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FURTHER CONSIDERATION OF THE DRAFT GUIDELINES SUPPORTING THE UNIFORM AND EFFECTIVE IMPLEMENTATION OF IMO'S MID-TERM MEASURES

Example methods for estimating the wind propulsion contribution to the attained GFI, with supporting case studies

Submitted by IWSA

SUMMARY

Executive summary:	This document sets out, in the annex, example methods for calculating the wind propulsion contribution to the GHG fuel intensity (GFI) equation under each of the four tiers outlined in the guidance document ISWG-GHG 23/3/4 (Norway). For each tier, it describes the calculation process, the required input and equipment, and the approach to verification and accuracy. A set of case studies is also provided in the annex, providing added context, including a Tier I method applied to three wind propulsion systems (WPS), benchmarked against a high-fidelity prediction. Also included is a comparison of Tiers II and III on one ship, using hindcast and measured wind, respectively and another compares Tiers I to III for the same WPS installation. The tiered structure in general enables the assessment effort to be matched to the accuracy required, with a reliability factor to be assigned for each tier, thus delivering comparable results. This document's purpose is to support the proposed guidance relating to wind propulsion energy provision in the GFI by demonstrating how each tier would be applied in practice, and to indicate where further development is required.
Strategic direction, if applicable:	3
Output:	3.2
Action to be taken:	Paragraph 3
Related documents:	MEPC 81/INF.39; MEPC 82/7/9; MEPC 83/7/33, MEPC 83/INF.33; MEPC 84/7/21, MEPC 84/7/22, MEPC 84/WP.5; ISWG-GHG 20/2/17; ISWG-GHG 21/2/1, ISWG-GHG 21/2/7, ISWG-GHG 21/INF.2 and ISWG-GHG 23/3/4

Introduction

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2 A set of case studies is also provided in the annex to this document, providing added context, including a Tier I method applied to three wind propulsion systems (WPS), benchmarked against a high-fidelity prediction. Also included is a comparison of Tiers II and III on one ship, using hindcast and measured wind, respectively and another compares Tiers I to III for the same WPS installation.

Action requested of the Working Group

3 The Working Group is invited to note the information provided in this document.

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ANNEX

EXAMPLE METHODS FOR ESTIMATING THE WIND PROPULSION CONTRIBUTION TO THE ATTAINED GFI, WITH SUPPORTING CASE STUDIES

Introduction

To accurately measure, calculate and report the contribution of wind propulsion energy into the calculation of the Greenhouse Gas Fuel Intensity (GFI) achieved ($GFI_{attained}$), three initial methods at different levels of complexity were proposed in MEPC 83/7/33 and its Appendix MEPC 83/INF.33 (Tiers I, II and III). A fourth method has since been added, following the proposal in ISWG-GHG 21/2/7 (China) that was adopted in MEPC 84/WP.5. Because the new method is a variation of Tier II, it has been inserted as Tier III, and the method originally designated Tier III is now redesignated as Tier IV. This document uses this new four-tier numbering throughout.

By adopting this multi-level assessment approach, the user has the flexibility to choose the inherent trade-off between reliability of the results vs. cost of the analysis according to their specific needs and means. To balance the level of accuracy of the calculations of each tier, and thus to:

a) make the results from the calculations of different methods comparable and;
b) create an incentive for performing the more accurate, but more complex analyses of subsequent tiers.

After a period of experience building a Specific reliability factor will be allocated to each tier and these will be adjusted to align with observed results from different those tiers. Table 1 gives an overview of these methods (Tiers I–IV).

ISWG-GHG 23/3/4 draft guidance is based upon the MEPC 84/WP.5 Appendix 3, the 'Draft Guidance on how to Monitor, Report and Verify the Energy Derived from Wind Propulsion Systems (WPS)', which in turn is based upon the documents MEPC 82/7/9, MEPC 83/7/33, MEPC 83/INF.33, ISWG-GHG 21/2/7.

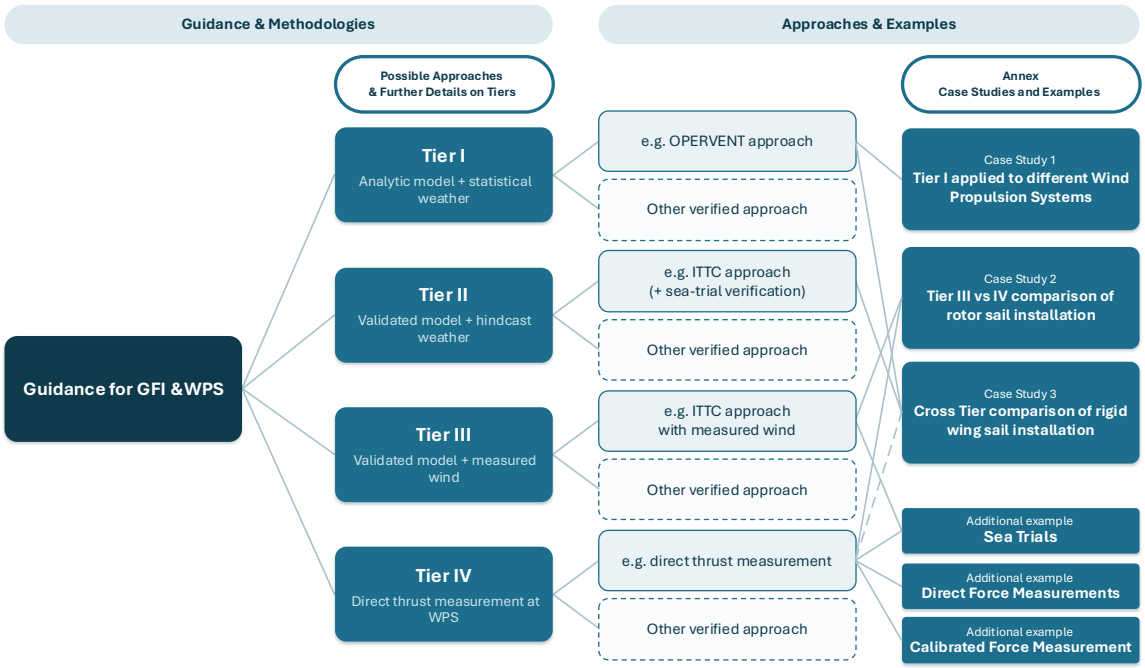


Figure 1: Overview of Guidance and Example Approaches.

The purpose of the methods explained here is to calculate the propulsive energy derived from a WPS. Four tiers of measurements/calculations can be applied as shown in Table 1:

i. Tier I: Simplified analytic power model combined with statistical weather data;
ii. Tier II: Ship-specific power model validated by sea trial, combined with hindcast weather data;
iii. Tier III: Ship-specific power model validated by sea trial, with measured wind-field data under operational conditions; and
iv. Tier IV: Direct thrust measurement on or in the vicinity of the WPS.

Table 1: Overview of methods for each Tier (for reference reproduce from ISWG-GHG 23/3/4 guidance paper)

	TIER I	**TIER II**	**TIER III**	**TIER IV**
Purpose	Simplified analytic power model combined with statistical weather data	Ship-specific power model validated by sea trial, combined with hindcast weather data	Ship-specific power model validated by sea trial, with measured wind data during operation	Direct thrust measurement
Reliability factor	Not defined	Not defined	Not defined	Not defined
Power model	ITTC 7.5-02-03-01.9 [9] Level I or higher. Alternative methods may be accepted.	ITTC 7.5-02-03-01.9 [9] Level II or higher, verified and correlated based on a short sea trial, for example as per ITTC 7.5-04-01-02. Alternative methods may be accepted.	ITTC 7.5-02-03-01.9 [9] Level II or higher, verified and correlated based on a short sea trial, for example as per ITTC 7.5-04-01-02. Alternative methods may be accepted.	Direct thrust measurement
Data resolution	Departure and arrival, [and when traversing predefined geographic zones]	one hour	one hour	one minute average
Position and speed data	Port and time of departure and arrival	Onboard data acquisition system	Onboard data acquisition system	Onboard data acquisition system
Weather data	Statistical from hindcast	Statistical from hindcast	Onboard monitoring	N/A

There will be an experience building period during which further operational data, simulations and other relevant feedback will be delivered. This will enable each of the tiers to be adequately assessed for accuracy and reliability. With current standing, higher tiers are assumed to provide increased accuracy but also come with increased requirements for monitoring and calculation model complexity. These increased requirements also come with an increase in cost and effort.

A reliability factor is estimated and included for each tier based on the approximated accuracy of the measurement / calculation method, resulting in a more conservative (i.e. lower) energy estimate for the tiers with lower inherent accuracy.

To ensure that any given approach under these tiers is suitable for regulatory purposes, the following key principles must be met:

- Transparency: Easy to verify by non-experts and technologically neutral.
- Robustness: Strong scientific foundation and accurate results.
- User-friendliness: Practical for implementation, with accessible data and reasonable costs.
- Stress-tested: Demonstrated through diverse and validated use cases.

In the submission MEPC 83/INF.33 (IWSA), examples of three of these approaches were given and it was noted that the methods for these original Tiers I, II, and III are already in use within the industry. An additional tier was agreed upon at MEPC 84 which added a new Tier III, a variant of Tier II using operational wind data rather than hindcast data. Consequently, the direct measurement approach was relabeled as Tier IV. These tiers are all under active development; first trials have been conducted, and the data evaluation is ongoing. The appendix presents several industry examples.

It is the objective of this paper to expand on this and to show through concrete examples, how the examples of the methods defined in the wind propulsion appendix of the GFI guidance documentation can be applied in operational reality. Therefore, the document is split in two:

- The first half (Possible Approaches and Further Details on Tiers - main body) presents concrete methods, i.e. concrete practical approaches (calculations, simulations, and/ or experiments), for estimating propulsive power contribution from the WPS suitable for each of the proposed Tiers I, II, III and IV, respectively. These examples are not meant to be definitive nor restrictive in nature but are intended to be illustrative of likely approaches that would be acceptable to adopt under each tier methodology.

- The second half (Appendix: Case Studies and Examples) gives concrete case studies, which in turn serve as example of how specific methods have been applied to different ships and WPS types. Moreover, these cases contrast the WPS brake power saving estimates across different tiers as well as across different WPS devices.

Note: Figure 1 above shows the organization of this paper graphically.

Possible Approaches and Further Details on Tiers

Tier I: Simplified analytic power model combined with statistical weather data.

Tier I, as highlighted in Table 1 above, is primarily a "Simplified analytic power model combined with statistical weather data". Of all the tiers, Tier I requires the least amount of detailed information on a specific ship, and design data as well as the least effort on monitoring when in operation. In particular, this means that the Tier I formula:

- Needs only a limited set of aerodynamic performance characteristics.
- The method should describe the energy contribution from wind propulsion as a function of the operating route sailed by the ship with associated wind conditions.
- Logs only the departure and arrival point for each voyage and the fraction of the voyage where wind propulsion was actually enabled.
- Uses a standardized wind statistics data set common to all ships.
- Is empirical and inherently introduces uncertainties.

There is a relatively high dependency of the results on the model assumptions, i.e. a relatively low reliability of the results with respect to the actual WPS performance. Tier I calculations will therefore be matched with a reliability factor that correlates with that dependency on those assumptions.

To mitigate residual concerns about the uncertainty delivering unfair benefits and remaining technology neutral, the entire method needs to be transparent, including any formulae and wind statistics. Only the aerodynamic performance inputs used for specific ships may be withheld.

The energy formula offered by OPERVENT is one example of a formula which meets the requirements listed above. It is used here because it is publicly documented [3], so the calculation can be reproduced and checked by any third party. Note, however, that OPERVENT is not the only option as other methods could meet the requirements as well. The following subsections set out the OPERVENT formula in detail. As a worked example this serves to illustrate how a Tier I approach would be applied in practice.

Defining characteristics. As described in the paper ISWG-GHG 23/3/4 [7], a Tier I method:

- is based on a mathematical formula that reflects the averaged Wind Propulsion Power (WPP), calculated via a simple formula (cf. section 8.2) and supplied to the ship for a given wind statistics matrix. This is similar to the result that would be calculated by combining a power matrix (or force matrix) and wind statistics.
- is based on a reduced number of parameters and accounting for the most influential physical effects experienced by a wind-propelled vessel,
- takes into account the averaged ship speed over the specific route sailed, as well as weather statistics for the region of navigation.
- is intended to be used with an associated reliability factor to take into account the fact that that it has been derived over a large range of wind propulsion configurations and may reflect imperfectly the performance of a specific installation and avoid any overestimation.

This method is designed to fulfil the following criteria:

- Compliance with GFI expectation: Energy supplied to the ship must be collected and aggregated over the considered period. This implies that operating conditions are taken into account, especially ship speed and wind conditions. Thus, any flat-rate approach is avoided.

- Simplicity: The proposed method has been designed to be the simplest method able to comply with the specification of the GFI.
- Transparency: The method will be public and fully disclosed. To consider the operating route sailed by the ship, the wind propulsion energy supplied to the ship will be based on weather statistics per geographical zones (see MEPC 83/INF.33) common for all ships and publicly available.
- Technological neutrality: The proposed formula reflects the most influential physical effects involved in wind propulsion energy production. It has already been tested on a wide range of WPS As the method is fully disclosed and available, any potential bias will be easily identified.
- Robustness: The proposed formula is based on a restrained set of parameters, each of them having a physical meaning. Hence, parameters of similar installations are expected to be similar. However, parameters can be slightly adjusted to reflect the actual performance of any single WPS and of the associated ship. The formula is provided with a range of validity for each parameter defined based on test sample used to validate the formula. The formula and method easily evolve with time in order to include experience feedback as the fleet of WPS installed vessels grows.
- Reduced cost: The position of the Tier I method is to deliver a low cost/effort option in comparison with other tier approaches and in comparison, to the cost required for the declaration of other sources of energy, including fuels of any kind.
- Validated: the accuracy of the method is assessed (see Appendix) in comparison to the use of a power matrix combined with wind statistic. The reliability factor associated with the method can be defined on the accuracy assessment.
- Adjustable: the method and the associated formula can be refined and adjusted in the future with increased experience.

As the method will be relatively straightforward and publicly available, the calculations can be undertaken without special expert knowledge. Moreover, additional tools will be made available to help facilitate the use of the method as much as possible.

Outline of the process

A Tier I method can, for example, apply the following process:

Step 1 Data collection. For each trip the ship declares:

- the port and time of departure,
- the port and time of arrival.
- Time fraction of WPS in normal operation (e.g. from the hour meter of the WPS: sum of the time when the system is activated; can include standby time in case of adverse operating condition; excluding time when the system is disabled).

The route accounted for is the great circle route (while avoiding land) between the ports. The length of the route is calculated on this basis, with an opportunity to adjust where necessary.

The duration of the trip is derived as the difference between the time of arrival and the time of departure.

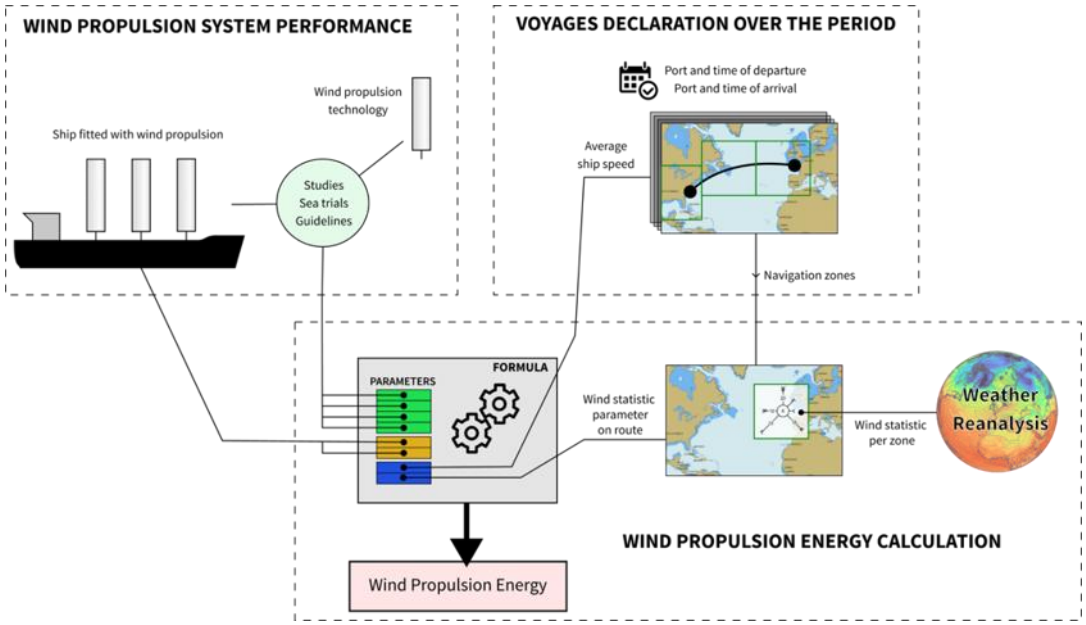


Figure 2: The Tier I process based on the use of the OPERVENT formula (proposed at the Wind Propulsion Conference 2024, London, UK – hosted by Royal Institution of Naval Architects (RINA) in association with International Windship Association (IWSA)

The average ship speed on the route is the ratio between the route length and the duration of the trip.

Step 2 Route analysis. Instead of obtaining wind speed at the vessel at each instance during the compliance period (as done with Tiers II and III, "Point by Point method" shown in Figure 3 below), the Tier I method uses aggregated wind statistic. These aggregates are calculated from hindcast data for distinct geographic zones. Similarly, the route is then divided into segments:

- per wind statistic zone (cf. Figure 3),
- for any significant course change, for example in the case where the shortest route needs to avoid land.

