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RETROFIT SOLUTIONS TO ACHIEVE 55% GHG REDUCTION BY 2030

Sea trials protocol for WASP systems

WP 7 – Technology Demonstration
Task 7.1 – WASP systems installation and see trial protocol
D7.2 – Sea trials protocol for WASP systems
Partners involved: B4B, ATD, RINA, LASK
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Acronyms

Acronym	Description
ALARP	As Low As Reasonably Practicable
ALS	Air Lubrication Systems
ARA	Average Rudder Angle
AWA	Apparent Wind Angle
AWS	Apparent Wind Speed
CFD	Computer Fluid Dynamics
COG	Course Over Ground
CPP	Controllable Pitch Propeller
FAT	Factory Acceptance Test
FOC	Fuel Oil Consumption
GHG	Greenhouse Gas
GPS	Global Positioning System
HAZID	Hazard Identification
HAZOP	Hazard and Operability
HMI	Human-Machine Interface
NSP	Net Saving Power
PLC	Programmable Logic Controller
PTO	Power Take-Off
RPM	Revolutions Per Minute
SAT	Site Acceptance Test
SMS	Smart Energy Management
SOG	Speed Over Ground
SRIA	Strategic Research and Innovation Agenda
SS	Suction Sail
TWA	True Wind Angle
TWS	True Wind Speed
UPS	Uninterruptible Power Supply
WASP	Wind-Assisted Ship Propulsion
ZEWT	Zero-Emission Waterborne Transport Partnership

Executive Summary

The RETROFIT55 project aims to develop decarbonization solutions and green technologies that shipowners can adopt to reduce fuel consumption and Greenhouse Gas (GHG) emissions by 35% with respect to the 2008 level. This project primarily focuses on ship retrofitting using new energy-saving solutions, combining mature technologies (i.e., ship electrification, hydrodynamic design optimization, operational optimization) and innovative technologies (wind-assisted ship propulsion and passive air lubrication).

In this context, WP7 aims to demonstrate the effectiveness of the technologies developed in the RETROFIT55 project. In particular, the goal is to prove that it is possible to integrate these technologies in real scenarios, potentially, leading to significant reductions in vessel fuel consumption, without affecting the performance of the vessel and its safety standards.

Within the WP7, Task 7.1 (WASP systems installation and sea trial protocol) lead by B4B, establishes the best practices for the WASP installation and the definition of a sea trial protocol for its validation, which will be detailed in the current deliverable. The sea trial protocol has to assess the operational behaviour and the primary performance of the WASP system, to support the required demonstration activities in WP7.

1 Introduction

RETROFIT55 aims to develop decarbonization solutions and eco-friendly technologies available to shipowners to reduce fuel consumption and Greenhouse Gas (GHG) emissions and to enhance the ship efficiency. This can be achieved by making us of technologies such as Passive Air Lubrication Systems (ALS), hydrodynamic and operational optimization, Wind Assisted Ship Propulsion (WASP) and the use of renewable or low-emission energy sources, like fuel cells or photo-voltaic panels, to hybridize the main propulsion system and the auxiliary power systems. The project goals fit in the Waterborne Strategic Research and Innovation Agenda (SRIA), particularly emphasizing Retrofit and striving to meet the targets of Zero Emission Waterborne Transport (ZEWT) partnership. ZEWT aims to develop and showcase strategies to decrease waterborne transport fuel consumption by at least 55% before 2030 compared to 2008, which is reflected in the project's name, RETROFIT55: "*RETROFIT SOLUTIONS TO ACHIEVE 55% GHG REDUCTION BY 2030*". The project does not include the replacement of current fossil fuels with synthetic or climate-neutral energy sources (a subject addressed in separate EU initiatives).

It is acknowledged that a single retrofit solution will not lead to the required GHG emission reduction. Hence, combining existing high Technology Readiness Level (TRL) systems and elevating the TRL of other less mature solutions to 7-8 becomes essential. It is crucial to note that retrofit systems interact, often diminishing the individual gains but resulting in the most substantial overall improvement when applied together. Achieving the optimal balance poses a significant challenge, and RETROFIT55 proposes an appropriate approach to address this challenge.

In the context of RETROFIT55 project, the WP7 – *Technology demonstration* – aims to showcase the viability of combining the technologies developed in WPs 2-6 in real operational conditions, to achieve a substantial reduction in the ship emissions, without compromising the ship performance and safety. These demonstration activities are intended to provide ship-owners and related stakeholders (shipyards, designers, technology providers, etc.) with a clear understanding of the short to medium-term potential of the retrofitting solutions in terms of their environmental, safety, and economic benefits.

The Task 7.1 – WASP systems installation and sea trial protocol – seeks to establish best practices for the implementation and validation of the WASP systems. Moreover, it aims to define a sea trial protocol that supports the necessary demonstration activities for the WASP systems. This specific task has been summarized in the present deliverable.

The primary objective of this deliverable is to present the sea trial protocols intended for the comprehensive testing and validation of the WASP systems. It includes a safety checklist and an assessment of the vessel manoeuvrability with the installed WASP system. Additionally, it outlines the important data to be gathered during these sea trials.

This report is based on the current experience of B4B in suction sails, in particular in the innovative eSAIL® (see Figure 1), but it could be easily adapted for any other kind of WASP technology. In fact, most of the requirements for the validation of the technology are the same, whereas most of the differences are on the safety aspects

For contextualisation purposes, the eSAIL® integrates aviation aerodynamics into newly designed wing-sails tailored for an enhanced "clean" propulsion of vessels, thereby reducing fuel consumption and pollutant emissions. The eSAIL® functions as a WASP system, utilizing active boundary layer control through suction. In its passive state, when exposed to wind without suction, the wing-sail generates drag, like any non-lifting structure. However, upon activation of the suction, a small volume of air is drawn in, effectively reattaching the flow to the sail. This process generates significant lift, while maintaining low drag. Compared to conventional sails, the eSAIL® produces 6-7 times more lift, with a very low power consumption and a simple mechanical design. The simplicity of the system ensures operations without inertial loads, vibrations, or constant movement, ensuring a straightforward and dependable system. Furthermore, the eSAIL® is designed for easy operation and maintenance.

The B4B eSAIL® is a compact and cost-effective system, engineered to deliver maximum fuel savings. As a result, the eSAIL® stands out as the most cost-efficient and effective wing sail system for commercial vessels. Based on the computational modelling, wind tunnel tests and preliminary full-scale demonstrations conducted at B4B, the eSAIL® can potentially save up to 30% of fuel and correspondingly reduce the GHG emissions, though actual savings vary based on routes and conditions.

