full picture of how wind propulsion may reduce or eliminate cavitation, reduce considerably URN levels and ultimately better protect marine life.