Developing the statistics for each wind zone is subject to ongoing work. [2] provides an intermediate report.

For each segment, the Wind Propulsion Energy supplied to the ship is then calculated using the formula and the specific set of coefficients adapted to the wind statistics and the course of the ship.

The total Wind Propulsion Energy supplied on the route is the sum of the individual contribution on each segment.

$$E_{\text{wp}} = \sum_i \frac{L_i}{V_s} F_{WPPi} \qquad (1)$$

where:

E_{wp} Energy supplied to the ship on the route.

L_i Length of segment i

V_s Averaged ship speed

F_{WPPi} Wind Propulsion Power supplied to the ship on the segment i calculated using the WPP formula.

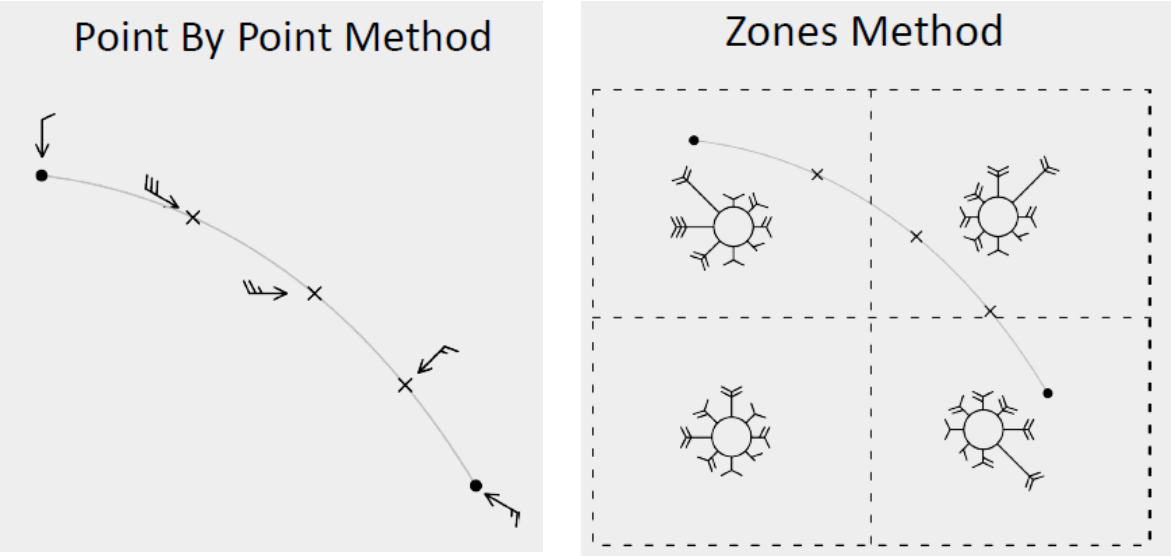


Figure 3: Point by point method (left) vs. zones method (right). For the zones method the figure illustrates splitting the route into geographical segments (three segments in this example) for which statistical weather data (illustrated by the wind arrows) has been calculated. Graphics from [2], courtesy of CRAIN Technologies.

The Wind Propulsion Power (WPP) formula

One example of a Tier I method is using the analytic formula developed in the OPERVENT project [3]. This formula, in the following called WPP formula, offers a relatively easy way to calculate F_{WPPi}, the Wind Propulsion Power supplied to the ship on the route segment.

This mathematical formula is based on a limited number of coefficients derived from the main properties of the ship and of the WPS fitted on that ship. This formula has already shown the ability to properly estimate the contribution of any kind of wind propulsion technologies on the basis of the IMO global wind matrix statistics (see Appendix, Case Study 1).

Details on the formula are presented in the OPERVENT project report [3].

The formula is designed to account for the most influential effects on wind propulsion energy production. It provides an averaged contribution for a given wind statistics matrix. However, the formula is not intended to be used to derive the wind propulsion performance for a specific operating point and this may lead to unexpected results.

Required input

For this method, the following input data is required:

- WPP Formula's coefficients (Validated for ship installation)
- Routes and voyage times (i.e. averaged ship speed)
- Wind statistics
- Associated reliability factor

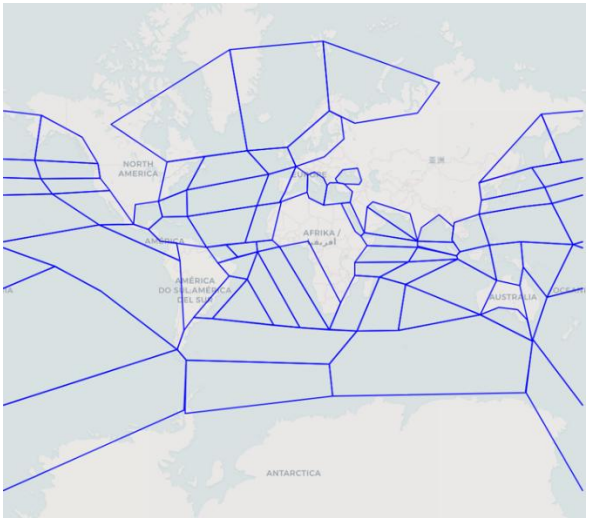


Figure 4: Example of geographical zones that could be used for the derivation of wind statistics. (currently under development)

On-board equipment needed

In terms of on-board equipment, only a log of the use time (e.g. a reading of the hour meter of the WPP at start and at the arrival of the voyage) is required.

Practical implementation

For practical implementation, the geographical zones (cf. Figure 4) and associated weather statistics must be established. These are common for all ships and will be derived once on the basic of a re-analysis product (such as ERA5 from the ECMWF, see www.ecmwf.int). The resulting statistics will then be made available to users of this method.

Once wind statistics and voyages are available (ports of departure and arrival, dates), the energy supplied by the WPS system to the ship is directly calculated by applying the WPP formula from section 8.2. A spreadsheet derived or other formatted tool will be made available to do so.

Verification & Monitoring. The coefficients used in the WPP formula are defined for the ship with its specific WPS installation. The precise validation process is yet to be defined inline with the validation process of other tiers. It is expected that once the coefficients are validated, they will remain valid until any modification is made to the ship.

The calculation method itself is fully disclosed. Thus, any OPERVENT calculation can be checked as soon as the input data (formula's coefficients and trip declaration) are known. Since the coefficients of similar WPS on similar ships are expected to be close to each other, any unusual deviation in the coefficients will be obvious and immediately flagged.

The process can be imagined as follows:

(a) The brake power saving (GFI) calculations for any given ship and reporting period are conducted using a (verified) tool. The results are then declared to the governing authority, which can be checked if necessary.

(b) Alternatively, since the calculations are straight forward, a ship could declare its trips and the GFI components which were then calculated directly by the governing authority, thus avoiding any need for checking results.

Accuracy and limitations.

The accuracy and limitations of this method are derived from two main sources:

a) The accuracy of the wind matrix: The method applies wind statistics per geographical zone rather than the wind conditions encountered by the ship and averages the wind propulsion power over each route segment rather than evaluating it continuously. Both approximations contribute to this source of deviation.
   Work to quantify the resulting deviation is ongoing. According to [2], an accuracy of ±15% is a realistic prospect.
b) Aerodynamic performance coefficients used in the WPP formula. The case study in the Appendix presents a comparison of the OPERVENT formula vs. a high-fidelity model. This comparison between the WPP and the high-fidelity method gives an estimate of the accuracy of the WPP formula and an indication of any possible overestimation of results.

Other Candidate Approaches

Following MEPC.1/Circ.896 and ITTC 7.5-02-03-01.9 [9] Level 1 directly can be an option, too, e.g. CFD-based input power data as detailed in the Appendix, case study 4.

Tier II: A Ship-specific power model validated by sea trial, combined with hindcast weather data

A Tier II method may yield increased accuracy compared to Tier I. This, however, comes with an increase in (calculation and experimental) effort. To meet this expectation, Tier II reaches beyond Tier I in two main aspects:

a) Ship specific performance prediction calculations with more details than in Tier I are required, resulting in a digital model of the specific wind installed vessel.
b) Sea trials (e.g. ON-OFF trials) are performed to ensure the performance prediction calculations are representative of the respective ship on the water. If necessary, the calculations are corrected to match experimental data.

Defining characteristics: In principle, a Tier II method derives the equivalent brake power supplied by the WPS (PB_{WPS}) by combining a brake power saving matrix with the wind logged during the compliance period. The brake power saving matrix is derived by calculations for each specific ship and should be verified with a short sea trial. The wind along the ship's path is recovered from (publicly available) meteorological hindcast data such as e.g. ERA5.

Only after sufficient agreement between sea trial experiments and the digital model is reached, the digital model is then used to assess the WPS delivered energy as a function of wind speed, wind angle, ship speed, loading condition and wind propulsion state.

As the uncertainty in this method is reduced due to the insights gained from the sea trials, a higher reliability factor than Tier I will be assigned to Tier II. Since this method still relies on performance determined in simplified calculations and idealized trials, the results will still not be perfect. To account for potential deviations between calculations and the ship's operating reality (e.g. due to degraded device functioning, large ship motions, improved control), the reliability factor will be lower than for the subsequent tiers, which will eliminate some of these potential deviations.

The ITTC, procedures on sea trials [10] and guidelines on performance prediction [9] can provide the base line for Tier II. However, other methods could be elaborated as well.

In the following we describe one example method which would be suitable for determining the WPS power contribution on a Tier II level.

Outline of the process:

A Tier II method can, for example, follow the process below:

Step 1 Prediction. Before operation, the WPS brake power saving matrix $PS_{i,j,k}$ is determined using recognized performance prediction methods such as ITTC 7.5-02-03-01.9 [9], Level II or more.

The brake power saving matrix consists of $PS_{i,j,k}$, the net power saving due to a WPS, compared to the same ship without the WPS, at the apparent wind speed i, apparent wind angle j and ship speed k.

Step 2 Verification. The brake power saving matrix is verified and correlated (spot-check) based on a short sea trial, for example as described in ITTC 7.5-04-01-02 [10]. During the sea trial, wind is measured by an anemometer onboard. The disturbance of air flow from the ship itself should be corrected for based on LiDAR, hind-cast or CFD (or a combination), according to the same ITTC guidance and upcoming ISO standards. [8].

Note: The number of tested wind conditions and their distribution should also follow the ITTC guidelines and later ISO standards too.

Step 3 Logging in operation. The wind speed at the ships position during the compliance period is extracted from hindcast data from recognized meteorological offices (e.g. ERA5 from ECMWF).

Then, for each data point when the WPS was on:
- Wind speed and direction is derived from the hindcast data
- The corresponding brake power saving is derived by linear interpolation in the brake power saving matrix.

Required input

For this method, the following input data is required:
- Predicted WPS brake power saving matrix
- Hindcast wind data

On-board equipment/data collection needed

The following data is logged onboard:
- Ship's position, with date and time
- Ship's Speed through water
- Heading
- Log of time events during which the WPS delivers propulsion power

Practical implementation

Verification & Monitoring.

The verification of the brake power saving matrix is based on an acceptance criteria involving average comparison error and uncertainty of the sea trial, according to an upcoming ISO standard [8].

$$\overline{E} = \frac{\left(\sum_{k=1}^{N}\left(\Delta P_{pred_k} - \Delta P_{st_k}\right)w_k\right)}{\sum_{k=1}^{N} w_k} \quad (2)$$

where w_k is the weights in the Global Weather Matrix. [6]. Verification is met when $\overline{E}$ is within a given threshold. Setting the acceptance limit of is subject to ongoing development.

If the found brake power savings do not match the predicted brake power saving matrix, then the prediction modelling must be adjusted. It is possible to verifying the brake power saving matrix again during operation to reflect any change in the performance during the ship's lifetime.

Scope of verification: The verification procedure should include a review of the performance prediction calculations, the sea trial result and the following power matrix adjustment. Data from the compliance period are checked to ensure that the WPS operational limitations are consistent with those assumed in the brake power saving matrix.

Accuracy and limitations. The accuracy of approaches under both Tiers II and III will increase over time due to the use of ship specific sea trials, which spot-check the brake power saving.

Limitations: Since the performance is only verified once, these approaches will not detect if the WPS performance changes over time.

Other Candidate Approaches
Other data driven models exist which could work for a Tier II analysis. However, from the current perspective these seem more complex and difficult to standardize and verify.

Tier III: Ship-specific power model validated by sea trial, with measured wind-field data under operational conditions.

A Tier III method is very similar to a Tier II method, with the only difference that for Tier III the wind data is no longer derived from hindcast data but measured directly through appropriate wind speed sensors on board of the ship under consideration.

Defining characteristics: Under the conditions that these measurements are carried out with sufficient rigour and that interaction effects (mainly the effect of the ship's freeboard) are accounted for correctly, the direct wind measurements of Tier III eliminate a level of inaccuracy within the Tier II method: now, the actual wind speed during operation is the basis for determining the WPS power contribution, no longer an extrapolation from hindcast data.

Thus, a Tier III method could therefore result in a higher level of accuracy in the WPS power estimations. If this is confirmed, then a higher reliability factor would be appropriate for Tier III.

Besides this source of the wind speed data (hindcast vs. on-board measurement), a Tier III method follows the same principle outlined for the Tier II method above: the brake power supplied by the WPS (PB_{WPS}) is derived from combining a brake power saving matrix with the wind time series logged during the compliance period. The brake power saving matrix is derived by calculations for each specific ship and should be verified with a short sea trial. The wind data is measured directly on board.

As for Tier II, sufficient agreement between sea trial experiments and theoretical predictions is required before the predictions are used to assess the WPS delivered energy as a function of wind speed, wind angle, ship speed, loading condition and wind propulsion state.

Outline of the process:

The Tier III process is almost identical to the Tier II process.

Step 1 Prediction. Same as Tier II.

Step 2 Verification. Same as Tier II.

Step 3 Logging in operation. Here, in contrast to Tier II, wind is logged in one of the following ways during the compliance period:

a. LiDAR set up to measure sufficiently far away from any near field disturbances or
b. Anemometer, including documented correction for ship disturbances.

In any case, the same reference must be used in both sea trial and compliance period.

Table 3 below gives an overview of the suggested methods for obtaining wind data and the allocation to Tier II and III.

Once the wind speed is known, the process for determining the WPS power contribution through a Tier III analysis is virtually identical to a Tier II analysis. Therefore, instead of elaborating further, the next section details the process of obtaining reliable wind speed measurements on board.

Table 2: Methods for Recording Wind

Tier	Sea trial	Compliance period
II	Corrected anemometer using met-ocean hind-cast	Retrieved wind from met ocean hindcast, position and time.
III	LiDAR measurement	LiDAR measurement
III	Corrected anemometer readings using LiDAR, CFD, hind-cast	Corrected Anemometer, corrected in same way as sea trial

Practical examples of wind measurements.
It is known that ship anemometers come with significant uncertainty due to airflow disturbance from the superstructure and most off all the freeboard rather than an imprecise instrument itself [14]. These disturbances are dependent on the direction the apparent wind arrives at the ship. Figure 5 shows the wind flow field around an MR tanker. The influence of the ship hull (low velocity areas close to the main deck in blue and green shades) can be clearly seen.

Thus, for Tier III to yield less uncertainty than Tier II, the following must be kept in mind:

- Above all, the disturbance on the anemometer should be minimized. CFD can be used to identify positions where the flow is least disturbed. Moreover, installing more than one anemometer should be considered, as this allows the least disturbed signal to be selected for each wind angle.
- Then, a correction is required. This may be derived e.g. from full-scale CFD of the ship above the waterline with the wind propulsion system active, from a forward-facing LiDAR measuring the undisturbed wind ahead of the vessel, or from hindcast wind data over an extended reference period. In each case the correction is expressed as a function of apparent wind angle.

Detailed procedures for each of these options are under development for the coming ISO 26204 [8].

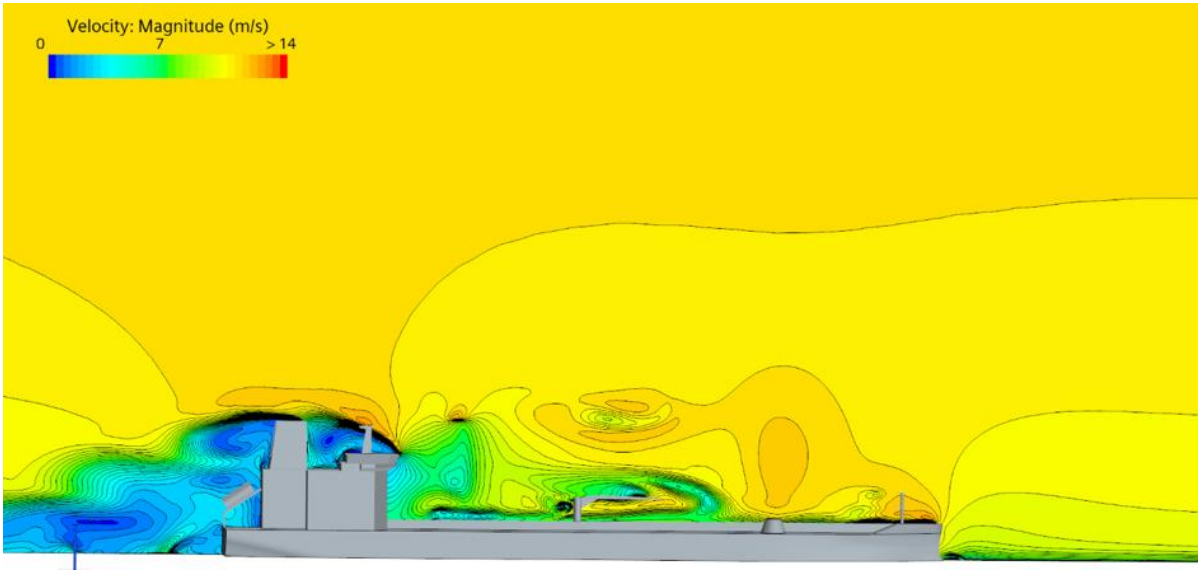


Figure 5: CFD of the airflow around an MR tanker, showing how the flow field at the anemometer position deviates from the far field. CFD by RISE SSPA Maritime Centre, supplied for this submission.