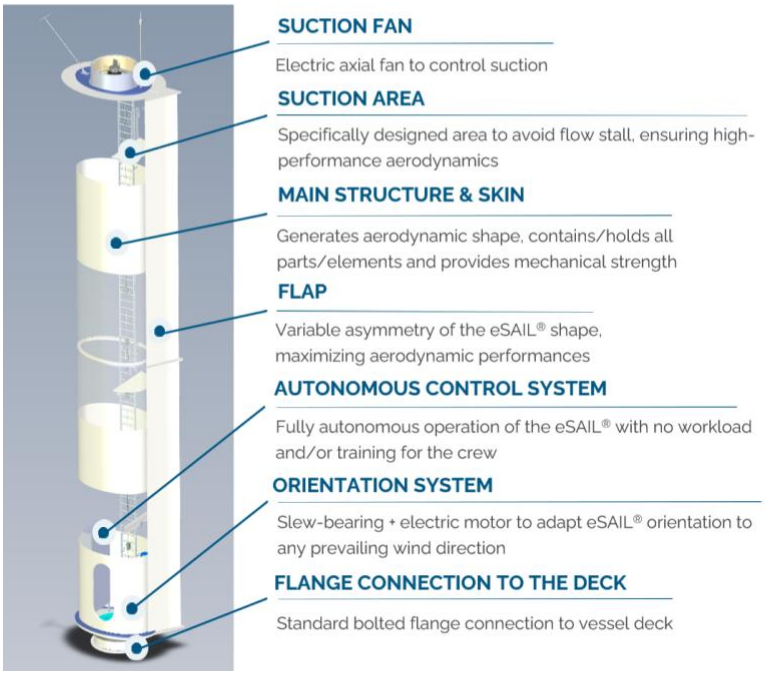

Figure 1: Main components of the B4B eSAIL®

The information obtained from extensive sea trials will serve the purpose of validating the accuracy of digital twins and of estimating the environmental impact of the system. Such results will be supported by the surrogate models developed in WP1. These demonstration activities are geared towards assisting ship owners and associated stakeholders (such as shipyards, designers, and technology providers) to understand the immediate to medium-term environmental, safety and economic advantages associated with the tested retrofitting solutions.

According to the experience gained by B4B, in order to define a safe and successful sea trial protocol, a three-stage procedure must be followed, which is summarized below:

1. Risk-assessment: As part of IMO, Class requirements and best industry practices, a Risk Assessment is required to be carried out to address any introduction of alternative design in order to identify potential hazards that could be introduced and to ensure that these hazards are managed appropriately.
2. **Pre-sailing check:** the main purpose of this phase is to carry out several checks of all relevant mechanical/electrical systems and devices related to the WASP system. It should normally be performed at port or in a shipyard.
3. **Vessel manoeuvrability assessment**: once the vessel starts sailing with the WASP system installed, it is necessary to carry out a few tests to ensure that the vessel has maintained its manoeuvrability, especially in emergency situations such as stops or close turns. In this phase, the master and all the crew members are trained in operating the new WASP-equipped vessel.
4. **Functionality and savings test:** the last phase is focused on the manoeuvres required to data acquisition under real operation conditions to obtain reliable saving values.

The afore-mentioned phases will be detailed in the following sections of this document.

It is necessary to point out again that the document is as generic as possible, to be compatible with any WASP technology. The aspects related to the vessel safety or manoeuvrability must be carefully defined by the technology developer, considering the regulations in force and in collaboration with the shipowner and the classification society.

1.1 Key operational parameters

These are the definitions of some of the concepts that are used in this report:

- AWA is defined considering bow =0° and stern = 180°;
- TWA is defined considering bow =0° and stern = 180°;
- TWS is measured in knots and with sail equipment;
- Heading: the direction the ship is pointing, expressed in degrees, clockwise from true north, may be obtained by ship equipment;
- Average rudder angle is obtained from existing rudder angle indicator;
- COG is taken from GPS;
- SOG is taken from GPS.

1.2 Relevant documentation.

As part of the engineering activities developed by the WASP technology provider in collaboration with the ship owner and the naval engineering office in charge of the vessel transformation design, several technical documents and drawings are developed and sent to the classification society for review and approval.

This engineering activities are beyond the scope of this deliverable, however, to get a comprehensive overview of the whole process, a summary of the most critical technical documents is detailed below.

- Inclining test or lightweight survey report and final stability manual
- Electrical schematic drawing

- WASP control and monitoring system functional description (incl. emergency procedures)
- System block diagram (topology)
- User interface documentation and manuals
- Power supply arrangement
- Data sheets with environmental specifications
- List of controlled and monitored points
- Circuit diagrams
- Software change handling procedure
- Manoeuvring booklet
- General arrangement plan
- WASP foundation calculation report and plan
- Navigation lights plan
- Radar visibility

It should be noted that this summary of work documents is based on the experience of bound4blue, therefore, the content may change according to the specific WASP technology characteristics, the vessel characteristics or operational constraints. Furthermore, the scope and detail of these technical documents varies greatly depending on the classification society in charge of their approval.

2 Phase 0: risk assessment.

2.1 Risk assessment approach.

The integration of wind propulsion systems on vessels introduces a range of potential hazards and operational challenges that must be carefully evaluated and mitigated.

Conducting a thorough risk analysis prior to the installation of a wind propulsion system is essential to ensure the safety, reliability, and effectiveness of the technology. This analysis involves identifying potential hazards, assessing their likelihood and impact, and developing strategies to manage these risks. Key considerations include structural integrity, navigational safety, crew training, and emergency response procedures.

This phase is identified as "0" due to the necessity of conducting a risk assessment prior to the vessel transformation engineering activities. Additionally, a continuous monitoring of potential risks should be carried out, with particular emphasis before sea trials. Given the relationship between potential risk and the first sailing of a WASP-equipped vessel, a preliminary approach to the risk assessment is detailed in this document and section.

This section outlines the critical steps and methodologies for performing a comprehensive risk analysis for wind propulsion system installations on vessels. By proactively addressing potential risks, we can facilitate the successful adoption of wind propulsion technologies, contributing to a more sustainable and resilient maritime industry.

The proposed approach for the risk assessment for a wind assisted vessel is to undertake the following risk assessment:

- A Hazard Identification (HAZID) Study; and
- A Hazards and Operability (HAZOP) study.

The objectives of the proposed risk assessment for the vessels equipped with WASP are to:

- ✓ Identify the various relevant Hazards associated with the introduction of the Wind Assisted System, the eSAIL® for the users within the Vessels.
- ✓ To assess hazardous scenarios and the subsequent risk generated directly by or related to the introduction of the eSAIL® system to the users within the Vessels
- ✓ Eliminate or mitigate any adverse effect to the persons on board, the environment, or to the Vessels, to ensure that residual risk is As Low As Reasonably Practicable (ALARP).

In summary, the combined objective of the above is to satisfy the risk assessment expectations from the classification society and for the Flag Administration, as well as any specific requirements of the Owner, that are related to the introduction of the WASP system for the Vessel.

The scope of the HAZID and HAZOP will include, to the extent possible at this stage, the following:

- The WASP system, in the context of this document, the eSAIL developed by bound4blue.
- Associated Utilities (e.g. Electrical connections, Firefighting, etc).

The wind propulsion system should be assessed based on specific “issues of concern” and “Guidewords” to allow a focused discussion covering all relevant hazards posed by the additional WASP facilities on the Vessel and by the Vessel (and its operations) on the WASP facilities. The following section provides a brief overview of the recommended methodology that should be followed by the WASP technology developed in collaboration with the class society and the shipowner.

2.2 HAZID Methodology

The HAZID study consists of a structured brainstorming session that involves an experienced multi-disciplinary team led by an independent facilitator. The focus should be the hazards associated with the WASP and how the design addresses them.

An example of the overall HAZID review process usually followed by B4B is summarised in the key steps below:

1. Introductory briefing, including project and technology characteristics.
2. Division of the WASP installation into suitable review areas for the study.
3. Selection of a review area.
4. Discussion about the current engineering design and operating philosophy with respect to the specific review area.
5. Identification of hazards, scenarios or issues of concern.
6. Brainstorming to identify all potential causes related to the specific hazard, scenario and issue of concern.
7. Identification of worst-case credible consequences associated with the specific scenario/hazard under consideration.
8. Identification of safeguards and controls that are planned to be in place to prevent the scenario from initiating and/or to mitigate the potential consequences.
9. Performing a risk ranking for each of the identified scenarios and/or hazards.
10. Assessing whether the planned controls and safeguards are considered adequate and, if not, then look to identify complementary safeguards and controls that may be able to help reduce the risk.
11. Identification of areas where further analysis in required to better understand the risk and to record these as recommendations or actions.
12. To repeat for each of the systems until the full scope of the installation has been studied.

As detailed in the steps above, where no recommendation or action items were recorded during the HAZID, it was inferred that the controls and safety measures in place are adequate at this stage (even though the full details of some of the controls are not yet fully documented). Recommendations/actions were only recorded to enhance the design to further mitigate the risk and the specific Hazards identified.

A proposed Risk Matrix for this HAZID is detailed below (Table 1).

Table 1: Risk assessment Matrix

Hazard type	Hazard	Causes	Consequences	Safeguards	Current Risk	Recommendations	Residual Risk	Remarks

					S	L	RR	Recommendation	Responsibility	S	L	RR	

S=severity of hazard, L= likelihood, RR=relative risk

The main hazard categories to be considered are as follows:

- Structure: loads, structural integration, etc.
- Stability: centre of gravity and Damage stability.
- Equipment: control system failures, electrical, etc.
- Location/environment: port operations, hatches, crane operations...
- Materials.
- Operating parameters.
- Operating modes.
- Emergency scenarios: fire, collision, escape routes...
- Natural and environmental hazards.
- Man-made hazards.

2.3 HAZOP Methodology

The HAZOP must be undertaken on the WASP system following completion of the HAZID. A Hazard and Operability (HAZOP) study is a systematic evaluation performed to identify causes that could result in undesirable consequences to personnel, facilities, and the environment.

The process/ methodology adopted for the HAZOP workshop will be in compliance with each classification society standards and guidelines.

As a general approach, all identified hazards and/or impacts will be register by documenting the deviations, causes, consequences, applicable safeguards, risk ranking, and any recommendations. The most critical step to conduct a HAZOP study are as follow:

- Documentation: collection of all necessary documents, such as ship design plans, process flow diagrams, operational manuals, safety reports, previous incident reports, risk assessments, and relevant regulatory requirements.
- System division into Nodes: division of the system into manageable sections or nodes ensuring each node corresponds to a specific part of the process or system flow.
- Identification of possible deviations: by using standard HAZOP guide words such as NO, MORE, LESS, AS WELL AS, and OTHER THAN to explore potential deviations from the design intent and applying these guide words to various process parameters such as flow, pressure, temperature, and composition.

- Evaluation of causes and consequences: identification of the potential causes for each deviation (e.g., equipment failure, human error, external events) and the assessment of the possible outcomes and impacts of these deviations on safety, operations, and the environment.
- Safeguards identification: review current safety measures, control systems, and operational procedures that are in place to mitigate identified risks and evaluate the effectiveness of these safeguards in preventing or mitigating hazards.
- Recommend Actions: propose additional safety measures, design changes, or operational modifications to address identified risks, prioritizing the recommended actions based on their potential impact on safety and operability.

Similar to the HAZID assessment, specific documents and reports detailing findings, recommendations and action plans will be generated during the process.

2.4 Review and update of the risk assessment.

This section outlines the critical steps and methodologies for performing a comprehensive risk analysis for wind propulsion system installations on ships. By proactively addressing potential risks, we can facilitate the successful adoption of wind propulsion technologies.

Conduct regular reviews of the HAZID/HAZOP study are highly recommended, especially after significant changes in the system, operational procedures, or regulatory requirements. In the context of this deliverable, focused on the sea trial process for innovative WASP technologies, the review of the risk assessment is mandatory after completing the trial campaign.

Furthermore, continuous improvement of the risk assessment, incorporating lessons learned from incidents, near-misses, and operational feedback is a must to continuously improve safety and operability of the WASP-equipped vessel.

3 Phase 1: Pre-sailing check

The purpose of this phase is to check that all the relevant systems and devices of the WASP system installed on the vessel work properly and that the systems/devices are in compliance with all the safety standards.

These checks should be normally carried out in port or in a shipyard when the vessel is not sailing. According to the specifications of the WASP system, a significant part of the components must be checked during the manufacturing stage, therefore, prior to sailing. Therefore, only the systems that may be affected by the logistical operations and by the WASP installation process (lifting, assembly, etc.) need to be checked.

The safety aspects to be considered are outlined below.

3.1 Mechanical pre-sailing check

Considering that the WASP system, before being delivered to the port/shipyard, is already fully assembled and ready to be mounted on the ship, the checklist of the mechanical components to be inspected is limited to the bolted joints connecting the WASP to the vessel deck.

Other quality tests are covered by the Factory Acceptance Test (FAT), performed at workshop and prior to the WASP delivery. This inspection aims to identify any potential issues that could compromise the performance, safety, and overall functionality of the vessel.

Due to the wide variety of WASP systems, the assembly of secondary elements necessary for the normal operation of the system, such as masts to hold the weather sensors and lighting rods, aerodynamic accessories, lifting tools, etc., falls outside this scope of this mechanical checks and should be defined according to the specific requirements of the WASP system.

Given that most mechanical aspects are subject to factory inspection (FAT test) and that the most common type of connection between the WASP and the deck is achieved using a bolted connection, at first it is essential to verify the bolted connection, once the tightening torque has been set and verified by the installers.