15.5 Whichever route is taken, and also where no correction is applied, the result should be checked against an independent set of hindcast data, and the uncertainty of the correction quantified as a function of apparent wind angle. In contrast to Tier II, however, hindcast data enter the Tier III process only as a long-term reference for the systematic, angle-dependent part of the measurement error, and not as the wind input to the power calculation itself.

This is the basis on how a Tier III approach improves on Tier II. Hindcast wind is an average over a grid cell of typically 0.25° by 0.25° and over an interval of typically one hour, so it resolves the wind encountered at a particular place and moment only approximately, whereas a calibrated anemometer measures that wind at the ship's actual position and time. The hindcast comparison is made once, over a reference period of several months, to characterise the ship's own flow distortion, after which the operational measurement stands independently of it. The forthcoming ISO standard [8] will establish a basis on which this calibration can be conducted and confirmed.

NOTE: For Tier III to improve upon Tier II in sailing conditions where the atmospheric boundary layer is expected to depart significantly from the standard power law profile, for example during trials close to land with pronounced topography, it might be necessary to use a locally measured wind profile (e.g. from a wind LiDAR).

Tier IV: Direct Thrust Measurements

Tier IV is expected to yield a highly accurate assessment of wind propulsion energy since it no longer relies on idealized models but directly accounts for any increases or decreases in performance in actual operation. For this, in-service force measurements capture the actual performance, i.e. the WPS power actually delivered.

Of the four tiers, Tier IV is the least mature. Work on the approach is ongoing. The areas of ongoing development are stated explicitly at the relevant points in this section rather than omitted, so that the current state of the work is clear.

In principle, a Tier IV method measures the thrust provided by the WPS directly and continuously during operation. Unlike Tiers I–III, which rely on a pre-computed power model combined with wind data, Tier IV measures the aerodynamic contribution of the WPS from onboard force measurements. This reduces dependence on meteorological/anemometer input and detects real-time deviations in WPS performance, for instance due to changes in the atmospheric boundary layer, loading condition/cargo arrangement, mechanical integrity of the sail or other operational changes.

Residual uncertainties remain due to the translation of the measured quantity (e.g. sail forces, or mast base moments) to the actual fuel savings. Moreover, assuming that measurement is done on the WPS itself, a correlation needs to be in place to correctly translate the result from WPS force to the impact on shaft power and also account for secondary effects on the ship's power requirements through the WPS' influence on hull and appendage performance (specifically induced drag due to, e.g. leeway) as well as propeller efficiency when unloading the propeller through WPS thrust.

Defining characteristics: Compared to the previous three Tiers, Tier IV particularly differs in two points:

a) WPS force is measured directly (instead of calculated) and translated to brake power savings via a formula. The translation function is verified using ON-OFF tests.
b) The direct measurement accounts for any (possibly adverse) ship motions, device malfunctioning and/ or (trim-) control influences as well as secondary effects.

In order to check and possibly adjust the translation function from measured WPS force to brake power savings, a performance prediction and trial is executed as specified for Tier II.

As the method covers the most influential factors of real-life operations and thus is the most complete it is expected that Tier IV will be matched with the higher reliability factor.

Tier IV work is ongoing by system suppliers. Independent parties already indicate the potential for this method to better reflect real performance than Tier II or 3. Several studies are currently underway to demonstrate the reliability of the methods, in preparation for offering Tier IV for adoption.

The following section describes an example method suitable for determining the WPS energy contribution at Tier IV. The method described is neither exhaustive nor universally applicable, and alternative methods will be applicable. Depending on the WPS concerned, for example kites or soft sail rigs with fixed lines, the methods may need to be adapted or replaced by other suitable approaches.

Outline of the process

The presented example of the Tier IV method consists of two parts:

1. Force measurement: the longitudinal thrust force F_x and the lateral side force F_y are measured continuously at each WPS unit.

2. Translation to brake power saving: the measured forces are converted to an equivalent brake power saving using a pre-verified translation function that accounts for both the primary aerodynamic benefit and the secondary hydrodynamic effects (such as leeway resistance, yaw moment).

The translation function should be established prior to operation and verified against sea trial ON-OFF test results.

Step 1: Force measurement

To measure the thrust and side force delivered by each WPS unit, one can choose from two principal methods possible:

1a) Strain gauge or optical measurement of structural deformation - Strain gauges or optical fibre sensors are installed at structural points in the base, mast, or support structure of the WPS unit. The correlation between measured strain levels and forward and lateral forces should be determined and verified through calibration.

NOTE: Corrections shall be applied for inertial loads arising from vessel motions (heave, pitch, and roll), and where the steady trim or heel of the vessel is not negligible, a corresponding correction to the resolved force components shall be applied.

1b) Pressure-based measurement - Pressure taps are positioned across the outer surface of the WPS device. The number of sensors used needs to be high enough for a full surface pressure field reconstruction. Integrating the pressure field over the device surface yields the resultant thrust and side force vectors.

Step 2: Translation of WPS force to brake power saving

The translation from measured forces to brake power saving is conducted in two distinct phases: a preparatory phase carried out before the vessel enters the compliance period, and an operational phase running continuously during service. The preparatory phase establishes and verifies the translation function; the operational phase applies it.

2-1) Preparatory phase (before operation): The brake power saving is predicted using a Performance Prediction Programme (PPP) corresponding to ITTC Level III. Based on the simulation results, a translation function is constructed that relates ship speed, the total sum WPS thrust forces (Fx), the yaw moment (Mz), and WPS side forces (Fy) to the resulting brake power savings (P). The translation function shall cover the full expected operating envelope of ship speed and aerodynamic forces.

NOTE: Whether or not yaw moment should be considered is a topic still under discussion as well as the level of detail needed here (e.g. the inclusion of parameter for vessel draft and trim). As this discussion evolves, the main goal will be to ensure compatibility with tiers I to III.

Once established, the conversion table is to be verified through sea trials, e.g. by conducting ON-OFF sea trials following the ITTC 7.5-04-01-02 procedure [10]. At each test condition, the brake power saving derived from the simultaneously measured force signals and the translation function (P_{Force}) is compared against the brake power saving measured directly from the ON-OFF test ($\Delta \mathrm{P}_{\mathrm{ON-OFF}}$). The comparison error E is computed in the same way as for Tier II, equation 1, but replacing $\Delta \boldsymbol{P}_{\boldsymbol{pred}}$ with P_{Force}.

NOTE: Acceptance criteria for the conversion are to be identical to the PPP acceptance criteria for Tier II and III (cf. section 12.4)

Once the translation function is populated and validated (Part 2-1) it can be used during WPS operation to establish WPS brake power saving at any sailing condition from the load measurements directly. This is Part 2-2.

2-2) Operational phase (during operation): Conversion to brake power saving. The processed one-minute averages of thrust and side force, together with the associated ship speed, propeller operating point, are passed to the translation function populated and validated in part 2-1 to compute the one-minute brake power saving. These are accumulated over the reporting period to yield the WPS brake power saving ΔP.

Step 2 (alternative): Step-wise conversion of measured forces to brake power

As an alternative to establishing the conversion table described in step 2 above, the conversion may be performed by explicit step-wise processing. Prior to operation, the following should be determined by model tests or CFD, for example as part of the design verification using a PPP according to ITTC 7.5-02-03-01.9 Level 3 [9]:

- (alternative) Added resistance, R_i, on hull and appendages induced by the WPS side force, as a function of ship speed and the side force.
- (alternative) Propeller propulsive efficiency, η_D, as a function of propeller torque and propeller rotation rate (and propeller pitch, if a controllable pitch propeller is used).

During operation, the following processing is performed for each time step of measured data to calculate the WPS brake power saving contribution P from the thrust measured at each WPS:

$$P_{WPS} = V_S \times \sum_k F_{x,k} \quad (3)$$

Where:

V_S is the ship speed through water

$F_{x,k}$ is the thrust measured at wind propulsion unit k, directed forward along the ship's centreline.

This then is corrected for the additional resistance (e.g. due to leeway) caused by the WPS:

$$P_{E,WPS} = P_{WPS} - V_S \times R_i\left(V_S, F_y, [M_z]\right) \quad (4)$$

Where:

R_i is the pre-processed induced resistance due to WPS side force $F_y$and yaw moment M_z;

Finally, this can be translated to the WPS equivalent power contribution P (the "WPS brake power saving contribution"):

$$P = \frac{P_{E,WPS}}{\eta_D(Q_{PROP}, n_{PROP}[, PD_{PROP}])} \quad (5)$$

Where:

η_D is the overall propulsive efficiency;

n_{PROP} is the propeller rotation rate;

Q_{PROP} is the propeller shaft torque; and

PD_{PROP} is the propeller pitch setting (only with controllable pitch propellers).

Inputs needed

Translation function derived from performance prediction corresponding to ITTC Level III.

Required equipment

- Thrust measurement on all wind propulsion
- Data acquisition system to get common ship measurement signals, which should include all signals stated in 8.3

Practical implementation

The following outlines the practical considerations that govern the quality of a Tier IV result: the factors that drive its accuracy, the calibration and measurement integrity it depends on, and the processing of the measured data.

Accuracy and limitations
The accuracy of this method is fundamentally driven by two factors

a) The quality of the load data.
b) The conversion of the load data to brake power savings.

To address the latter, sea trials are conducted to make sure that measured and real brake power savings agree. To ensure load data quality, rigorous sensor calibration is needed. Then, adequate data processing ensures data integrity.

21.5 Calibration and measurement integrity

Since the brake power saving is derived from measured forces, a Tier IV result is only as credible as the calibration behind it. In this example, calibration is carried out on installation, at intervals during operation, and after any significant modification:

- initial calibration: After sail installation and prior to entering service, the force measurement system is calibrated using reference loads of known magnitude applied to the WPS structure. This calibration establishes the relationship between measured strains and the forces and moments transferred from the WPS to the ship across the full expected operating range. Calibration is conducted in longitudinal and lateral directions and the calibration documentation and made available to a 3rd party verifier. For pressure-based systems, the calibration shall include determining the zero-position of the angular/orientation measurement.

Following the initial calibration, the continued validity of the force measurement system in service shall be ensured through a documented measurement-integrity programme. This applies irrespective of the sensing technology employed. The programme shall be capable of detecting drift, offset, or a change in the relationship between the measured quantity and the applied forces of a magnitude that would materially affect the reported energy contribution. The measurement-integrity programme shall include, as a minimum:

- trending of the zero-load offset checks of over time, with defined alert and action thresholds;
- periodic end-to-end verification of the measurement chain by a means that does not require the application of external reference loads and that is appropriate to the sensing technology and configuration – for example shunt (electrical) calibration for strain-gauge systems, interrogator verification against a reference wavelength for optical-fibre systems, or, for pressure-based systems, confirmation of the expected sensor response to a known

physical input – performed at e.g. quarterly intervals or, where such a check is inherent to normal operation, continuously;
- temperature dependence of any sensor output should be confirmed to remain adequately compensated, this being relevant to electrical strain gauges, optical-fibre sensors and pressure-based sensors alike;
- traceable calibration of the signal-conditioning, interrogator and data-acquisition equipment, which is removable for bench calibration, at an interval established under a recognised method (e.g. ILAC-G24 / OIML D10); and
- cross-comparison of the primary measurement against independent or redundant indications of the delivered force or of general WPS performance, used as a plausibility check wherever the WPS configuration makes them available.

Moreover, a full recalibration by application of known reference loads shall be performed:

(a) after any significant repair, structural modification, or replacement of sensors or foundation affecting the load path;
(b) whenever the measurement-integrity programme indicates a deviation exceeding the defined action threshold; and
(c) at intervals not exceeding [5 years], aligned where practicable with the vessel's scheduled dry-docking or special survey, as a backstop.

Where a reference-load recalibration falls due but the required conditions cannot reasonably be arranged, the interval may be extended subject to the operator demonstrating to the verifier, on the basis of the programme records, that no significant change in the measurement system has occurred.

NOTE: The maximum calibration interval is still subject to ongoing discussion and will be defined in the proposed GFI guidance.

21.6 Signal processing and data handling

Raw sensor signals are processed as follows before being used in the brake power saving computation:

- Filtering: appropriate low-pass or moving-average filtering is applied to remove high-frequency noise while preserving the aerodynamic signal.
- Time averaging: signals are averaged over one-minute intervals to avoid noise and fluctuations. Time alignment between force signals and vessel motion signals is verified to avoid phase errors in the inertia correction.
- Inertia correction: Vessel motions load the WPS structure inertially, and this appears in the measured force signals. The contribution is removed using the measured motion signals and the known mass distribution, and the correction is validated.

Trim and heel correction: Since the steady trim and heel of the vessel in this case study is non-negligible over the reporting period, the resolved aerodynamic force components are corrected accordingly.21.7 Verification & Monitoring

The force measurement system underpins the entire Tier IV result, so it is verified before service and monitored throughout operation. In this example, the scope of verification covers:

- Annual review through a 3rd party (e.g. class) of recorded data, including calibration and zero-check logs, flagged and fallback periods, and the accumulated Energy_WPS computation is intended.

Annual verification will include a review of any changes to the force measurement system or conversion model, recalibration records, and a plausibility check of the accumulated energy results, including comparison against Tier II or Tier III estimates where available.

- Review and approval through a 3rd party (e.g. class) of:

- the force measurement system design, sensor placement, FEM or pressure-integration model, and initial calibration records and calibration method
- the signal processing and inertia correction methodology
- the conversion model

The verification of the conversion model against the sea trial ON-OFF test results (analogous to Tier II & III sea trials), confirmation that the comparison error E is within the specified acceptance criterion to be defined.

Moreover, the data acquisition system includes plausibility checks to flag or reject erroneous data points, such as signals outside physically expected ranges or sudden step changes indicative of sensor failure.

NOTE: Standardised data quality acceptance criteria, flagging thresholds, and fallback procedures are to be developed. Moreover, detailed guidance on verifier qualifications, the scope of annual verification, and audit trail requirements for force measurement data is in ongoing development.

22 Other Candidate Approaches

As mentioned in paragraph 20, alternative methods may be applicable depending on the WPS concerned, for example kites or soft sail rigs with fixed lines.

Appendix

Case Studies and Examples

This Appendix contains a series of case studies and additional examples that support the tier methods described in the main body. Their purpose is to show how the four tiers perform when applied to real ships and real trial data rather than in principle. Each example documents the vessel, its wind propulsion installation and the tier or tiers applied, together with the resulting estimate of the wind propulsion contribution. Taken together, they illustrate the trade-off between accuracy and effort across the tiers and thus can form the base from which the reliability factors will be derived.

These studies were carried out by independent research institutes, with funding from national research programmes and/or through industry-driven projects. The involvement of independent institutes supports an impartial assessment of each method and case study. The assessment criteria have been aligned wherever practical, so that results are comparable across projects. As these are externally produced analyses, the International Windship Association (IWSA) does not verify nor validate the case studies included. They are presented here as instructive and indicative of the results that the tiers can deliver.

The case studies and simulations to support the different tiers are summarized in Table 4 and the full outline of each one can be found in Appendix 1.

Some of the case studies cover more than one tier, which allows a degree of comparative analysis; others apply to a single tier only. As more vessels are fitted with WPS and the availability of simulation results, sea trial data and in-service measurements grows, so will the feedback into the various approaches, which in turn will help to validate existing methods or refine them where needed.

Table 3:Overview on case studies and additional examples.

#	SUPPLIER	OBJECTIVE	SHIP	WPS	TIERS	RESULTS SUMMARY –
1	CRAIN/ OPERVENT	Show that a Tier I method (OPERVENT) treats different WPS technologies fairly as well as the transfer from aerodynamic data to the formula coefficients	Generic reference ship (200 m long)	wing sail rotor sail suction sail	I	Tier I can closely match high fidelity PPP results if calibrated correctly
2	Norsepower (supplied by RISE)	Demonstrate Tier II & IV real-world applicability and their suitability for independent verification	Bulk carrier (100,000 DWT)	multiple rotor sails	II, IV	Tier II and Tier IV applied to the same vessel and sea-trial data; consistent results
3	BAR Technologies	Compare accuracy across tiers for same WPS & same ship	Bulk carrier Pyxis Ocean (80,962 DWT Kamsarmax)	2 × 37.5m BAR WindWings	I, II, III (+ IV outlook)	Tier I, II and III applied to the same WPS and ship; Tier IV outlook

				(retractable rigid sails)		
4	OceanWings	Evaluate Tiers I, II and III against multi-voyage operational data from an in-service vessel	Open-deck Ro-Ro (10,400 GT, 121 m LOA)	4 × OceanWings (2-element articulated wing sails)	I, II, III	Consistent power estimates over Tiers I, II and III, both with hindcast and onboard winds data.
ADDITIONAL EXAMPLES:						
A	RISE	Discuss a possible method for sea trials with WPSs.	N/A	N/A	II-IV	Concrete & demonstrated recommendations for sea trials.
B	Norsepower	Present a concrete example of direct force measurements on a WPS	Ro-Ro vessel SC Connector (12,803 GT)	2 x 35m Norsepower Rotor Sails (retractable)	IV	Initial assessment (small dataset) shows high reproducibility of performance estimates
C	MARIN	In-service report on direct force measurement and operational validation of WPSs.	General cargo vessel MV Ankie (3,638 DWT)	2x 13m Econowind VentiFoil (retractable suction sails)	IV	Demonstrate extended operational feasibility of direct force measurement

Case Study 1: Tier I applied to different Wind Propulsion Systems

The first case study provides a comparison of the application of a Tier I method across different WPS technologies. It shows that the Tier I method, as proposed here, is fair across the different technologies and produces results similar to the ones from a much higher fidelity method.

The objective of this case study is to provide some examples of the use of the OPERVENT formula [3] that could be used as a basis for Tier I methods for the calculation of the energy supplied to a ship by a wind propulsion device.

The case study focuses on the aerodynamic performance of the Wind Propulsion System (WPS) as this is the main contribution in the propulsive energy provision from wind propulsion and this is the component which is dependent on the specific WPS technology chosen.

The case study provides for three WPS examples the following:

a) the aerodynamic data used to derive the power contribution of the considered wind propulsion system (WPS), all of which have been derived from publicly available sources,
b) a calculation of the WPS power contribution using and comparing two different levels of fidelity:
   - the high-fidelity approach using a performance prediction program (PPP, see paragraph 33) calculating the WPS propulsive power for any relevant combination of True Wind Angle (TWA) and True Wind Speed (TWS) and then averaging brake power saving of the WPS using the IMO Wind global matrix for weather statistics, vs
   - a calculation of the WPS brake power saving using the Wind Propulsion Power (WPP) formula, here from OPERVENT [3] following the Tier I description (paragraphs 7ff).

The wind propulsion systems considered are:

1. a high lift wing sail
2. a rotor sail
3. a suction sail.

The aerodynamic performance of these systems has been based on some public data and does not represent the specific data of a provider.

A single system has been considered fitted on the ship for each of the cases in order to focus on the aerodynamic performance of the WPS rather than being potentially lost in the details of interaction effects between multiple WPSs.

Wind Propulsion Power (WPP): The objective of the OPERVENT project was to provide some tools able to assess easily the potential propulsive energy contribution of the WPS. For this reason, Wind Propulsion Power (WPP) formula from the OPERVENT project, introduced in section 8.2, focuses on the wind statistics provided by the IMO wind global matrix from [6]. Regional wind statistics, as presented in *Figure 4*, are currently still under development. Once these regional statistics are available, the coefficients that represent the weather influence in the WPP calculations need to be updated to these regional statistics.

Therefore, in the current absence of regional matrices, this case study uses IMO's global wind statistics.

In the framework of the GFI, this formula needs to be extended to any wind conditions and routes, this is an ongoing project.

In this case study we use the OPERVENT formula [3] for the WPP calculations (section 8.2), which is based on two main parameters to define the aerodynamic performance of the WPS:

- Clmax,
- CdClmax.

In order to model a large range of WPS, *Clmax* and *CdClmax* represent a reference operating lift coefficient and the drag coefficient associated to this lift coefficient. For wings, this reference lift coefficient is very close to the maximum lift coefficient, as shown in the calculations presented in this document and explains the origin of this notation. For a more general use and better understanding, the wording "operating" lift and drag coefficient should be preferred, however the coefficients and the formula remain the same.

Ship properties

The objective of this study is to focus on the aerodynamic performance of the WPS; hence the same ship has been used for each of the cases in the OPERVENT formula and is defined by its main properties.

Table 4: summary of ship parameters for Case Study 1.

Description	Symbol	Value	Comment
Ship service speed	VB	12 kn	
Efficiency of propulsion	eta_prop	0,7	A lower value increases the brake power saving of the WPS
Height of WPS unit bottom	HB	18 m	Taken above sea level
Water length	WL	200 m	
Effective Draft	T	10 m	
Deck Beam	B	32 m	

Performance prediction program (PPP)

A performance prediction program (PPP) is the standard tool used to assess the propulsion performance of sailing vessels. The PPP computes, and balance, if necessary, the forces generated by each element that influence the propulsion performance such as hull, propeller, rudder, superstructure... and of course WPS.

The propulsive power of the WPS is calculated by the product of the thrust generated by the WPS multiplied with the ship speed. The power at shaft saved by the WPS is obtained by dividing the propulsive power by the propulsive efficiency of the ship.

The PPP selects the "ideal" WPS operation. That is a point on the aerodynamic lift versus drag curve of the WPS which leads to the highest brake power saving. In case of active systems, WPS power consumption is accounted for in the optimization process.

Calculations are performed for each operating condition, defined by ship speed and wind speed and direction. A performance matrix is generated over a range of true wind speeds, from

5 to 50 knots in 5-knot increments, and true wind angles from head wind (0°) to downwind (180°) in 10° increments.

Wind statistics are derived using the same wind speed and angle ranges and increments.

Since the focus of this study is on the aerodynamic performance of the WPS, the following hypothesis are applied in the PPP:

- ship speed is constant and the ship is assumed to be balanced,
- the WPS brake power saving is based only on the thrust produced by the WPS and its consumption,
- a single WPS is considered per ship, so no interaction effect between devices,
- no interaction between the device and the ship superstructures,
- no extra resistance due to the balance of side force,
- constant propulsion efficiency

Thus, the PPP is a high-fidelity method. It requires significant engineering and computational effort on the one hand. On the other, however, it offers robust and very accurate results. Thus, it constitutes a solid baseline to compare the averaged WPP (OPERVENT) calculations against.

System 1: high lift wing sail. This section of the case study is concerned with a generic high lift device showing the aerodynamic performances given in Figure 6. It is assumed that the data has been obtained using state of art method, such as wind tunnel test or validated numerical methods. The results shown below are extrapolated from [1] for a device showing a sail area of 432 m^2, so a span of 36 m for a chord of 12 m and a flap angle of 20°.

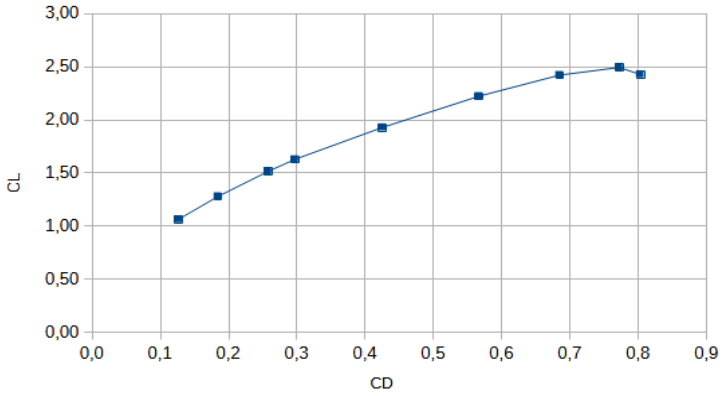


Figure 6: Polar performance curve of the high lift wing sail.

The aerodynamic coefficients (Clmax and CdClmax) required to use the OPERVENT formula are directly read from the polar chart. The Cdoff parameter takes into account the drag of the system when not in use has been taken as 0,10.

Table 5: The aerodynamic coefficients for the high lift wing sail.

Description	Symbol	Value	Comment
Sail area	Sa	432 m^2	
Span	Span	36 m	
Chord		12 m	

Maximum lift coefficient	Clmax	2,49	Obtained directly from polar curve
Drag for Clmax	CdClmax	0,77	Obtained directly from polar curve
Drag system OFF	CdOff	0,10	Device drag when the system if off

Brake power saving calculation (PPP): The brake power saving matrix is calculated from the PPP detailed in section 33 for a set of TWS (True Wind Speed) and TWA (True Wind Angle). For each case, the best operating point is selected. This is the point of the polar curve leading to the highest brake power saving. The system is assumed to be stopped while not propulsive. The brake power saving matrix is combined with IMO Global Wind Matrix in order to derive an average brake power saving on this route.

The average brake power saving resulting from the PPP calculations is 225 kW.

OPERVENT Formula: The formula is applied using the following coefficients, given in Table 7.

Table 6: OPERVENT coefficients used to derive the brake power saving of the high-lift wind sail.

Description	Symbol	Value	Comment
Maximum lift coefficient	Clmax	2,49	Obtained directly from polar curve
Drag for Clmax	CdClmax	0,77	Obtained directly from polar curve
Energy consumption coefficient at Clmax	CaClmax	0	No consumption for this device (passive system)
Efficiency of Ca	etaCa	0	Not used for a passive system
Drag system OFF	CdOFF	0,10	Device drag when the system if off
Sail area	Sa	432 m^2	Purely geometric data
Span	Span	36 m	Purely geometric data
Number of WPS units	Nwps	1	
Ship service speed	VB	12 kn	
Efficiency of propulsion	eta_prop	0,7	
Height of WPS unit bottom	HB	18 m	
Water length	WL	200 m	
Effective Draft	T	10 m	
Deck Beam	B	32 m	

The brake power saving as calculated by the OPERVENT formula is the sum of four contribution terms.

Table 7: OPERVENT formula results for the high lift wing sail.

Description	Symbol	Value	Comment
Power wind thrust WPS ON	P_ON	224 kW	
Power Wind thrust WPS OFF	P_OFF	-4 kW	
Power WPS consumption	P_CO	0 kW	
Power hydro from Side Force	P_SF	-8 kW	
Net Power production of WPS	P_NET	211 kW	Sum of above contribution
Reference power		**219 kW**	**Excluding P_SF**
High-fidelity brake power saving		**225 kW**	**For comparison**

Conclusions for the high lift wing sail

The high-fidelity calculation leads to an averaged brake power saving of 225 kW whereas to WPP formula (OPERVENT) from section 8.2 leads to an averaged brake power saving of 219 kW (excluding losses associated with side force not taken into account) in the PPP.

This amounts to a relative difference of -3%.

System 2: rotor sail. This section of the case study is based on a rotor sail wind propulsion device. The aerodynamic performance of the rotor has been taken from [4] and are shown on Figure 7. The rotor sail shows several specificities compared to a device based on a wing section:

- the magnitude of the lift is controlled by the spin ratio instead of the angle of attack,
- some energy is required to rotate the rotor,
- there is no obvious maximum lift coefficient as the lift goes on increasing with the spin ratio. However, the energy required to rotate the device increases dramatically.

The device considered here is a 24 m high rotor with a diameter of 4 m. The sail area is then 96 m^2.

The rotor consumption is not given in [4]. Hence, the consumption of the rotor has been selected as the function shown in Figure 7.

The consumption is given as non-dimensional coefficient Ca such that:

$$P_{WPS} = \frac{1}{2}\rho_a V_a^3 SCa \quad (6)$$

The consumption of the WPS must not be accounted for in the calculation of the GFI because this energy is supplied to WPS by the ship equipment, such as generators, and therefore, the consumption of the WPS is naturally considered.

However, this consumption will increase the power demand and is required to have a proper overview of the influence of the WPS on the ship.

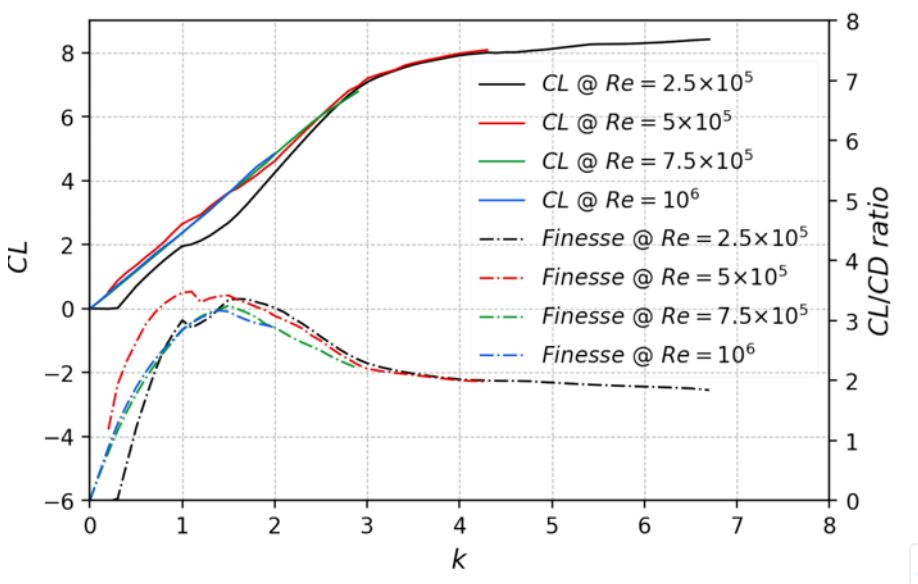


Figure 7: Aerodynamic performance used to derive the brake power saving of the rotor sail. The case at Re = 750 000 has been selected (green curves).

The aerodynamic coefficients (Clmax and CdClmax) required to use the OPERVENT formula are directly read from the polar chart. The Cdoff parameter takes into account the drag of the system when not in use has been taken as 0,10.

1.1 **Brake power saving calculation (PPP):** The brake power saving matrix is calculated for a set of TWS (True Wind Speed) and TWA (True Wind Angle) via the same PPP as described in section 0. For each sailing condition, the PPP best operating point is selected. This is the point of the polar curve leading to the highest saving. In case of the rotor sail, the consumption has to be considered to select the best operating point. The system is assumed to be stopped while not propulsive.

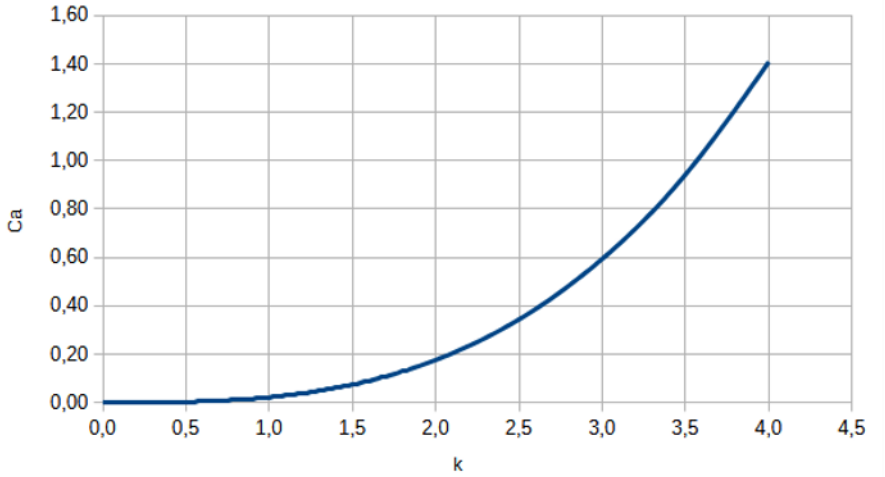


Figure 8: Energy consumption coefficient (Ca) of the rotor as a function of the relative rotational velocity.

Once the brake power saving matrix is combined with IMO Global Wind Matrix from [6] the average contribution on this route is obtained as 79 kW.

OPERVENT Formula: In the case of the rotor sail, there is no obvious maximum lift coefficient. For simplicity of this study, the coefficients to be used in the OPERVENT formula, are calculated as the average lift coefficient from the brake power saving calculation carried out in the previous paragraph, excluding situation where the rotor sail is not running. Once the method is used for operational brake power saving calculations, these coefficients could be

supplied directly from the WPS manufacturer (and potentially with a third-party validation required).

The average lift calculation calculated is Cl=6,31. The associated drag and consumption are the corresponding values for this lift coefficient

The formula is applied using the following coefficients, given in Table 9.

Table 8: OPERVENT coefficients used to derive the brake power saving of the rotor sail.

Description	Symbol	Value	Comment
Maximum lift coefficient	Clmax	6,31	Average operating lift coefficient for the rotor
Drag for Clmax	CdClmax	2,64	Drag coefficient associated with the average lift coefficient
Energy consumption coefficient at Clmax	CaClmax	0,40	At operating lift coefficient
Efficiency of Ca	etaCa	0,75	Electrical motor and drive, gears...
Drag system OFF	CdOFF	0,60	Device drag when the system if off. Derived from wind tunnel test.
Sail area	Sa	96 m^2	Purely geometric data
Span	Span	24 m	Purely geometric data
Number of WPS units	Nwps	1	
Ship service speed	VB	12 kn	
Efficiency of propulsion	eta_prop	0,7	
Height of WPS unit bottom	HB	18 m	
Water length	WL	200 m	
Effective Draft	T	10 m	
Deck Beam	B	32 m	

The brake power saving as calculated by the OPERVENT formula is the sum of four contribution terms.

Table 9: OPERVENT formula results for the rotor sail.

Description	Symbol	Value	Comment
Power wind thrust WPS ON	P_ON	99 kW	
Power Wind thrust WPS OFF	P_OFF	-6 kW	
Power WPS consumption	P_CO	-18 kW	
Power hydro from Side Force	P_SF	-2 kW	
Net Power production of WPS	P_NET	73 kW	Sum of above contribution
Reference power		**75 kW**	**Excluding P_SF**
High-fidelity brake power saving		**79 kW**	**For comparison**

Conclusions for the rotor sail

The high-fidelity calculation leads to an averaged brake power saving of 79 kW whereas to WPP formula (OPERVENT) from section 8.2 leads to an averaged brake power saving of 75 kW (excluding losses associated with side force not taken into account) in the PPP.