Few additional best practice recommendations:

- Perform a second check of some bolts (at least 20% of the total) to validate the correct application of the tightening torque.
- Mark with industrial paint or specific markers all bolts after assembly to have a visible reference in case the bolt loosens, as shown in the Figure 2.
- Perform a visual inspection to detect any anomalies during the installation process, as well as a general check of the WASP device to reveal possible loose elements or damages that may affect the WASP integrity and operation.
- Test all the operational mechanisms associated with the metal structure, such as hatches, doors, and manual movable components.
- Examine the protective coating and address any areas with coating damage, to promptly prevent corrosion.

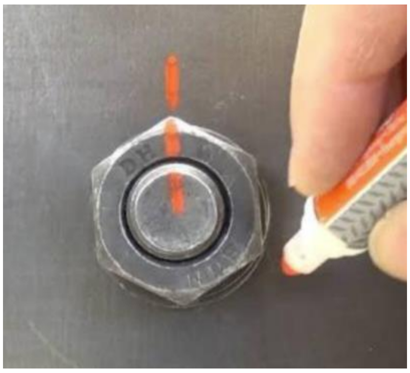

Figure 2: Example of bolt marking as a visual reference to verify loosening.

As a last point, it is necessary to review and compile all installation records, to ensure that the installation process complies with the regulatory standards and classification society requirement, and to document the results of the mechanical pre-sailing checks for future reference and regulatory compliance.

By meticulously performing these mechanical checks, shipowners and operators can gain confidence about the seaworthiness and reliability of the WASP system, ultimately contributing to the safety and successful operation of the vessel with WASP at sea.

3.2 Electrical pre-sailing check

The requirements for electrical integration of the WASP device into the vessel overall electrical and control network require a more in-depth checking protocol. In this section, different tests needed to satisfy the Site Acceptance Test (SAT) protocols are described.

3.2.1 Initial general inspection

After the system installation on the vessel, a verification is conducted onboard, ensuring that the WASP system and the associated electrical equipment are installed correctly. Such an activity includes several checks, listed below:

- Ensure safe and proper wiring throughout the installation.
- Proper labelling of control board and door elements.
- Ensure that the cabinet is free of tools and of other elements.
- Ensure the absence of provisional electric bridging on the board.
- Check that the features plate is installed on the cabinet.
- Install electric danger signs on the cabinet.
- Take photos of the cabinet and of the electrical installation.
- Complete the electrical installation and fill in the instrumentation check sheet.

3.2.2 Verification of the specifications

It is recommended to perform a visual check, to verify the features of each piece of the electrical instrumentation. It is strongly advised to compare the observed features with the "Design Value" specifications for motors, electric instrumentation, and the auto greasing system, if any.

3.2.3 Power check

Testing procedures are conducted to validate the functionality of all components within the electrical cabinet. In particular, it is recommended to perform a:

- 400 V power validation check, including an examination of the general switch, the differential protection, the circuit breakers, the variable frequency drive, the air conditioner, the primary coil transformer, the input power supply, the energy meter and the surge arrester.
- 230 V power verification, including a power check of the transformer output, differential protection device, cabinet plug, cabinet light and self-greasing unit.
- 24 V power validation, including tests of the power supply output, the functionality of the Uninterruptible Power Supply (UPS), the electronic fuses, the power bridge cabinet, the variable frequency driver, the communication/CPU, the digital input/outputs, the analogue inputs, and the sail lights.

3.2.4 Operation tests

These include the functional assessment of the various elements and devices that make up the control system, in particular the following tests are to be performed:

- An instrument reading of values, conducted upon instrumentation installation and check.
- A Human-Machine Interface (HMI) and tablet function test executed once the instrumentation is checked. Such a test includes a check of the status and of the functionality of the bridge HMI, of the tablet status and of the connections to the WASP device.
- Test of actuators operation, conducted in the port or shipyard with the WASP in operation.
- An alarm diagnosis, which consists in the activation of all alarms, a check assessing that their status correctly appears on the HMI, ensuring a proper system response. Any faults or warnings that occur should be recorded.
- Other functionality tests i.e. data-log records, WASP virtual connection, energy meter and remote connection to the device.

3.2.5 Control Logic tests

The purpose of the control logic tests is to confirm the correct functioning of the control logic programmed within the PLC (Programmable Logic Controller). This test must be performed while the WASP is in operation.

Three different test modes are listed below:

- Disable mode: with the fan off, flap to lateral position and eSAIL® in position 0º.
- Manual mode: with the suction on/off, RMP modification, insert target position, flap change lateral position and flap insert target position.

- Automatic mode: once the above tests have been completed, several test scenarios created to simulate different weather conditions can be used. This will allow an assessment of whether the WASP responds adequately to various “virtual” navigation situations, also verifying the trim control algorithm, the selected control strategies (i.e., max. savings), the automatic mode status and the transition between modes.

3.3 Class rules requirements check

The Class rules applicable to each vessel should be verified on a case-by-case basis, before the sea trials, to evaluate any possible additional measurement or test due to specific circumstances, operational context, environmental conditions, or in case of specific provisions by the Flag Administration which are to be verified by the Class society acting as its Recognized Organization.

A detailed testing program is to be approved by the classification society and it is to include:

- mechanical and electrical installation visual inspection, according to the approved drawings
- pre-sea trials tests at quayside, to verify the correct functioning of all WASP components
- sea trials aimed at verifying the safe operation of WASP at different configurations

Timely collaboration with the vessel’s classification society is essential to ensure that all aspects and regulatory requirements are addressed comprehensively, leading to a thorough and tailored evaluation of compliance.

4 Phase 2: Assessment of Vessel Manoeuvrability

The objective of this phase is to establish the testing procedures of the vessel manoeuvrability with the WASP integrated on board. No significant alterations to the overall operation of the ship, the underwater hull, or the main propulsion system are assumed. Minimal modifications to the exposed air drag surface might slightly impact steering capability in strong breeze conditions, irrespective of the sail fan being on or off. Consequently, this assessment will focus solely on navigational aspects, such as manoeuvrability and speed.

4.1 Conditions

Here, the conditions for evaluating the manoeuvrability capabilities of the vessel fitted with a WASP system are detailed.

Loading: the ship is prepared to achieve a condition as close as possible to either the ballast departure or the ballast arrival state, in accordance with the stability booklet. The drafts are accurately recorded prior to navigation.

Current: Ideally, open waters for testing should be devoid of significant currents. If currents are present, tests shall be conducted in both directions to account for any potential effects resulting from the current.

Meteorological conditions: For detailed WASP system design parameters, refer to the manufacturer's instruction manual. Below, an example from the B4B’s eSAIL® is provided:

- If conditions permit and if the apparent wind speed remains below than 31.6 knots, activating the fan can lead to fuel-saving scenarios. This mode involves a combination of mechanical propulsion via the propeller and sail, termed as **"WASP + motor" mode.**
- Under the same conditions, if the fan is switched off, fuel-saving benefits will significantly diminish as the sail lifting coefficient drops to very low levels, while the drag coefficient remains relevant. This mode will be referred to as **"motoring" mode**.