This amounts to a relative difference of -5%.

System 3: Suction sail. This case is based on a suction sail propulsion device which is an active device including a fan system to produce the suction effect. The aerodynamic performance of the suction sail has been taken from [11] and are shown on Figure 9. The suction sail shows several specificities compared to a device based on a wing section:

- the suction sail works similarly to a passive wing, the lift magnitude is controlled through the angle of attack and its shows a maximum lift coefficient.
- some energy is required to rotate the suction fan,
- the suction rate can be sometimes lowered in order to optimise the operating point of the suction sail.

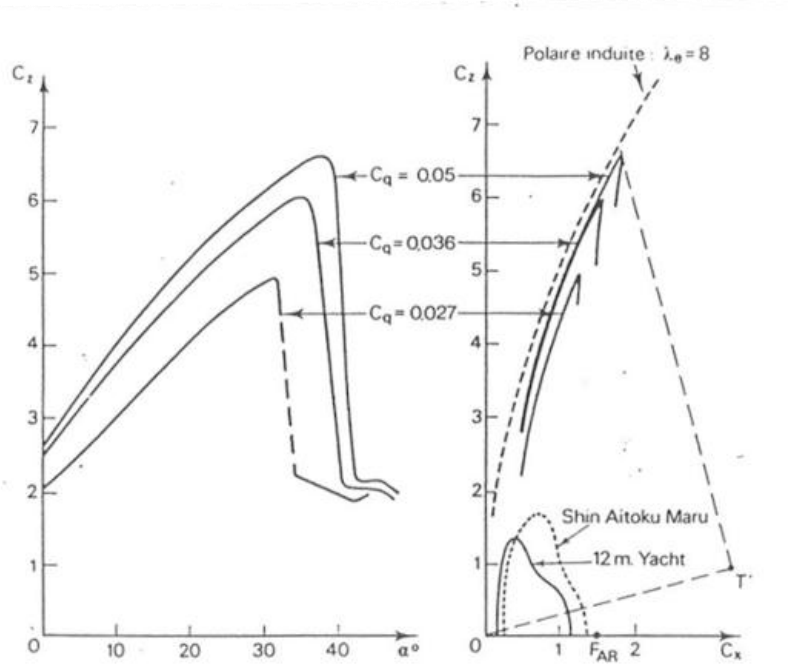


Figure 9: Polar performance curves of the suction sail.

Brake power saving calculation (PPP): The brake power saving matrix is calculated for a set of TWS (True Wind Speed) and TWA (True Wind Angle) via the same PPP as described before, section 0. For each case, the best operating point is selected. This is the point of the polar curve leading to the highest saving. In case of the suction sail, the consumption has to be taken into account to select the best operating point, and the suction rate can be adjusted in order to optimise the sail saving. The system is assumed to be stopped while not propulsive.

The brake power saving matrix is combined with IMO Global Wind Matrix in order to derive an average contribution on this route. The average contribution is 136 kW.

OPERVENT Formula: The formula is applied using the following coefficients, given in Table 11.

Table 10: OPERVENT coefficients used to derive the brake power saving of the suction sail.

Description	Symbol	Value	Comment
Maximum lift coefficient	Clmax	6,62	Average operating lift coefficient for the rotor
Drag for Clmax	CdClmax	1,82	Drag coefficient associated with the average lift coefficient
Energy consumption coefficient at Clmax	CaClmax	0,40	At operating lift coefficient
Efficiency of Ca	etaCa	0,60	Electrical motor and drive, gears...
Drag system OFF	CdOFF	0,20	Device drag when the system if off. Derived from wind tunnel test.
Sail area	Sa	150 m^2	Purely geometric data

Span	Span	30 m	Purely geometric data
Number of WPS units	Nwps	1	
Ship service speed	VB	12 kn	
Efficiency of propulsion	eta_prop	0,7	
Height of WPS unit bottom	HB	18 m	
Water length	WL	200 m	
Effective Draft	T	10 m	
Deck Beam	B	32 m	

The brake power saving as calculated by the OPERVENT formula is the sum of four contribution terms.

Table 11: OPERVENT formula results for the suction sail.

Description	Symbol	Value	Comment
Power wind thrust WPS ON	P_ON	210 kW	
Power Wind thrust WPS OFF	P_OFF	-3 kW	
Power WPS consumption	P_CO	-65 kW	
Power hydro from Side Force	P_SF	-7 kW	
Net Power production of WPS	P_NET	135 kW	Sum of above contribution
Reference power		**142 kW**	**Excluding P_SF**
High-fidelity power saving		**136 kW**	**For comparison**

Conclusions for the suction sail

The high-fidelity calculation leads to an averaged contribution of 136 kW whereas the WPP formula (OPERVENT) leads to an averaged contribution of 142 kW (excluding losses associated with side force not taken into account) in the PPP.

This amounts to a relative difference of +4%.

Mitigating performance overestimation risk

To further mitigate the risk of badly estimating the WPS brake power saving, the results of the OPERVENT formula have to be compared with the results of a high-fidelity (ref) method for a representative set of cases. Different wind propulsion technologies and ships out fitted with wind propulsion were compared.

The high-fidelity method derives the force matrix for each TWS (True Wind Speed) and TWA (True Wind angle) and then combines this force matrix with the wind statistic matrix such as the IMO global wind matrix.

This comparison (Figure 10) between the WPP (OPERVENT) and the high-fidelity method gives an estimate of the accuracy of the WPP formula and an indication of the possible overestimation of the results. A dot located on the red dashed line means that the result of the high-fidelity method and the WPP formula are identical. A dot above this line means that the high-fidelity method predicts a higher power than the formula, and vice versa.

Figure 10 shows that most of calculation points (blue dots) are above the red dashed line, showing that the formula does not overestimate the WPP. This was a clear specification of the OPERVENT project. The comparison of the WPP formula with high fidelity method shows that the OPERVENT formula is already conservative.

However, the initial reliability factor has to take into account the quality of the force matrix evaluation and the completeness of the physical effects accounted for.

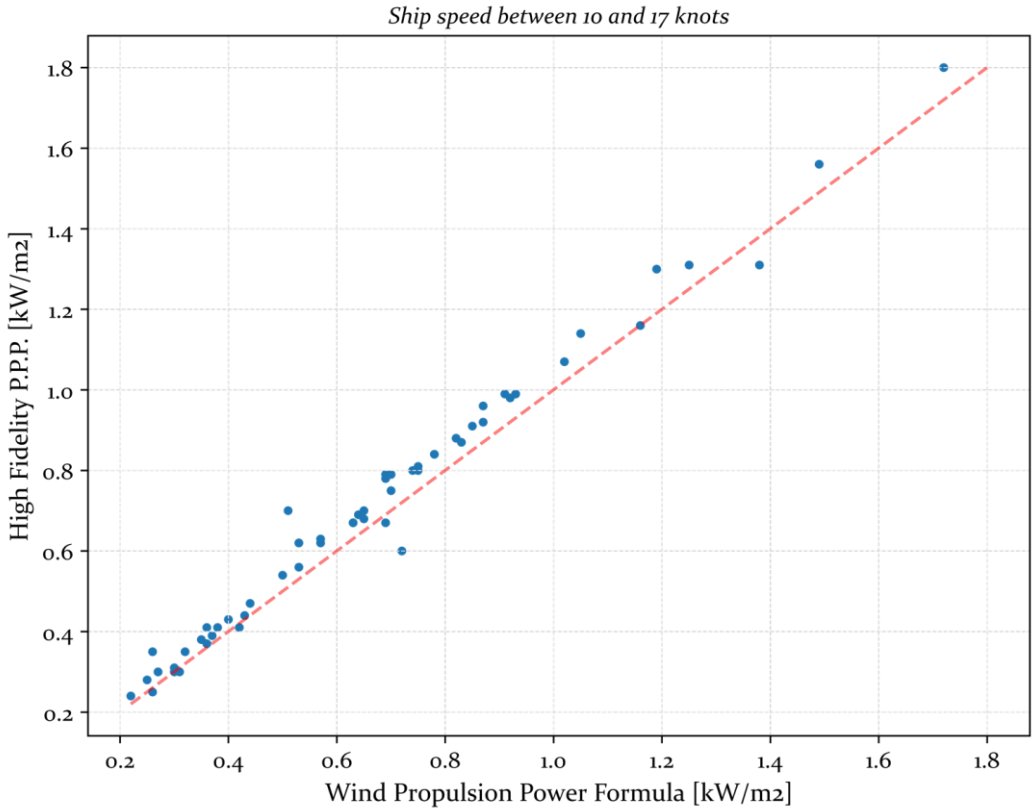


Figure 10: Comparison between the WPP from OPERVENT formula and a high-fidelity method for a large range of wind propulsion systems (WPS)

2 Conclusions

This case study sets out to show that a Tier I method, by the example of the OPERVENT Wind Propulsion Power (WPP) formula, treats different wind propulsion technologies fairly and can reproduce the brake power savings of a much higher-fidelity method. To test this, the same generic reference ship (Table 5) was numerically fitted in turn with three aerodynamically distinct systems (wing sail, rotor sail, suction sail) and for each the average brake power saving from the Tier I OPERVENT formula was compared against a high-fidelity performance prediction program (PPP) baseline, both evaluated over the IMO global wind matrix.

The two fidelity levels agree closely for every system: 225 kW (PPP) against 219 kW (WPP) for the high-lift wing sail (-3%), 79 kW against 75 kW for the rotor sail (-5%), and 136 kW against 142 kW for the suction sail (+4%). The Tier I formula therefore stays within about ±5% of the high-fidelity baseline across passive, rotating and active-suction technologies, confirming that it does not systematically favor or penalize any particular WPS type.

Widening the comparison to a larger set of systems and vessels (section 37) shows the same pattern, with most points falling on the conservative side of the parity line: the WPP formula tends to under- rather than over-predict the brake power saving, in line with the design intent of OPERVENT. These findings support the premise that a correctly calibrated Tier I method can closely match high-fidelity PPP results. Two points qualify this: First, the input coefficients must be calibrated to each technology; for the rotor an average operating lift coefficient was used in place of a true maximum. Second, pending the introduction of regional wind statistics, the brake power savings reported here rely on the IMO global wind matrix and will be refined once route-specific statistics become available.

NOTE: The hydrodynamic power loss from balancing the side force is not considered here. Since this component does not primarily depend on the choice of wind propulsion technology, it should thus not significantly alter the results. Instead, the hydrodynamic side force balance is governed mainly by the ship's main particulars and by any additional means of balancing the side force, such as dagger boards or rudders.

Case Study 2: Tier III vs IV comparison of rotor sail installation

This case study conducted by RISE SSPA Maritime Centre and Norsepower in collaboration, provides a **comparison of a Tier III and a Tier IV method** applied to the same ship, the same wind propulsion installation and the same sea trial data. It shows that the two tiers give consistent results over the demonstration period, and that the difference between them lies in the sensitivity of the result to the wind measurement rather than in the level of brake power saving obtained.

The objective of this case study is to demonstrate that both a Tier III and a Tier IV method can be applied to a vessel in regular commercial operation, and that both can be verified by an independent third party. Because the two tiers are applied to the same vessel and verified against the same set of on-off runs, the differences between the results can be attributed to the method rather than to the ship, the installation or the weather encountered.

The case study provides the following for each of the two tiers:

- the prediction of the brake power saving and its verification against the sea trial data, expressed as a weighted average error over the tested runs,
- the quantity measured on board during operation, being the ship's anemometer for Tier III and the forces on the individual rotor sails for Tier IV,
- the resulting brake power saving over a common demonstration period, shown side by side in *Figure 12*.

Ship properties
The ship is a 100.000 DWT bulk carrier on ocean crossing trade. It is retrofitted with multiple rotor sails. The operational speed is 9-12 knots. The same vessel is used for both, the Tier III and Tier IV examples.

Tier III process
The demonstration was conducted by an independent 3rd party (RISE). As outlined above (paragraphs 10-12) the Tier III method follows a three-step process:

Step 1 Prediction. WPS brake power saving matrix $PS_{i,j,k}$ was determined using RISE performance prediction tool, following ITTC 7.5-02-03-01.9, Level III.

Step 2 Verification. The brake power saving matrix was verified based on in service sea trial following ITTC 7.5-04-01-02. The campaign consisted of 34 on-off runs, collected over a period of five months in regular commercial operation including several draught conditions. The runs were around 20 minutes long and with sufficient time between to reach stable condition. Data was recorded through the ship's standard logging system. The signals include wind measurements, ship speed, shaft power, shaft speed and global navigation satellite system position.

The tests were conducted by the crew following detailed instructions by RISE. The high-frequency data was transmitted to RISE via electronic files extracted from the ship's performance monitoring system.

The anemometer was verified using hind-cast data from ERA5 for more than one year of operation.

A comparison between the sea trial and the prediction is given in Figure 11. The average error according to equation (2), weighted with the weather probability from Global Weather Matrix, is $\bar{E} = 3\%$.

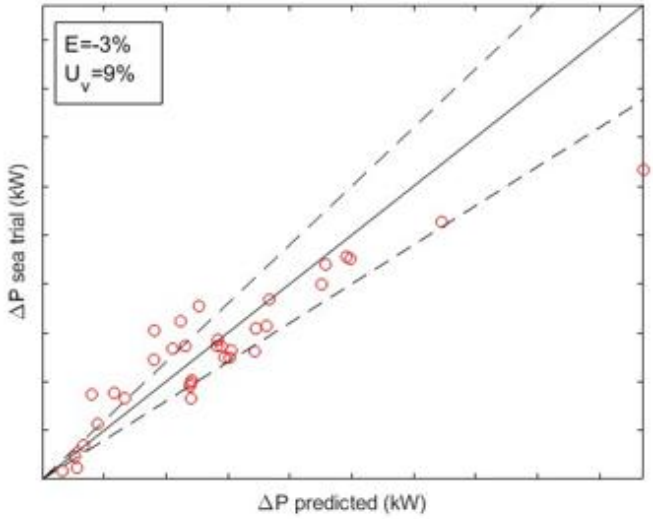


Figure 11: Verification of brake power saving (dotted lines represent 20% difference interval).

Step 3 Logging in operation. A short period of the operation is shown in Figure 12 for demonstration. The red curves give the brake power saving from Tier III approach. The wind was logged using the ship's anemometer.

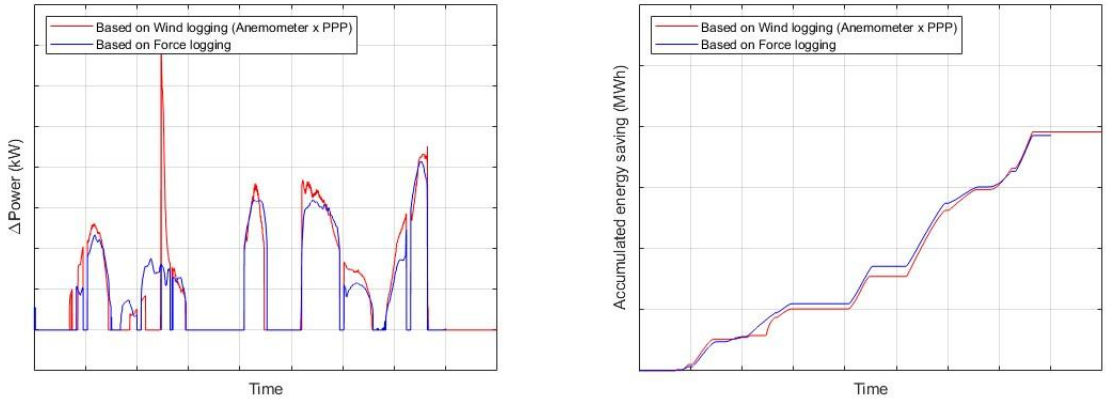


Figure 12. Example of brake power savings monitoring based on force logging and wind logging combined with verified model.

Tier IV process.
The rotor sails were also instrumented with force measurement in each device, providing both longitudinal and transversal force components. These measurements are based on surface pressure readings obtained from pressure transducers mounted on the rotor sails.

Step 1 Conversion of force to brake power saving. RISE in-house Power Prediction Program was used to model the relation between rotor force and brake power saving.

Step 2 Verification of Conversion model. The conversion model was verified using the same on-off sea trial runs as described for Tier II. The verification is shown in *Figure 13*. The weighted average error is around 1%.

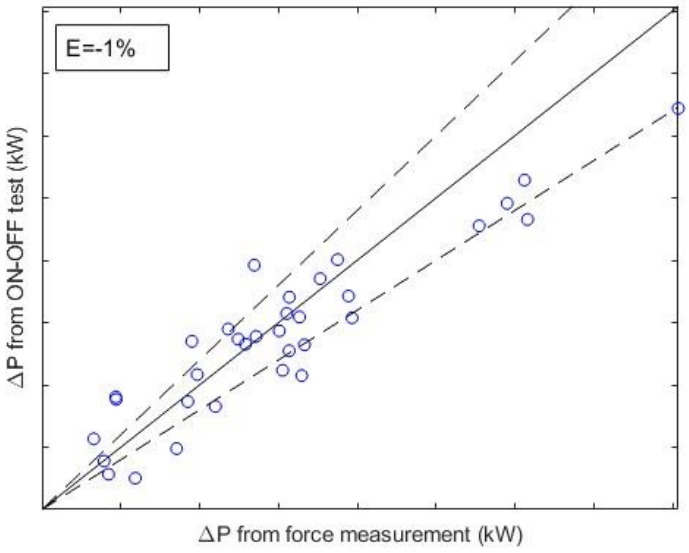


Figure 13. Validation of conversion of wind propulsion force to brake power saving (dotted lines represent 20% difference interval).