During these trials, the ship navigational capabilities are maintained in both situations.

- Should the apparent wind speed exceed 31.6 knots, the fan must be automatically switched off. Despite this, the ship should maintain a steady course and continue to progress. It is worth noting that the sail and its associated structure have been engineered to withstand extreme conditions of wind up to 97 knots (50 m/s).

Maximum wind speed: During the open water trial, it is recommended that the TWS generally exceeds 22 knots (maximum Beaufort scale 5) for a ship speed of 10 knots.

For example, the maximum TWS corresponding to the AWA at a ship speed of 8 knots are reported in

Table 2.

Table 2: Maximum TWS according to the AWA and TWA for a ship speed of 8 knots.

AWA	TWA	Max TWS [knots]
22.5	30	24
45	57	26
67.5	82	29
90	104	32
112.5	125	35
135	144	37
157.5	162	39
180	180	39

Minimum wind speed: A minimum TWS of 10 knots is desirable for open water testing. Meteorological conditions, particularly TWS, must be continuously monitored during the sea trials.

4.2 Open water trials

Special attention must be directed towards evaluating the ship manoeuvrability with both the WASP in operation and disconnected. Given that there have been no modifications to the underwater hull or to the main propulsion system, the scope of trials should be confined accordingly.

4.3 Harbour manoeuvring

The navigation is conducted with the WASP in its standard position. Typically, during slow manoeuvres in harbours, the WASP system is deactivated. The WASP is engineered for fuel efficiency, therefore its use in brief transitions from the quay to the sea can be bypassed. In these tests it is important to show that ship maintains a similar steering capability to that before the WASP installation.

4.4 Steering testing

As already detailed previously, during regular navigation under safe conditions, the WASP system can either be operational or turned off, representing two modes:

- "Motoring mode"
- "WASP + motoring" mode

In both modes, the ship is expected to maintain a consistent course and be capable of altering its direction, as required. Given the different performance of the WASP systems in these two conditions, distinct procedures should be followed, as suggested below.

4.4.1 Procedure for motoring mode (WASP switched off)

In this context, two key aspects require examination.

- **Motoring into the wind:** the ship should maintain a direct course into the wind (wind dead ahead), ensuring that it can sustain both speed and course, as deemed safe.
- **Maintaining course with lateral force:** it is important to note that maximum lateral force will manifest with apparent beam wind.

The WASP measurement instruments installed on board must ensure that the ships course remains at a 90º angle with respect to the apparent wind TWA. Please note that the TWA may vary, based on the wind strength and ship speed. For reference, combinations of TWS, TWA and AWS are provided in Table 3, considering a ship speed of 8 knots and AWA of 90º (beam reaching**).**

Table 3: TWS, AWS and true wind direction (TWD) for a ship at a fixed ship speed of 8 knots at an AWA of 90º and considering 0º the forward part of the hull of the vessel (or bow).

TWS	AWS [knots]	TWD [0º = Bow]
32	31	104
26	25	108
23	22	110
19	17	115
17	15	118
13	10	129
10	7	139

After reaching the prescribed course and ensuring vigilance for potential wind variations, the heading will be recorded as an average value.

Additionally, the average rudder angle will be noted, while plotting the true heading of the ship in correlation with Course Over Ground (COG) and Speed Over Ground (SOG). Due to its minor effect on the lateral force, assessing alternative Apparent Wind Angles (AWA) would be excluded.

4.4.2 Procedure for "WASP + motoring" mode (WASP switched on)

In this mode, the highest lateral force typically occurs for value of the AWA from 35 to 60º, considering 0º as dead ahead. Therefore, the manoeuvrability is evaluated within this range of AWA.

With the fan operating at approximately 90% of the main engine power, the ship maintains a course with AWA at 35º from bow to either side. During this process, the average heading and rudder angle will be recorded, and the true heading will be plotted in correlation with the COG and the SOG. The assessment focuses on the ability of the vessel with WASP to maintain the designated course and its capacity to change direction as required.

This same procedure is repeated for each 10º increment in AWA up to 60º from bow to each side. The trial data at each AWA are saved in a report, whose template is shown in Figure 3.

True Wind Sped (knots)	TWS				
True Wind Direction	TWD				
Sea State					
Apparent Wind Angle	AWA				
Apparent Wind Speed (knots)	AWS				
	Time	COG	Heading	Leeway	Rudder Angle

Figure 3: Report template for the trial data collected in the “WASP + motoring mode”.

4.5 Crash stop tests

These tests aim to assess the ship crash stopping capability. In fact, with a stern wind, the crew must deactivate the WASP if the ship needs to halt. The eSAIL® has the ability to automatically orient itself to generate zero lift, helping the halting procedure significantly.

The crash stops tests consist in recording the total distance and time taken from the command of stop at full speed to the actual moment at which the ship reaches zero speed.

4.6 Turning circle tests

If requested by a Class Society, the ship turning capability must be evaluated, following the WASP installation. However, if restrictions are in place, this assessment can be conducted by disconnecting the WASP. By doing so, the remaining small sail area has a minimal impact on manoeuvrability, especially if this has been observed during prior tests.

Assuming no modifications have been made to the steering gear, the integration of the WASP system is verified not to significantly alter the ship turning ability.

5 Phase 3: Functionality and savings test

5.1 WASP test methodology

The purpose of this phase is to define the testing procedures to evaluate the functionality of the WASP systems installed on a vessel. WASP systems, such as suction sail (i.e. B4B's eSAIL®), present unique requirements for sea trial testing, tailored to accommodate shipowner specifications, vessel availability, and ensuring robust results.

Currently, there are several approaches to measure and validate the potential savings of WASP technology, in fact, each classification society usually offers a methodology based on different procedures from lab simulations, direct measurements during sea trials, validation through digital models, among others.

The unique aerodynamic characteristics of bound4blue´s suction sail technology make validation laboratory wind tunnel testing extremely difficult, resulting in inaccurate results. Therefore, the proposed sea trial methodology involves multiple runs, each of which includes two legs in opposing directions (see

). Each leg is divided into two phases, one with the WASP activated, the other one with the WASP deactivated. This test configuration allows to capture possible meteorological effects during the data collection. In addition, the WASP activation and deactivation occurs at the same location but with different headings, further enhancing data acquisition.

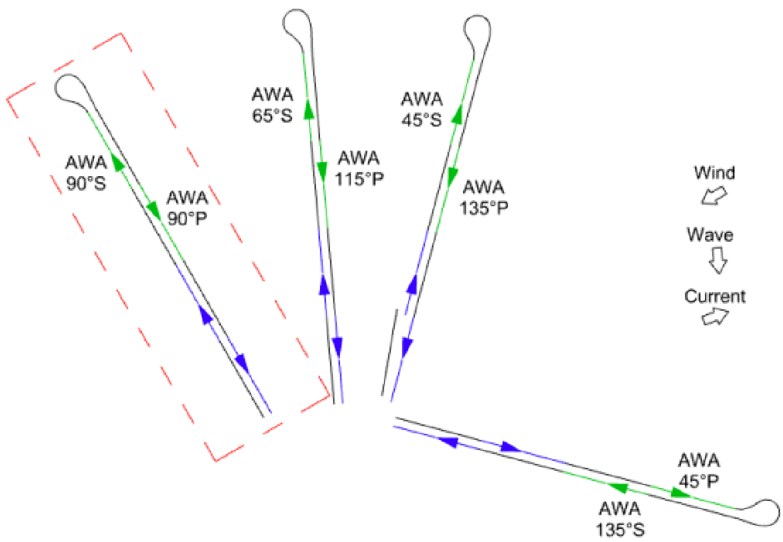

Figure 4: Illustration of the proposed short-term sea trial approach. The blue/green lines indicate the leg with the WASP system activated/deactivated respectively. The red dashed rectangle contains one entire run.

To assess the impact of hull and propeller conditions on sea trial durations, an analysis of sea trial data is necessary, specifically focusing on runs where the WASP system is deactivated, and the vessel encounters head and following seas.

These data should be compared with the existing speed-power curves, derived from model testing, Computational Fluid Dynamics (CFD) simulations, or previous sea trials. This comparison aims to evaluate the extent of propulsion power loss due to fouling (following the Class Society standards) or any alterations in the propulsion power. Additionally, when the WASP system is inactive, deductions must be made for its aerodynamic drag.

It is important to acknowledge a certain level of uncertainty inherent in sea trials, given the variations in currents, speeds, and directions. This uncertainty can be mitigated by analysing the speed over the ground and the speed through the water for each run during the trial.

5.2 Sea trial runs

Given the time constraints, it is estimated that conducting a maximum of four runs, as showed in Figure 4 (*e.g.*, true wind angles 45°S/135°P, 65°S/115°P, 90°S/90°P, 120°S/60°P, where P denotes wind from the port side and S for starboard), at a certain engine speed is feasible within a single day.

In particular:

- Each run is estimated to last about 90 minutes, resulting in a total duration of 7.0 hours for 4 runs or 8.5 hours for five runs. It is crucial to allocate time for unexpected complications during the trial.
- Maintaining the ship engine speed (constant RPM) may result in speed fluctuations, these discrepancies will be rectified to achieve the desired speed using an established speed-power curve.

The number of data points gathered during the sea trial depends on various factors, such as the shipowners' preferences for the TWA, weather conditions on the trial day, ship headings, data quality and acquisition efficiency. The selection of pertinent TWA directions to cover and the trial duration shall be established.

Note: The tilting or retractable system functioning it to be verified for all operation modes and configurations foreseen for the use of WASP elements.

5.2.1 Tests required by Class

Classification societies establish testing requirements to ensure the safety, reliability, and performance of marine vessels and offshore structures. These requirements encompass a comprehensive set of standards and procedures for materials, construction, and equipment.

Tests typically include structural integrity assessments, globally and locally, such as hull stress analysis and fatigue testing, as well as evaluations of machinery, electrical systems, and safety equipment.

The sea trial tests are critical for compliance with classification requirements, serving as the ultimate validation of a vessel's seaworthiness and operational capabilities. During sea trials, the vessel is subjected to real conditions to assess her performance, manoeuvrability and stability.

These trials include:

- speed tests
- turning circles
- crash stops
- endurance runs

The results from these tests are to be meticulously documented and analysed to confirm that the vessel meets all regulatory standards and specifications set forth by the classification society and Flag, as applicable. Successful completion of sea trials is essential for obtaining the necessary certifications and approvals for the vessel and her systems to enter into service.

According to RINA Rules for the classification of ships [3], the following tests are to be performed during sea trials:

- recording of performances with WASP on (active) and off (tilted or retracted) during navigation at established service speed of ship
- all operational modes and configurations of WASP foreseen during navigation
- manoeuvrability tests with WASP on (active) and off (tilted or retracted)
- emergency stop/shutdown of WASP elements from control station

Before conducting sea trial tests, in general, an inclining test must be performed to assess the stability of the vessel with a newly installed system onboard. This test involves determining the vessel's metacentric height (GM) by measuring its response to known weights placed at specified locations. The inclining test provides critical data on the ship's center of gravity and overall stability, ensuring that the newly installed system does not adversely affect the vessel's stability. This step is crucial for maintaining safety and performance standards for the vessel safety.

5.3 Vessel performance monitoring system

To ensure compliance with ISO15016 [1] and ISO19030 [2] standards, it is essential to implement a continuous performance monitoring tool onboard. This tool should systematically record and assess both the ship and the WASP performance, according to stipulated standards. The system will be used during the sea trial to acquire data related to:

- The vessel with WASP installed, but not in operation.
- The vessel with WASP installed and operating.

As a general recommendation, the monitoring system must acquire the channels listed in Table 4 and in Table 5.

Table 4: ISO19030-2:2016 [1] required channels assuming a fixed pitch propeller.

	Parameter	**Measurement device/source**
Primary parameters	Vessel speed through water	Vessel speed log
	Delivered power based on circulation of shaft torque	Torsion meter (and shaft revolutions)
	Time and date	(D)GDS
Secondary parameters	Shaft revolutions	Pick-up, optical sensor, ship revs counter
	Relative wind speed/direction	Ship anemometer
	Heel and pitch angle	Weather station
	Speed over ground and ship heading	D(GPS), gyro compass, or compass
	Rudder angle	Rudder angle direction
	Water depth	Ship echo sounder

	Static draught fore and aft	Information from loading or stability computer or equivalent sources for static draught such as an electronic sounding tube
	Water temperature	Thermometer

Table 5: Additional channels to ISO19030 [2] for the WASP systems

Status	**Parameter**	**Measurement device/source**
Required	Status of SS (on/off)	SS control system
	Power consumption SS (To determine net power saving)	SS control system
	Position (longitude and latitude)	(D)GPS
Required if specific analysis is needed	Pitch and roll angle (to determine SS performance with vessel motions)	Inclinometer
	Sea state (wind seas and swell; height, period, spectrum)	Wave radar or hindcast data source (TBC)
Optional	Fuel consumption (optimal if have reliable shaft power)	Fuel meter for the total fuel supply (main and auxiliaries)
	SS delivered force to ship	B4B measurements if available
	Air pressure	Barometer
	Ambient air temperature	Thermometer
	Environmental data (hindcast; wind speed/wind direction/water depth/atmospheric pressure/atmospheric air temperature/water density)	Hindcast data source (TBC)/ship sensor

According to specifications of ISO15016 [1] and ISO19030 [2], data must be acquired from three distinct sources:

1. Ship data status from an external continuous performance monitoring system
2. WASP system performance gathered from a secondary continuous system
3. Noon reports to supplement data not available through the preceding two sources

In the cases where weather data is not accessible via the sensors onboard, could be integrated or estimated using available weather datasets, like MetOcean or similar ones to ensure comprehensive data coverage.