Step 3 Logging in operation. A short period of the operation is shown in *Figure 12* for demonstration. The blue curves give the brake power saving from the Tier IV approach. The rotor forces are logged with high frequency, converted to brake power saving using the verified conversion model, and integrated over time.

Conclusions

In general, the two approaches give similar results over the demonstration period, which indicates that the two tiers are consistent for this installation. Measured against the same set of 34 on-off runs, the Tier III brake power saving matrix showed a weighted average error of 3%, while the Tier IV conversion model reproduced the trial results to within approximately 1%. The difference in variability follows from where the wind enters the calculation: a Tier III result depends on the measured wind at every time step, whereas a Tier IV result is derived from the forces on the devices themselves.

The two tiers also differ in what they require of the ship, Tier III running on the ship's standard logging system and Tier IV requiring force measurement on every rotor sail together with a verified conversion model. Both approaches were possible to conduct and to verify through an independent third party, which is a prerequisite for regulatory use. The results cover a single vessel, a single wind propulsion technology and a limited demonstration period, and a more extensive uncertainty assessment remains to be conducted.

Case Study 3: Cross Tier comparison of rigid wing sail installation

This case study, conducted by BAR Technologies, analyses WPS power contribution through Tiers I–III for the same WPS on the same ship. The case study wraps up with an outlook on an initial analysis of the same vessel with a Tier IV method. Thus, this case repeats and strengthens the findings from the case study 2 (paragraph 39ff). It moreover adds a comparison with Tier I (paragraph 26).

Vessel

A Kamsarmax bulk carrier, Pyxis Ocean, retrofitted with two WindWings® (3-element rigid wing sails) with a span of 37.5 m and chord 20 m.



Figure 14: The Pyxis Ocean, a Kamsarmax bulk carrier retrofitted with two WindWings.

High fidelity reference method

To establish a high-fidelity reference, Pyxis Ocean is modelled using a Performance Prediction Program (PPP) incorporating coupled aerodynamic and hydrodynamic models of the vessel and its WindWings. The PPP accounts for both ship-to-wing and wing-to-wing aerodynamic interactions.

The following principal inputs are used:

- WindWing aerodynamic performance: lift and drag characteristics derived from CFD;
- Atmospheric boundary layer: vertical wind-speed profile;
- Ship-to-wing aerodynamic interaction: CFD-based model of the modification of local flow by the vessel and superstructure;
- Wing-to-wing aerodynamic interaction: in-house model derived from CFD;
- Superstructure aerodynamic forces and windage: CFD-derived;
- Hull hydrodynamic forces: including resistance, leeway and rudder angle, derived from CFD;
- Engine model; and
- Propeller model.

The wing-to-wing interaction model takes the wing angle and camber of the interacting wings as inputs and provides the resulting changes in local wind speed and wind direction at the surrounding wings. These modified local conditions are then used to calculate the aerodynamic forces generated by each wing.

For each environmental and operational condition, the PPP solves for the vessel's force and moment equilibrium and optimises the operating condition to minimise fuel consumption. The resulting calculations provide the reference performance of the vessel, allowing the performance predicted by the lower-tier methods to be assessed against the high-fidelity reference.

The operating angle and camber of each WindWing are optimised simultaneously as part of the overall vessel optimisation. The optimum therefore does not necessarily correspond to maximum thrust from each individual wing. For example, slightly depowering an upstream wing may improve the flow available to a downstream wing and increase the overall system performance.

Tier I

Using the previously outlined OPERVENT formula [3] with the corresponding coefficients for WindWings®, a value for net power production can be obtained. Plugging the maximum lift coefficient, drag at maximum lift coefficient, and drag of the system in its off configuration into the OPERVENT formula gives us a power production value. For this, the coefficients associated with the wing sail are generated from CFD by BAR Technologies. Power production from the high-fidelity model is calculated by combining the power matrix with the IMO Global Wind Matrix statistics.

For comparison, the Tier I calculations are again compared to a high-fidelity PPP, which uses not only CFD-derived lift and drag curves but also accounts for interactions between WPS, including local changes in wind speed and angle. It also considers aerodynamic and hydrodynamic interactions between the WPS and ship (such as e.g. leeway), windage from the superstructure, and changes in propeller loading and efficiency. Moreover, atmospheric boundary layer wind profiles are used to represent wind variation with height. To obtain a solid reference point, the high-fidelity PPP used here has been independently validated by a third party using real measured data.

At 12 knots vessel speed this results in the following:

$$\frac{Tier\ 1\ Formula\ Power\ Production}{High\ Fidelity\ Power\ Production} = \frac{Tier\ 1\ Formula\ [\frac{kW}{m^2}]}{High\ Fidelity\ P.P.P.\ [\frac{kW}{m^2}]} = 1.1 \qquad (7)$$

In this case, the Tier I Formula overpredicts power production by 10% compared to the high-fidelity PPP. At the time of writing this case study, the Tier I formula does not account for interaction affects between the ship and WPS, or the interaction affects between WPS themselves. Reliability factors will be derived and applied to the Tier I power production formula to account for these effects; these will reduce the value that results from the formula. In contrast, the high-fidelity model accounts for both of these interaction affects.

More work is required to ensure the formula can be applied with varying weather conditions based on any specific route. The values that are used in the formula relating to the wind propulsion system itself should be verified by a 3rd party.

Tier II and III

For Tiers II and III sea trials are conducted to validate the WPS performance calculations. We first describe the on-off sea trials that were carried out, then show how the results are applied under each of Tiers I, II and III.

On-off test experience

An independent third party verified the performance of the retrofitted wind-assisted propulsion system on Pyxis Ocean. The verification focussed on a series of on-off tests that were performed on the vessel over an 8-month period. The tests followed the steps set out below.

Step 1:

The predicted power contribution matrix was determined according to ITTC 7.5-02-03-01.9 [9] Level IV using a performance prediction program (PPP) as described in section 46.2. This PPP is used to populate a power production matrix, listing WPS power as function of vessel speed, wind speed and angle (TWS, TWA).

The brake power savings calculated from on-off tests are then used to compare to these predictions.

Step 2:

An on-off test switches between two modes, where the sails are either active (on) on the one hand and inactive (off) on the other. It should be noted that the sails are a passive system, and do not require spinning or sucking power. The sails remain upright throughout the duration of the test; the off segment is represented by the wings being rotated into a position of minimal drag and zero lift (active feathered configuration). Each on or off segment consists of an approach time, and a measurement period where the measurement period is such that the vessel's speed has settled sufficiently. High frequency data was recorded by the ship which included the following channels: speed through water, speed over ground, course over ground, wind measurements, shaft power and shaft rpm, and rudder angle. Vessel draft was also recorded.

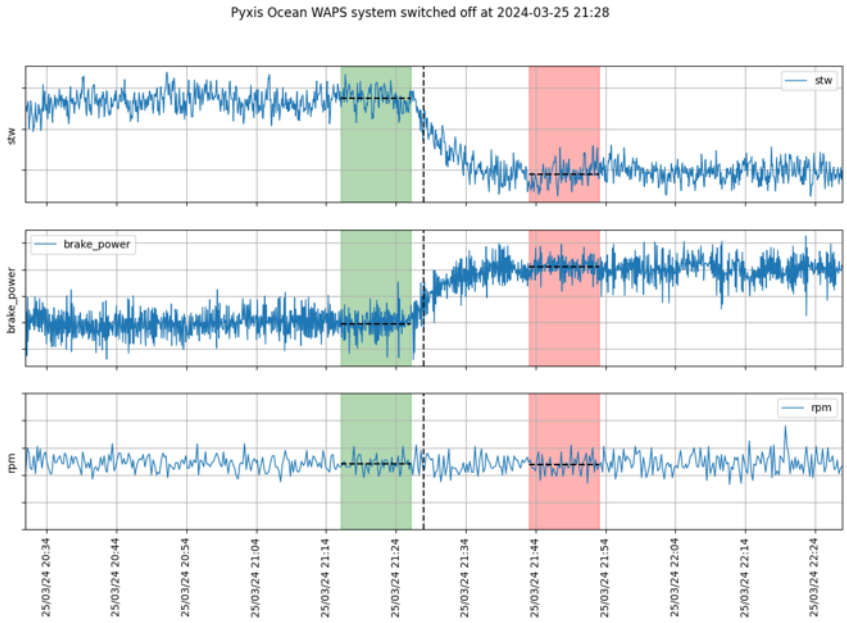


Figure 15: An example on off switch. Green is the "On" measurement period and the red is the "Off" measurement period; in between is the transition phase.

The live wind was measured by anemometers on the ship; these readings were corrected with CFD to account for accelerations and deflections due to the ship's hull and superstructure. Moreover, anemometers were installed at the bow and superstructure of the ship. Finally, the corrected wind data was verified against hindcast wind sources to ensure alignment.

An automatic procedure was applied by the 3rd party to identify switch instances between on and off modes (Figure 15), with the identified instances were double-checked manually. On-off switches were deemed to be acceptable only if propeller rpm, shaft power, heading and course over ground are sufficiently stable. The switches are also checked for significant changes in wind – if variation is too large, these tests are discarded. In total, 63 tests were accepted by the 3rd party verifiers.

As a verification of the measurement process and data integrity the 3rd party conducted an uncertainty analysis on the brake power saving results for the 3 following cases: on/on, off/off, stowed/stowed tests. In theory, the brake power saving for these fictional tests should be zero. The 3rd party expect the uncertainty of on/off tests to lie between the observed uncertainty of the on/on and stowed/stowed tests. The average standard deviation of error across the three variations of tests is 3% of the engine brake power, which is thus established as the measurement limit due to noise.

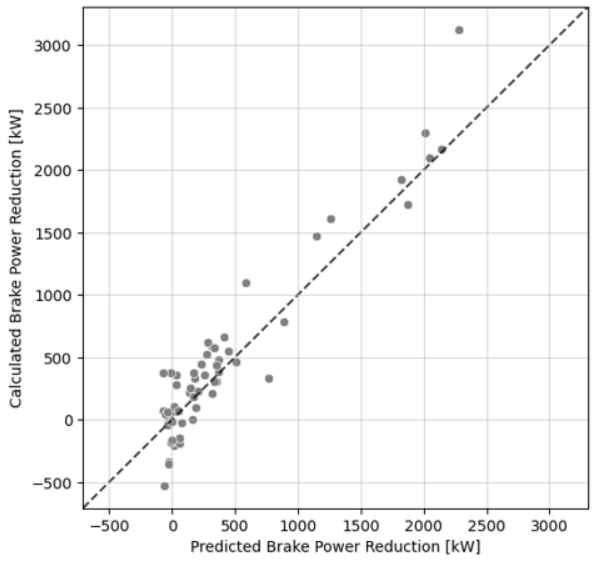


Figure 16: Comparison of calculated brake power saving from on-off tests vs predicted brake power saving (from the high-fidelity model (PPP, section 46.2).

A measure of error can be presented with a metric similar to Equation (2) from the Tier II. Here, w_k for each test is determined by linearly interpolating between the probabilities defined in the global wind matrix as a function of TWA and TWS. The error calculated between the measured brake power saving and the predicted brake power saving is normalised with the total engine brake power for a given test. This leads to:

$$\bar{E} = 4.2\%$$

Since this is relatively small, the calculations are thus deemed sufficiently accurate.

NOTE: For installations where the expected WPS power contribution is significantly smaller than in this case study, an error of 4% of the total engine brake power like in this case study might be relatively large and in the order of the measured effect (i.e. the WPS power contribution). This must be taken into account for example through a sufficiently large number of tests to ensure statistically robust and representative results.

Step 3:

As described in Step 2, high-frequency operational data is logged, including speed through water, wind speed, and wind angle. Using the brake power saving matrix populated in Step 1 and verified in Step 2, the actual brake power saving at each instance can now be determined by mapping each recorded data point (speed through water, wind speed, and wind angle) through the brake power saving matrix to its corresponding brake power saving value. This is done for each moment when the WPS was active, Finally, the results are aggregated along the ship's voyage (Figure 17).

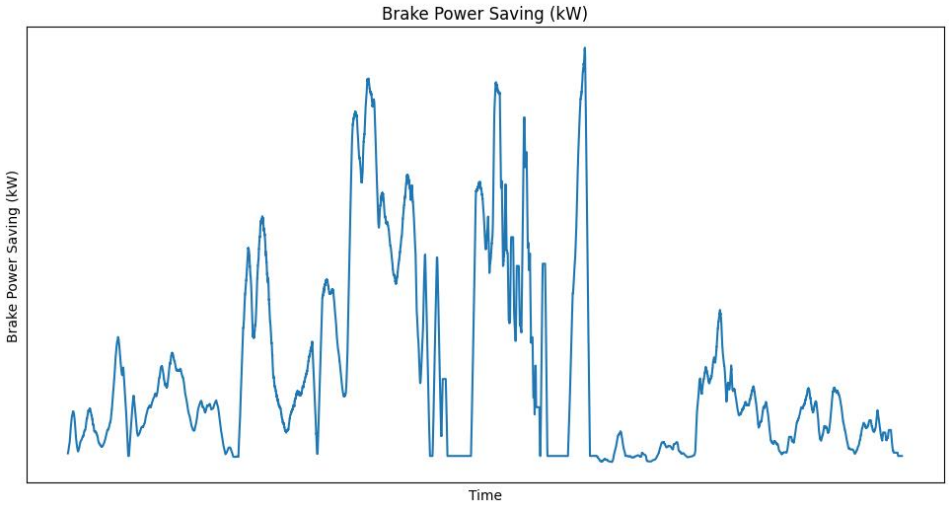


Figure 17: Brake power savings against time using a model validated by on off tests

In the present case study, the 3rd party verifier identified the wind measurements and the validity of the "off" mode as a no WPS representation as the main overall sources of uncertainty.

Comparison of results for Tier II vs. Tier III (hindcast vs. measured wind)
The process of section 46.4 is identical for Tiers II and III besides the source of the wind data used to calculate the WPS brake power savings from the power matrix. In the following part of this case study, we compare the results obtained from each respective wind source.

Based on the available hindcast data and corrected anemometer wind measurements, a comparison was carried out to assess the differences in predicted brake power savings when using hindcast wind data versus measured wind data. Moreover, the data is put in relation with results from Tier I.

A sample of 8 voyages was selected, and the savings over each voyage were calculated using predictions based on decoupled polars (where wind and wave effects are not assumed to be coupled). Hourly hindcast wind data was obtained from Copernicus (ERA5), while wave data is available at 3-hour intervals. Hindcast data was interpolated between timestamps where required. Although some wave parameters, such as wave height and wave period, are measured onboard, investigations into this wave data indicated that the hindcast wave data is more reliable and were therefore used throughout the analysis.

Figure 18 shows a scatter plot comparing anemometer-measured true wind speed (with CFD corrections applied) against hindcast ERA5 true wind speed. Further calibration of the anemometer measurements is possible using LiDAR data, if available. It can be seen that, if data collection is carried out rigorously, both sources yield virtually the same data.

It is the subject of ongoing investigations to determine whether this high correlation is due to a high agreement in instantaneous data, or if we observe rather an averaging effect over time, that is: sometimes ERA5 overpredicts, sometimes the on-board data overpredicts. Over a long enough period of time the effects average out and both datasets converge. Whatever is the reason, the result is encouraging: both methods yield almost the same input wind data into step 3 above.

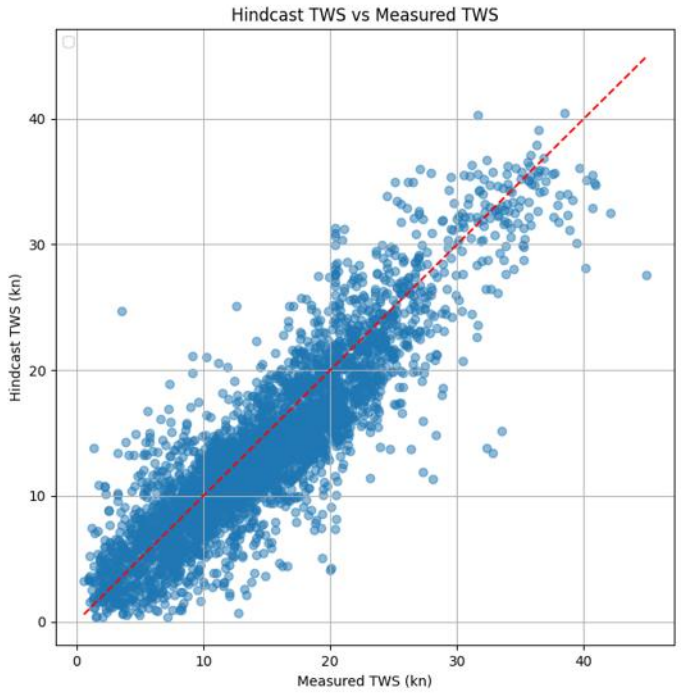


Figure 18: Hindcast and measured true wind speed comparison for the sample of 8 voyages. The ratio of hindcast/measured true wind speed = 0.97.