It is recommended to incorporate a sufficient level of redundancy in the data storage system, to ensure data provision in case of in case of malfunctions of the acquisition systems. In addition, maintaining data storage for a minimum period of 12 months is recommended for archival and reference purposes.

5.4 Performance data analysis

After conducting the sea trial and gathering the comprehensive dataset of raw performance data, an in-depth analysis of the WASP data is needed. This analysis aims to facilitate a calculation of power-saving.

The data analysis will adhere to the standards outlined in ISO19030 part 2, which describe a procedure to identify outliers and to verifying data quality, to guarantee the integrity of the data streams utilized for analysis.

Corrections for hull and propeller fouling, for environmental conditions and for vessel load condition (ISO 19030) should be applied when needed. Depending on the trading pattern of ship, hull and propeller fouling could substantially contribute to an increased Fuel Oil Consumption (FOC) over the sea trial period. Should fouling significantly impact the data, it will be crucial to adjust for the fouling influence to ensure accurate comparisons.

The performance study of the WASP system typically involves comparing the reduction in shaft power at consistent vessel speeds to derive the gross savings (see Figure 5). Measurements can be corrected for the same vessel speed by using a speed versus shaft power curve derived from CFD, from model tests, or from other sea trials data.

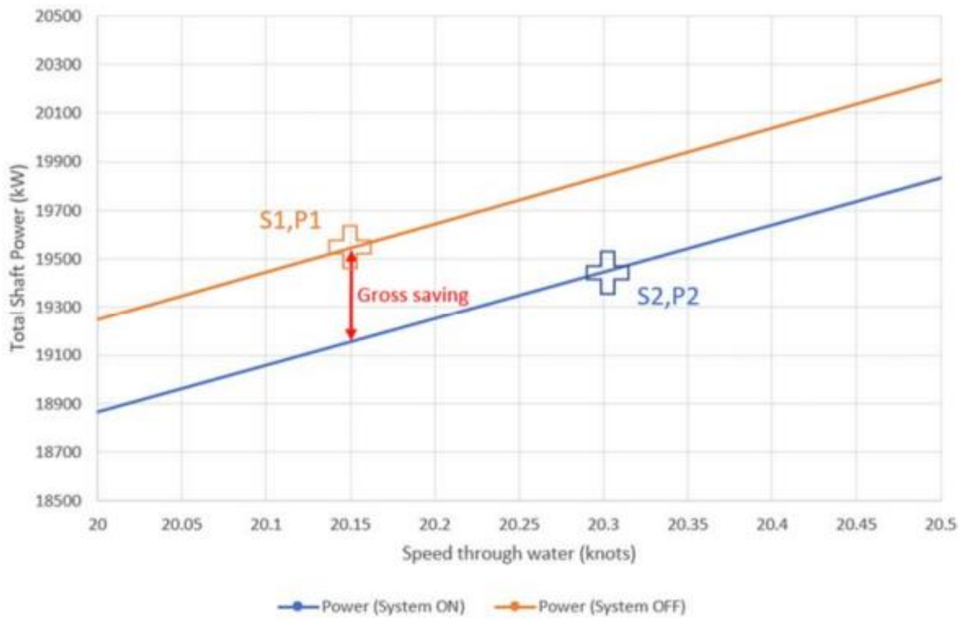

Figure 5: Example of a speed vs shaft power curve, illustrating the difference between the cases WASP active (S2 and P2) inactive (S1 and P1).

To calculate the overall Net Saving Power (NSP), the data analysis must provide information on the power associated to the WASP system. Additionally, the potential increase in aerodynamic drag because of the WASP compared to a vessel without the WASP is considered as shown in Figure 5.

Using these pieces of information, a comparison can be made between the NSP coming from the sea trial the expected values derived with a theoretical model, as shown in Figure 6.

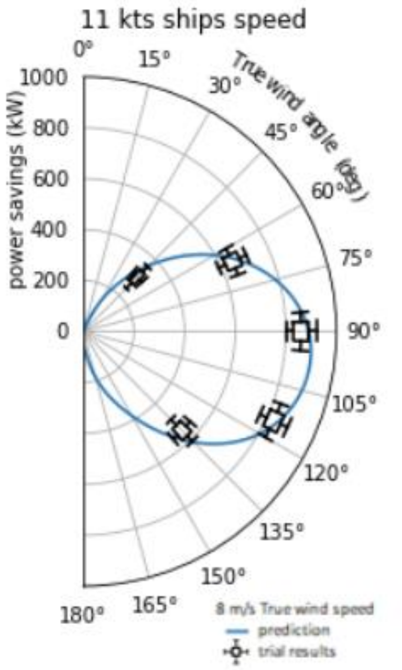

Figure 6: Example of a NSP polar plot obtained from a sea trial, displaying its associated variance, and compared to the theoretical values.

5.4.1 Calculations for IMO's EEDI, EEXI, and CII Indices

New mandatory measures to cut the carbon intensity of international shipping have been adopted by the International Maritime Organization (IMO), including new Energy Efficiency Indices:

- Energy Efficiency Design Index (EEDI)
- Energy Efficiency Existing Ship Index (EEXI)

These indices are the metrics used for the ship efficiency or emission assessment. They are based on design parameters of the vessel and refer respectively to new and existing ships. They measure CO2 emissions per cargo ton and mile.

EEXI is a measure introduced by the IMO to reduce the greenhouse gas emissions, related to the technical design of a ship, entered into force in 2023. EEXI is mandatory and applicable to existing vessels above 400 Gross Tonnages (GT). The required EEXI value is determined by the ship type, the ship's capacity and principle of propulsion and is the maximum acceptable attained EEXI value. The attained EEXI must be calculated for the individual ship, which falls under the regulation in the applicable scenario for each ship.

Statutory compliance is achieved by:

- calculating the EEXI value,
- comparing the required and attained EEXI values,
- generating the EEXI technical file and
- submitting the technical file for the approval of the Administration.

Class compliance depends on the technical solution adopted, in particular on changes in the vessel's structure or on any important component or system on board. The documentation is to be submitted for approval, and after approval of the documentation and installation/changes on board, a surveyor has to verify the changes implemented.

The final implementation consists in the verification that the ship's attained EEXI and technical file are in accordance with the requirements. This shall take place at the first annual, intermediate or renewal survey after 1st January 2023. The survey is part of the scope of the IAPP survey, and compliance is documented by issuance of the IEE certificate.

In addition to these Indexes, the Carbon Intensity Indicator (CII) is an attempt to measure how efficiently a ship transports goods or passengers; it is expressed in grams of CO2 emitted per cargo-carrying capacity and nautical mile.

The calculations of the new IMO indices — EEDI, EEXI, and CII — are detailed and rigorous, involving specific formulas and a variety of input parameters to ensure accurate assessment of a ship's energy efficiency and carbon emissions.

EEDI and EEXI are calculated using the basic principle:

$$\text{EEDI} = \frac{\text{CO}_2 \text{ emissions per voyage}}{\text{transport work}}$$

Where:

- CO2 emissions per voyage are determined based on the ship's fuel consumption and the carbon content of the fuel.
- Transport work is the product of the ship's capacity (in deadweight tonnes or DWT) and the distance travelled.
- This value is influenced by factors such as the ship's speed, hull design, engine type, and energy-saving technologies.

The EEXI verification for existing ships involves:

- Evaluating the ship's current design and equipment efficiency
- Considering potential retrofits or modifications to improve energy efficiency
- Applying correction factors for older ships to align them with current standards

The Carbon Intensity Indicator (CII) is calculated on an annual basis and is defined as:

$$\text{CII} = \frac{\text{annual CO}_2 \text{ emissions}}{\text{annual transport work}}$$

where

- Annual CO2 emissions are calculated from the total fuel consumed over the year, considering the carbon factor of each fuel type used.
- Annual transport work is the total cargo carried multiplied by the distance travelled over the year.

Its evaluation results in an annual rating, Vessels, based on their performance, will receive an environmental rating of:

- A (major superior)
- B (minor superior)

- C (moderate)
- D (minor inferior)
- E (inferior performance level)

The rating thresholds will become increasingly stringent towards 2030. The CII is an operational efficiency index which applies to all cargo, Ro-Pax and cruise ships above 5,000 GT and came into effect in 2023 as well.

Calculation of effective power of WASP

The available effective power of wind assisted propulsion systems as innovative energy efficient technology is calculated by the following formula:

$$(f_{eff} \cdot P_{eff}) = \left(\frac{1}{\sum_{k=1}^{q} W_k}\right) \cdot \left(\left(\frac{0.5144 \cdot V_{ref}}{\eta_D} \sum_{k=1}^{q} F(V_{ref})_k \cdot W_k\right) - \left(\sum_{k=1}^{q} P(V_{ref})_k \cdot W_k\right)\right)$$

The fore term of the formula defines the additional propulsion power to be considered for the overall calculation.

The term contains:

- the product of the ship specific speed
- the force matrix
- the global wind probability matrix

The aft term contains the power requirement for the operation of the specific wind assisted propulsion system which has to be subtracted from the gained wind power.

The aerodynamic forces of a wind assisted propulsion can be evaluated with a full-scale test during sea trials.

These calculations ensure that ships are evaluated on a standardized basis, promoting transparency and consistency in efforts to improve energy efficiency and reduce greenhouse gas emissions in the maritime industry.

A comprehensive guide for the calculation on treatment of innovative energy efficiency technologies for calculation and verification of the attained EEDI and EEXI can be found in the IMO MEPC.1/Circ.896 [6].

5.4.2 Periodic reporting on operational conditions

The significance of the sea trials will be determined by the diverse range of conditions encountered by the vessel throughout the testing phase. These conditions provide valuable insights into its continuous performance and any noteworthy deviations.

5.4.3 Quality Assessment of the Data Analysis

it is essential to verify the accuracy and validity of the analysis performed, to ensure the reliability of the conclusions drawn.

5.5 Example Table of Contents for the Report

To ensure an appropriate documentation of the sea trials, B4B recommends detailing a minimum of key points and sections to ensure full knowledge of the procedure followed, the quality of the data obtained and to give confidence to potential stakeholders in the true performance measurements of the WASP. Therefore, at least the following key points should be included in a test report for a WASP system:

- Protocol review.
    - Vessel track and days active/sailing.
    - WASP system use status.
- Data collection.
    - Vessel condition (load conditions, fouling, etc.).
    - Instruments used and their calibration reports.
    - Data acquired.
    - Data filtering according to ISO19030.
- Data analysis.
    - Currents.
    - Wind analysis.
    - Correction for the environmental conditions according to ISO19030.
    - Correction for fouling according to ISO19030.
    - Correction for vessel load condition according to ISO19030.
    - Vessel speeds.
    - WASP not in operation power correction.
    - Speed vs. power analysis by wind angle at a reference wind and vessel speed.
    - Polar plot presentation of the total WASP power (comparison to theoretical values)
- Total fuel savings.

After sea trials all relevant testing protocols are to be kept on board together with the operating and maintenance manual.

6 Closing remarks

The current deliverable describes an overall sea trial protocol designed to prove and validate a WASP system on a vessel, taking advantage of B4B expertise with eSAIL®.

Additionally, it incorporates a safety checklist encompassing mechanical and electrical aspects, along with a basic guide to evaluate the manoeuvring capabilities of a WASP-equipped vessel. These guidelines reflect B4B existing experience and highlight the need for ongoing refinement and enhancement.

To conclude this comprehensive sea trial protocol, it is essential to recognize its generic nature, designed to serve as a framework for the evaluation of different wind propulsion technologies for maritime applications.

Each technology provider is encouraged to meticulously adapt this plan to the special features of their WASP system and the characteristics of the vessel. Considerations on the complexity of the different WASP designs, materials and operational parameters must be seamlessly integrated into the testing procedures.

Furthermore, compliance with relevant standards, regulations, and classification society requirements should be a paramount concern during the adaptation process. This report outlines the class requirements, however, it is essential to consider the current regulations and collaborate with the vessel's classification society, as they may require additional measures to minimise potential risks. By tailoring this plan to suit individual technological differences, it is possible to ensure an accurate and relevant assessment of the WASP system performance and to contribute to the collective progress of the wind propulsion technology as a sustainable solution for the maritime industry.

References

[1] International Standard ISO 15016, “Ships and marine technology – Guidelines for the assessment of speed and power performance by analysis of speed trial data”, 2015.

[2] International Standard ISO 19030, “Ships and marine technology – Measurement of changes in hull and propeller performance, Part 2: Default method”, 2016.

[3] RINA rules for classification of ships Pt F, Ch 13, Sec 45.

[4] IMO RESOLUTION MEPC.333(76) 2021 Guidelines on the method of calculation of the attained ENERGY EFFICIENCY EXISTING SHIP INDEX (EEXI).

[5] IMO RESOLUTION MEPC.308(73) 2018 guidelines on the method of calculation of the attained ENERGY EFFICIENCY DESIGN INDEX (EEDI) for new ships.

[6] IMO MEPC.1/Circ.896 2021 guidance on treatment of innovative energy efficiency technologies for calculation and verification of the attained EEDI and EEXI.

[7] EMSA - potential of wind-assisted propulsion for shipping.