Once the wind data is available, average WPS brake power savings can be calculated following the method for Tiers II and III. For Tier I it is important to note that here the brake power savings are calculated from the spatio-temporal averages of global wind conditions defined in [3]. There is no factor applied for route specific conditions; Moreover, the average wind conditions smear over any temporal variations in wind conditions (e.g. wind vs not so windy voyages). Thus, compared on the basis of individual voyages, Tier I brake power savings are not expected to align very much with the savings calculated with hindcast or measured wind (tiers II and III). In the long run, however, when averaging over multiple voyages, the results from different tiers are expected to converge.

NOTE: For this case study, all brake power savings are calculated with measured speed through water, and draft. Tier II uses hindcast wind at hourly intervals, and Tier III uses measured anemometer wind with CFD corrections applied at hourly intervals where the data is averaged for that hour.

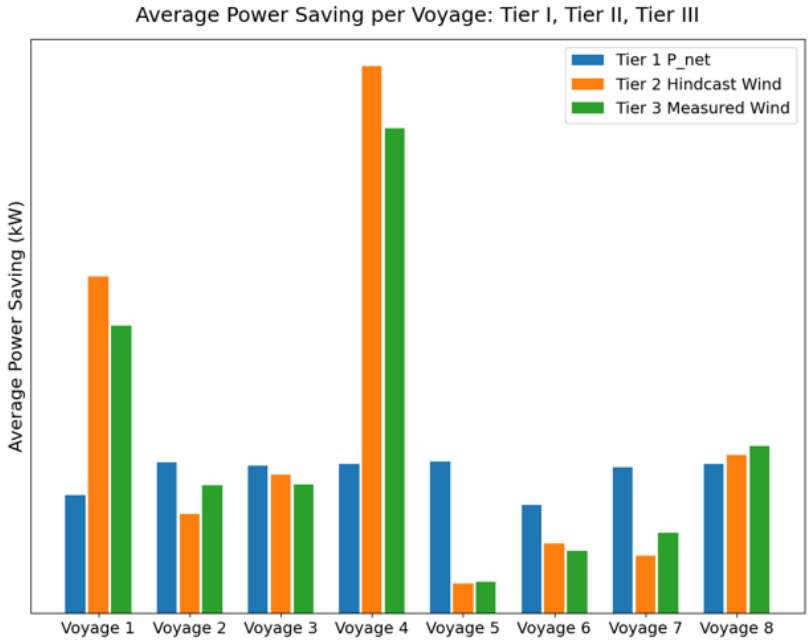


Figure 19: Comparison of calculated avg. brake power savings

The ratio of energy contributions calculated with hindcast wind (Tier II) compared to anemometer wind (Tier III) is calculated and presented below (Figure 20). The sailing hours are calculated for each voyage, and the order is independent of the order of voyages in Figure 19.

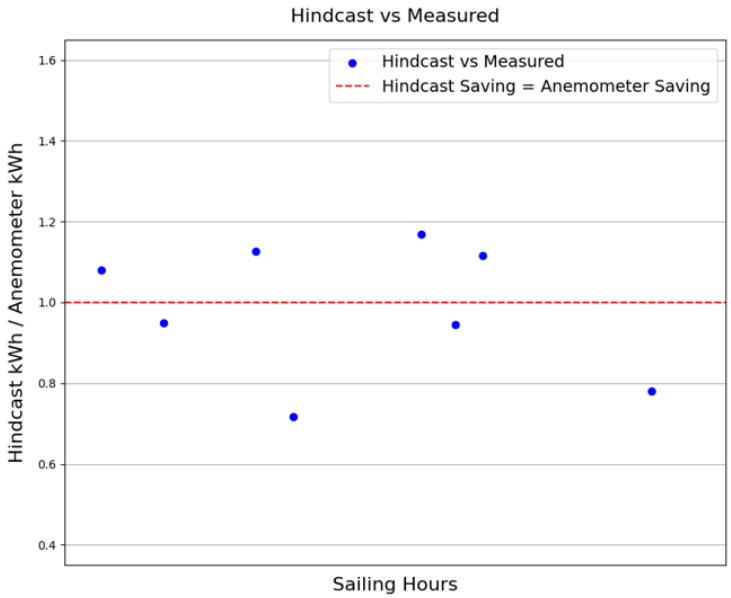


Figure 20: Hindcast wind brake power savings / measured wind brake power savings

We can calculate an error based on the brake power savings calculated from hindcast wind versus corrected anemometer wind. In the following we look at both

a) The root mean square error (RMSE), which gives us an idea of the difference in brake power saving to expect on average between Tier II vs Tier III results for a single voyage.
b) The mean error, which gives us an indication of the difference in brake power saving to expect on average between both tiers over many voyages accumulated.

The RMSE across the 8 voyages can be calculated as follows:

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{S_{H,i}}{S_{A,i}} - 1\right)^2} = 0.16 = 16\,\% \quad (8)$$

Where:

- $N = 8$: number of voyages in the sample
- $S_{H,i}$: predicted brake power saving for voyage i, using **hindcast** wind data
- $S_{A,i}$: predicted brake power saving for voyage i, using **anemometer**-measured wind data (CFD-corrected)
- Both $S_{H,i}$and $S_{A,i}$are computed with the same hindcast wave data, measured draft, and measured speed through water — so the only thing varying between them is the wind input

This rather significant divergence is expected because hindcast data points are typically available at hourly intervals and a spatial resolution of approximately 0.25°, limiting their ability to capture the local wind conditions experienced by the vessel. In contrast, a corrected shipboard anemometer provides direct measurements of the local wind and captures short-term fluctuations and gusts between hindcast timestamps.

On the other hand, since wind behaves almost like a Gaussian random process, the short-term differences between results from measured vs. hindcast wind on single voyages disappear almost completely when average over a longer time (i.e. over several voyages): Calculating the mean error for the complete sample of 8 voyages we obtain +2%. That means, after 8 voyages, the hindcast brake power savings are +2% higher than the anemometer wind brake power savings. This can be seen from the plot above as the relationship between hindcast and anemometer savings is scattered, with some hindcast data points higher than corrected anemometer data points, and some lower.

Conclusions

Comparing the Tier I brake power savings with the Tier III brake power savings, we find that, after eight voyages, the Tier I formula underpredicts the combined brake power savings by 19%. However, the mean square error is 147%, which is substantially higher because it is strongly influenced by large errors on individual voyages, rather than averaging these differences across the dataset. For example, Voyages 1, 4, and 5 show the largest discrepancies, where the averaged wind conditions used in the Tier I formula differ significantly from those actually experienced by the vessel. These discrepancies are expected to be reduced once regional weather-statistics datasets are defined for Tier I.

Table 13 summarizes the brake power saving results obtained from the calculations according to each of the first three tiers respectively. As can be seen Tier II and Tier III align well, and on average Tier I underestimates but is a fair representation of the brake power savings, yet on a route-by-route basis, we see large deviations which inflate RMS error.

Table 12: Comparison of brake power savings for the Pyxis Ocean (Kamsarmax bulk carrier) derived through different tiers of analysis.

	Tier I	Tier II	Tier III
Delta vs. Tier III (all voyages)	-19%	+2%	n/a (refs)
RMS error between Tier I and Tier III	147%	16%	n/a (refs)

Wind measurements are an important part of this case study. Thus, a few remarks:

Wind measurement – practical notes (bias and error)

To reduce uncertainty of wind measurements, anemometers should be installed as far away from ship structures and WPS devices as possible (cf. discussion under Tier III, sections 10ff). Additionally, is vital to apply corrections to the wind measurements to account for the flow field around the ship in order to obtain the most accurate wind readings. Ideally, anemometers should be installed at least at the ship's bow and at the superstructure; for example, if the only anemometer is at the bow, and the ship is sailing in a tailwind then the WPS devices may shelter the anemometer from the wind and result in inaccurate measurements. By installing anemometers at the bow and superstructure, depending on wind angle, either one or both can be used (and combined) to obtain the most reliable readings. This ensures the fairest comparison between predicted and measured results. Wind measurements must also be appropriately corrected for height.

It can be difficult to ensure that all biases and errors in anemometer measurements are corrected, which may result in brake power savings being over- or underestimated. One way to mitigate this is to use the same wind source for both the verification of the on–off tests and the calculation of brake power savings over complete voyages. In this way, any systematic bias in the wind measurements is largely accounted for once the Power Performance Prediction (PPP) model has been calibrated using a sufficient number of on–off tests. These on-off tests must span the full range of wind directions in order to ensure adequate calibration. Alternatively, both hindcast brake power savings and anemometer corrected brake power savings could be submitted to ensure that anemometer wind calculated brake power savings that are consistently above (or below) hindcast wind calculated brake power savings are flagged.

Wind measurement – next developments

This study considered the two sources of wind data currently available widely in practice. Both come with challenges. In one case (Tier II) the interpolation from hindcast data to the ships position. In the other (Tier III) the correction of disturbances of the wind at the site of measurement on deck due to the ship around. As a remedy, a third method, LiDAR measurements, is currently under development. LiDARs, currently at the verge of wider application, would resolve these issues, as they allow measuring the wind at the ship's position, but sufficiently removed from any interference with the ships structure to obtain real (undisturbed) data. Thus, once LiDAR data is available, should receive the highest reliability factor, as they provide the most accurate representation of the undisturbed wind field and are widely regarded as the highest-quality reference for wind measurements. There is analysis that has been conducted on wind uncertainty that can help determine the exact magnitude of the reliability factors.

Tier IV performance assessments are still under development. Nonetheless, to give the reader an impression of the shape a Tier IV performance analysis could take, we present another example of a Tier IV analysis below. This example is still incomplete. It is offered in addition to Case Study 2 (page 36) for further illustration of the method rather than to report a verified result.

For this example, BAR Technologies has integrated a load measurement system based on fibre optic strain gauges into a three-element rigid wing sail. This example follows method 1a (paragraph 21.1): With the help of strain gauges, the employed system thus allows to measure WPS loads transferred to the ship.

The fibre optic strain gauges calculate a delta strain from a known reference strain; therefore, they must be calibrated at a point in time when the loads are known. Three calibration approaches were evaluated: factory calibration prior to installation, calibration during wing raising operations (max bending moment), and in-situ calibration with the wings in a feathered configuration under controlled conditions (minimum bending moment) — calm seas, low wind speeds, level vessel trim, and a negligible angle of attack (<3°).

As discussed above (paragraph 21.4), the process confirmed vessel motions, such as roll and trim, as critical factors that required compensation. This is both in terms of long-term trends as well as wave induced oscillations and thus parasitic inertial loads. Since aerodynamic loads generated by the WSP system are frequently smaller than the gravitational and inertial loads acting on the wing, accurate motion correction is essential for reliable force measurement. Moreover, vibrations were found to introduce oscillatory noise and aliasing into the acceleration data (c.f. paragraph 21.4). These also required filtering and careful consideration within the analysis methodology – it is suspected that the source of these vibrations is from the engine or ship's hull.

Temperature compensation is accounted for with temperature sensors installed at each strain gauge location. It is assumed that any thermal stresses due to different components moving at different rates are low.

Initial results demonstrate a strong correlation between predicted and measured thrust and side-force values. BAR Technologies are continuing to develop this strain gauge method in close cooperation with suppliers.

For this example, two sails were instrumented with stain gauges:

A. For one sail, the strain gauges were installed at the base of the sail only.
B. A second, identical sail was instrumented all the way up the mast.

Thus, for sail A, a bending moment at the mast base is measured. To transfer this bending moment into a thrust force, the location (height) of the aerodynamic centre of sail loads has to be known. In the absence of a complete verification of the centre of pressure using the gauges up the mast, the aerodynamic centre of pressure was assumed for thrust force calculation based on the atmospheric boundary layer. A sensitivity study was performed to analyse the variation in measured force values with centre of pressure.

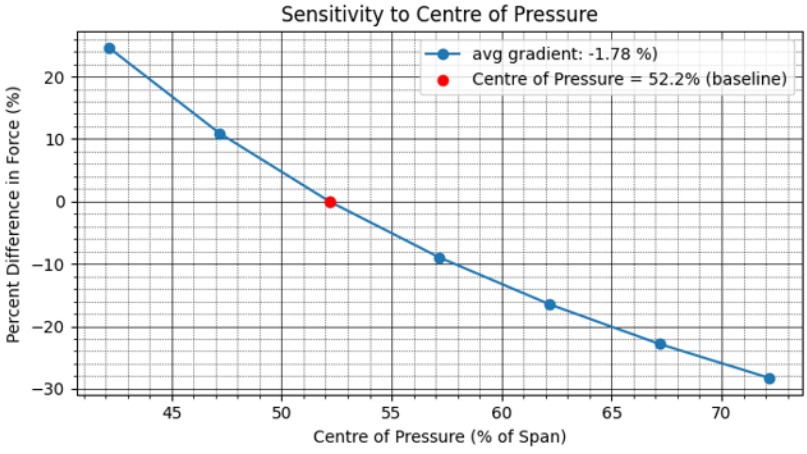


Figure 21: Sensitivity analysis of centre of pressure with force measurement

The baseline value (red dot – 52.2% of the wingspan) is calculated assuming an atmospheric boundary later profile, this assumption is reasonable because the top and bottom endplates are both identical and symmetrical, and the separation between the deck and the bottom of the wing is sufficiently large. This baseline value will be different for different systems. The above plot demonstrates how small errors in the centre of pressure can lead to relatively large errors in the force readings. These differences are quickly comparable to the errors in brake power savings using hindcast wind vs anemometer wind (cf. 46.4); this highlights the importance of this verification of centre of pressure.

Sail B, the forward WindWing® on Pyxis Ocean (cf. paragraph 46.1) has strain gauges installed up the entire span. This allows the assumption on the aerodynamic centre of effort to be verified (work yet to be performed). Ideally, strain gauges would be installed up the span of every device for this verification.

NOTE: Strain gauge reliability appears to vary between different systems and suppliers. It is essential to ensure close cooperation with suppliers to ensure correct installation and processing of data.

The conversion from load to brake power savings (paragraph 21.1, part 2) and the associated verification sea trials have not yet been carried out. As described above, this step will additionally account for the hydrodynamic effects introduced by the installed WPS, with the resulting force-to-power conversion verified against sea trial results (e.g. ON-OFF tests).

Details of this analysis are presented in [5].

Case Study 4: OceanWings Use Case (Tier I, II & III Evaluation)

This case study, provided by OceanWings, presents a real-world application of the proposed tiered framework, based on continuous operational data collected over more than 20 commercial transatlantic voyages of a Ro-Ro vessel equipped with four OceanWings wing sails.

Ship properties
The principal particulars of *the Ro-Ro vessel*, together with the vessel characteristics relevant to the assessment, are provided in Table 14.

Table 15 provides an overview of the analyses performed using the different tier methods in this study. It compares the approaches, core inputs and level of physical modelling applied in each tier, illustrating the increasing level of detail and the use of increasingly vessel- and operation-specific information.

Table 13: Summary of ship parameters as used in Case Study 4.

Parameter	Value / Description
Vessel Type	Open-deck Ro-Ro
Length Overall (LOA) / Beam	121.0 m / 22.0 m
Design Speed	16.5 knots
WPS Configuration	4 × OceanWings® OW363 (2-element articulated wingsails)
Total Sail Area	1,452 m² (4 × 363 m²)
Operational Route	Transatlantic: Europe ↔ French Guiana

Table 14: Overview of analyses through different tier methods included in this case study.

Assessment dimension	Tier I-a	Tier I-b	Tier II	Tier III
Approach	OPERVENT empirical formula.	CFD-derived aerodynamic force matrix including wing-wing and ship-wing aerodynamic interactions.	Ship-specific digital twin model calibrated on sea trials, using hindcast as input.	Same calibrated model as Tier II, using onboard wind measurements as input.
Core inputs	Basic WPS geometry, coefficients, vessel speed and draft.	Fx / Fy matrices, device consumption and operating vessel parameters.	Ship polars, GPS track, wave, current and wind hindcasts.	Ship polars, GPS track, wave and current hindcasts, and onboard wind measurements.

Assessment dimension	Tier I-a	Tier I-b	Tier II	Tier III
Physics captured	Simplified aerodynamic contribution without device-device or ship-device interaction. Simplified leeway-induced resistance.	Ship-device and device-device aerodynamic interactions, leeway induced drag either empirical or high-fidelity.	4-DoF equilibrium PPP with calibrated propulsion, rudder, leeway, windage and wave effects.	Tier II physics with onboard wind measurement.
Wind input	AWA & AWS representative of the wind encountered in the geographical areas being crossed.	Statistical wind matrix corresponding to the geographical areas being crossed.	Hindcast wind interpolated hourly along the actual route.	Onboard anemometer measurements corrected for ship flow disturbance.

Tier I-a (OPERVENT Formula) – Validation of the aerodynamic term
To evaluate the pure aerodynamic formulation independently of hydrodynamic coupling, the aerodynamic term of the OPERVENT formula was compared again (similar to case study 1, sections 26-38) to the CFD-based aerodynamics of a single OceanWings® 363. The pure aerodynamic power ratio is calculated according to Equation (9).

$$\frac{P_{OV}}{P_{CFD}} = 1.03 \qquad \textit{at the design speed}. \tag{9}$$

With

P_{OV} the power obtained from the from OPERVENT formula [3], and

P_{CFD} the power from detailed CFD simulations.

At the design speed. $\frac{P_{OV}}{P_{CFD}} = 1.03$ is obtained. Thus, similar to case study 1, the aerodynamic term of the OPERVENT formula shows less than 3% deviation from our high-fidelity CFD simulations which demonstrates that its framework allows a good match when supplied by lift and drag coefficients coming from CFD.

Multi-Tier Comparative Analysis: Tier I-b, Tier II & Tier III
Building on the aerodynamic validation above, this section compares the brake power savings estimated for Tier I-b, Tier II and Tier III, and examines the modelling differences that account for the remaining discrepancies between them.

Third-party validations of baseline data

The CFD full-ship model considered in Tier I-b has been validated by Bureau Veritas (BV) in accordance with IMO Circ 896 [6] for the calculation of the EEDI and the generic methodology was validated by DNV. Besides, the sea trials used as reference to calibrate the digital twin in Tiers II and III were conducted during the ship's first transatlantic crossing by Marin.

Average Brake Power savings

The calibrated multi-DoF Digital Twin (described above) was now evaluated over operational windows from more than 20 transatlantic voyages. Brake-power saving is assessed at each time step as $\Delta P_b = P_{b,\text{wings OFF}} - P_{b,\text{wings ON}}$ evaluated along the actual vessel track and at the measured ship speed, see Figure 23.

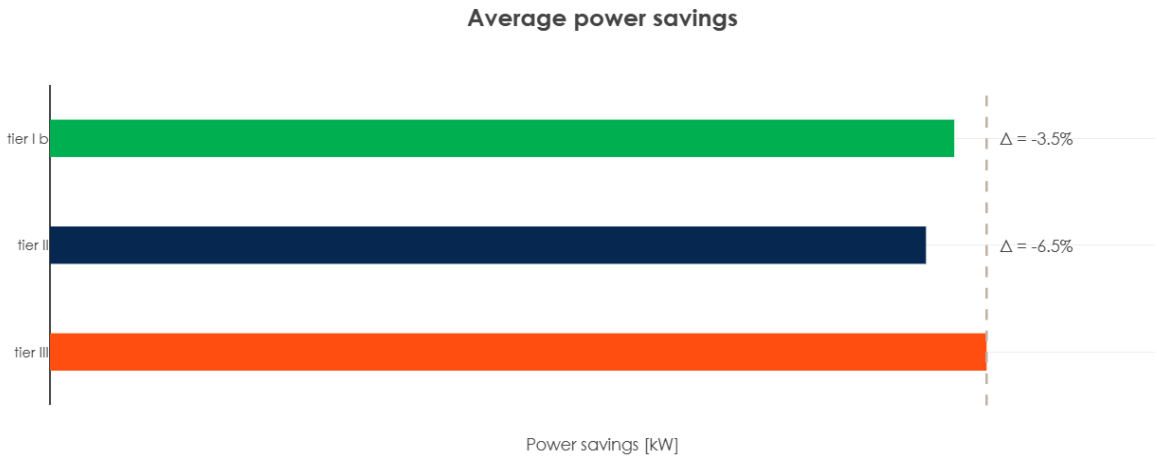


Figure 22: Average brake power savings of Tier I-b, Tier II and Tier III. Tier III considered as the reference.

Tier I-b vs. Tiers II and III

Tier I-b shows good overall agreement with Tier II and Tier III estimations. The aerodynamics being the same for the three tiers (full-ship CFD), the slight discrepancy arises from the following modelling differences:

- **Wind input & routing**: Tier I-b relies on 30-year statistical hindcast wind matrices applied along the Great Circle route, whereas Tier II and Tier III reflect actual weather-routing optimisation, i.e. the wind experienced along the vessel's real optimised track rather than the theoretical shortest path.
- **Ship speed and propulsion efficiency** are held constant in Tier I-b, while Tier II and Tier III compute them via the Power Prediction Program (PPP) for each operational condition encountered along the route.
- **Hydrodynamics**: Tier I-b does not account for added wave resistance or ocean currents. By contrast, Tiers II and III solve a full 4-DoF hydrodynamic equilibrium at each time step, incorporating leeway-induced drag, rudder angle adjustment, wave resistance, and ocean current effects.

Tier II (Hindcast) vs. Tier III (Onboard logs)

Tiers II and III use the same calibrated digital twin and differ only in their wind input, such that the comparison below isolates the effect of the wind source on the estimated brake power savings (hindcast versus onboard measurement):

- Tier II input: hourly metocean hindcast data (ECMWF - ERA5), interpolated along the GPS track.
- Tier III input: 5-mn averaged wind from onboard anemometers, corrected based on CFD to account for flow disturbance from the ship.

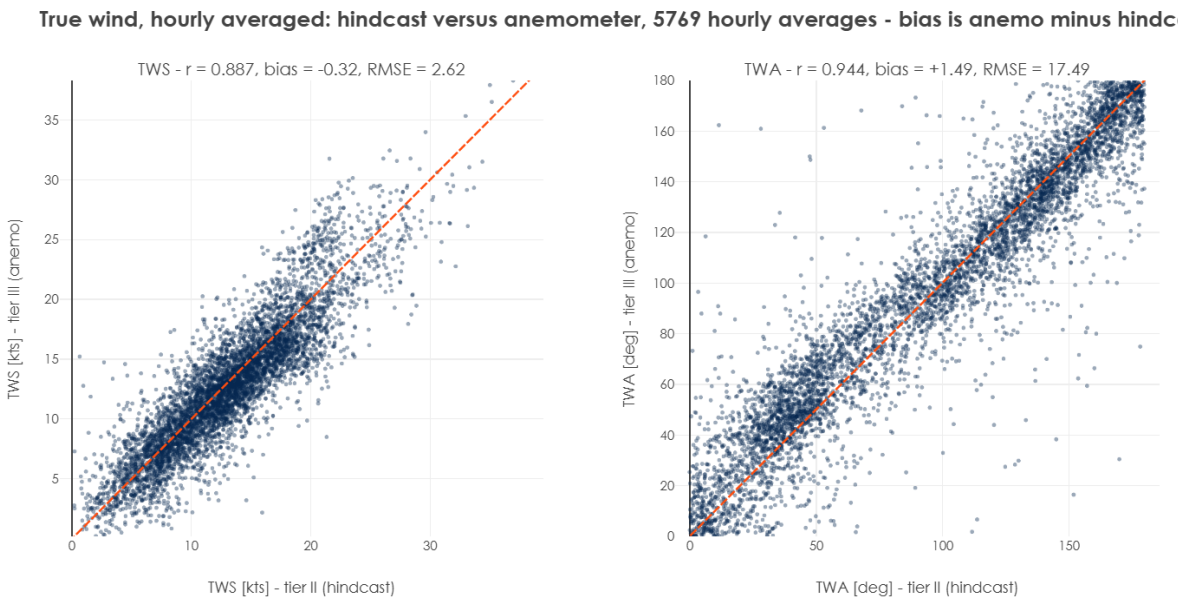


Figure 23: True wind speed and direction correlation between ERA5 hindcast and onboard logs.

First, it should be noted that none of these wind sources represents an absolute ground truth. Uncertainty remains both in the onboard measurement and in the hindcast data, which rely on highly robust but imperfect models.

The wind correlation plots in Figure 24 compare the same operational windows using two independent wind-input chains. As above, Figure 18 (case study 3), hindcast and measured winds align well across the multi-voyage dataset both in speed and direction, with very small bias. This validates the calculation chain to derive the true wind at 10m height from onboard measurements.

Figure 25 illustrates the wind-input time series and shows how 1-hour averaging, compared with 5-minute averaging, influences the estimated brake-power savings. The time series confirms the strong agreement between hindcast (Tier II, blue line) and anemometer (Tier III, orange line) measurements. It also highlights the level of wind fluctuations of the 5-minute average compared to the 1-hour average, and that these variations can propagate into large brake-power saving variations.

Figure 26 shows how Tier II and Tier III compares on a voyage-by-voyage basis. As above, Table 13 (case study 3), the two tiers show good agreement on average over the 23 transatlantic navigations combined. With less than 7% difference in estimated mean brake-power saving this number agree even better than above. Moreover, an interesting point to note is the low impact (-1.7% on 23 voyages) of the hourly averaging of the wind measurement on the average power of each navigation. In other words, the power fluctuations observed on the 5 min-frequency in Figure 25 almost averages out over each navigation and they are not the main source of deviation between hindcasts and measurements. It can be noted that although the frequency effect is limited, increasing the frequency always tends to slightly increase the brake power savings of Tier III because of the nonlinear convex shape of the wind speed to power relation.

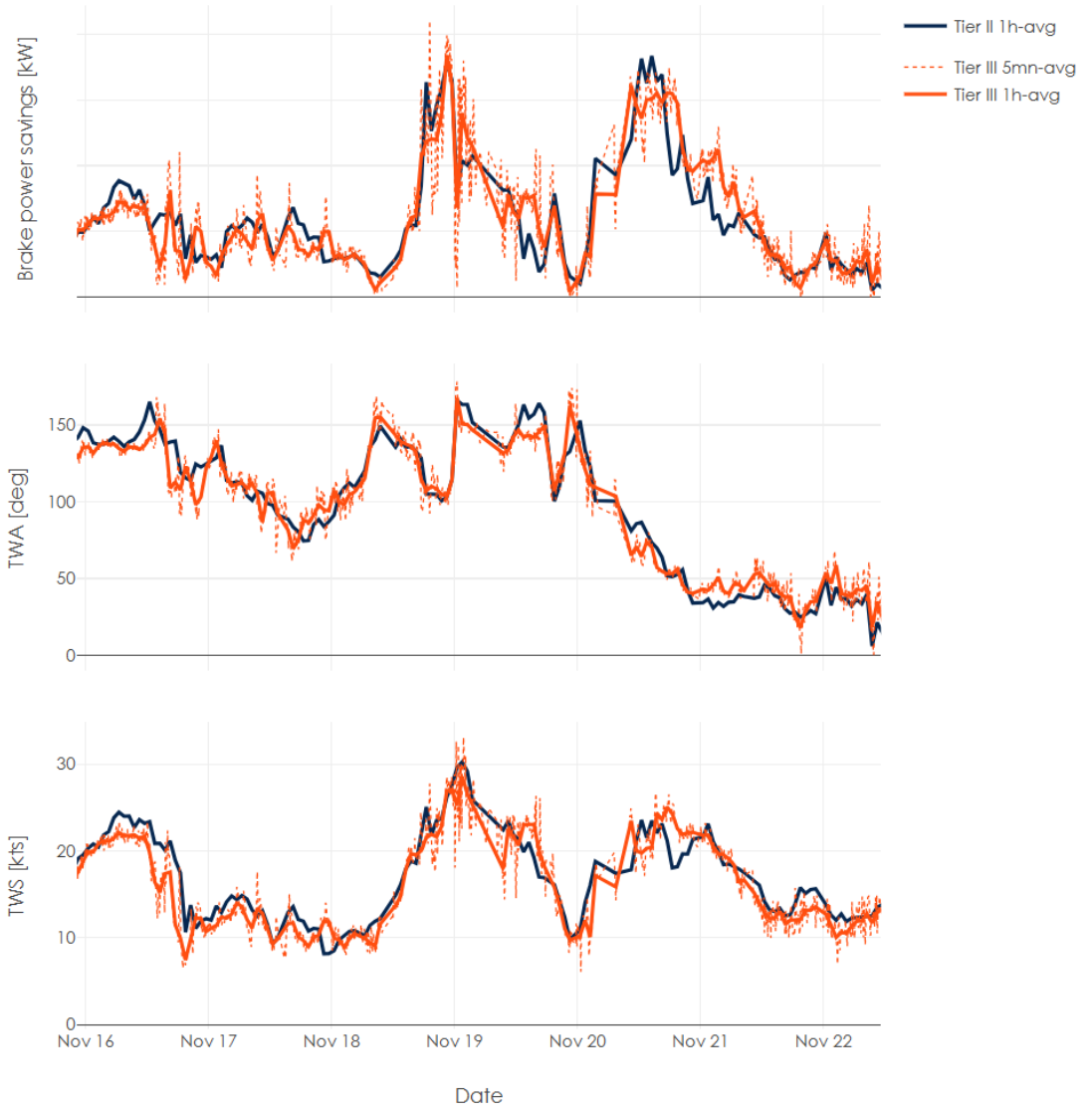


Figure 24 Wind-input time series and brake-power savings sensitivity to 5-minute and 1-hour averaging



Figure 25: Voyage-by-voyage brake-power savings comparison for 23 transatlantic crossings.

Conclusions

These results validate the tiered framework proposed for regulatory GFI reporting. Key quantitative outcomes from this study are summarised below:

- **Tier I-a aerodynamic accuracy**: The OPERVENT formula deviates by less than 3% from high-fidelity CFD results when supplied with CFD-derived lift and drag coefficients, confirming its suitability as a lightweight model.
- **Tier I-b reliability**: Tier I-b provides good overall agreement with Tier II and Tier III while remaining a simplified Tier I method. Its use of full-ship CFD captures ship–device and device–device aerodynamic interactions, supporting a higher reliability factor than Tier Ia.
- **Tier II vs. Tier III convergence**: Across 23 transatlantic voyages, the mean brake-power savings estimated by Tier II (ERA5 hindcast) and Tier III (corrected onboard measurements) differ by less than 7%, demonstrating the robustness of the hindcast-based approach over a multi-voyage dataset. That said, Tier III justifies a higher reliability factor than Tier II as it captures local wind effects. It is however highly recommended to check the local measurement against hindcasts to verify that there is no significant bias.

Taken together, these results provide a real-world basis for assigning differentiated reliability factors across the different tiers. The data support the position that Tier I-b and above should benefit from a meaningfully higher reliability factor than Tier I-a, and that the <7% convergence between Tier II and Tier III validates the use of ERA5 hindcast as a credible alternative to onboard measurement. While short-term wind fluctuations at the 5-minute scale can create substantial variability in estimated brake power savings, these oscillations average out over full voyages. This supports the use of time-averaged or hindcast-based wind inputs for GFI regulatory reporting, where annual or multi-voyage averages are the relevant metric.

Additional examples:

A – Sea Trials. Werner and Olsson [14] present a possible approach to WPS sea trials based on ON–OFF testing, in which the system is alternately activated and deactivated over short runs. This follows documented procedures available from ITTC [10]. An ISO working group was formed in December 2025 to consolidate these on the ITTC baseline. The paper sets out how such trials should be conducted and analyzed so that the result is defensible. It identifies the factors that govern accuracy – ocean current, the choice of speed–power curve and, above all, apparent wind angle uncertainty – and gives concrete measures for controlling each: trials at constant speed, high-quality wind measurement supported by calibration or CFD correction. It also proposes an acceptance criterion combining the comparison error with the validation uncertainty and demonstrates the complete process on a real multi-month campaign. The authors note that their methodology requires testing on a larger set of real cases before inclusion in recommended procedures.

B – Direct Force Measurements – Tier IV. Voutilainen and Paakkari [13] present a methodology for continuously measuring the performance of wind propulsion systems in full-scale operation, using direct measurements of sail thrust and lateral force together with ship shaft power and speed. For the rotor-sail application studied, the sail forces are obtained from surface-pressure measurements around the rotor, and a power-ratio formulation is used to translate the measured sail contribution into a reduction in main-engine power demand. The methodology accounts for the effects of sail-induced lateral force, drift, rudder action and changes in propeller efficiency, as well as the power consumed by the rotor sail, to derive a net wind-propulsion benefit. The approach is first assessed using a numerical 3-DOF ship model, where the predicted brake power savings generally agree within ±5% with equivalent numerical ON–OFF tests, with the largest deviations occurring in conditions where the sail produces predominantly lateral force. It is then demonstrated on a 154.5 m Ro-Ro vessel equipped with two rotor sails, using full-scale measurements over a range of wind and operating conditions. Comparison with conventional ON–OFF measurements yield good correlation, with an average difference of 6.9% and an RMSE of 74 kW for the independent measurements. The authors note that the current full-scale dataset is limited and that further validation is required but conclude that continuous measurement can provide a practical means of monitoring wind-propulsion performance across a broad range of operating conditions and over the lifetime of the system.

C – FEM-calibrated force measurement. The MARIN Green Deal validation study [12] demonstrates an in-service methodology for measuring the aerodynamic thrust and side force generated by Econowind VentiFoil® suction sails using strain gauges installed directly on the wing foundations. Twelve piezo-electric strain gauges were installed on the two foundations, with six sensors per side. A finite-element model was used to establish the relationship between measured structural strains and applied longitudinal and transverse forces through a conversion matrix. The system was integrated with measurements of wind, ship speed, shaft torque, propeller rpm, rudder angle and VentiFoil electrical power consumption, enabling wind-propulsion forces and vessel performance to be assessed simultaneously.

Dedicated sea trials comprising 37 runs covered different wind directions, VentiFoil configurations, angles of attack and suction-power settings, including single- and two-foil configurations to investigate interaction between the units. The monitoring system subsequently remained operational from October 2022 to August 2024, demonstrating its suitability for extended operational data collection. Although the WPS was operational for only part of the sailing time, the study demonstrates the feasibility of combining direct aerodynamic force measurement, ship-performance measurements and dedicated ON/OFF trials within an operational validation framework.

The project also showed that measuring the loads in the foundation of a WPS may require further improvement and investigation in two respects: 1) In an existing foundation which was not specifically engineered it is generally possible to determine only the local pitch and roll loads, not thrust and side force. An assumption about the centre-of-effort height is then required to calculate thrust and side force. The resulting uncertainty should be further investigated. The approach could also be improved by measuring pitch and roll loads at multiple heights, which would allow the centre of effort to be identified with some accuracy from the measurement itself. 2) It should be investigated how corrections for sensor drift and for inertia (also accounting for ice, fouling, or other changes to the structure) can be robustly implemented over the ship's lifetime.

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