Data-Driven, Route-Specific Framework for Wind-Assisted Propulsion Systems (WAPS) in Ship Design

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Abstract

Wind-assisted propulsion systems reduce fuel use and emissions, but performance depends on real weather and ship energy systems. This study presents a data-driven method integrating WAPS evaluation into ship design and energy modelling. AIS data are combined with ERA5 and Copernicus Marine datasets to reconstruct route-specific wind, wave, and temperature conditions. These inputs are used to estimate resistance, thrust, fuel consumption, and emissions under realistic operations. Seasonal variability is included by resampling voyages with different weather conditions. The method replaces simplified weather margins with real environmental data, improving prediction accuracy and supporting better design decisions for wind-assisted ships and regulatory compliance.

1. Introduction

Maritime shipping accounts for approximately 3% of global greenhouse gas emissions, and ship operators face increasing regulatory pressure to reduce fuel consumption and carbon footprint through frameworks such as the Carbon Intensity Indicator (CII) and the Fuel EU Maritime regulatory package. Consequently, modern ship designs include typically readiness for various energy sources, such as alternative fuels, renewable energy such as solar or wind and batteries and shore power. Also, energy efficiency optimization is an important part of ship design, and the regulatory requirements are typically connected to the ship energy- or emission performance as a function of the ship operational profile.

Wind-assisted propulsion systems (WAPS) are an interesting solution for many ship types to both reduce the ship energy consumption and decarbonize part of the ship energy mix. However, the assessment of WAPS performance in ship design is traditionally conducted in isolation: under ideal wind conditions, at a single service speed, and without explicit consideration of actual voyage characteristics. This approach leads to inflated performance estimates and design decisions that do not reflect operational reality. Advanced weather-integrated WAPS methods are not new; their novelty here lies in embedding them into the ship designer's standard toolbox for conceptual design, making rigorous, route-specific WAPS assessment accessible during the earliest stages of development rather than as a specialized, resource-intensive post-design exercise. The fundamental challenge is that WAPS performance depends critically on:

- Encountered wind speed, direction, and variability along the vessel's route
- Sea state (waves) and resulting added resistance
- Seasonal and route-specific meteorological patterns

Traditional ship design methods employ fixed empirical sea margins without accounting for route-specific weather variability. This paper presents an alternative: a data-driven methodology that replaces generic weather margins with actual metocean data extracted from global repositories.
The core innovation lies in the integration of three complementary datasets and models: Historical

AIS (Automatic Identification System) vessel data, defining actual voyage tracks. Global meteorological and oceanographic data from Copernicus (ERA5 wind, CMEMS wave) via automated API access, ship-specific hydrodynamic modeling via DeltaSeas, which couples wind propulsion, resistance, and rudder dynamics. This paper focuses on the weather data methodology and its integration with hydrodynamic modeling, demonstrating how terabytes of global climate data can be systematically accessed, organized, and interpolated to support route-specific ship design analysis.

2. Literature review

2.1. Development of Wind-Assisted Propulsion in Modern Shipping

Wind-assisted propulsion systems (WAPS) have re-emerged as a promising decarbonization solution for commercial shipping due to increasing environmental regulations and rising pressure to reduce fuel consumption and greenhouse gas emissions. The recent growth of WAPS is mainly driven by the shipping industry’s effort to reduce emissions and fuel consumption in response to international regulations, like the EU Green Deal. International regulations such as the IMO Initial and Revised GHG Strategies, together with measures including EEXI, CII, and the EU FuelEU Maritime framework, have increased the importance of operational energy efficiency and alternative propulsion concepts, *DNV (2025)*. Several recent studies have demonstrated that WAPS can reduce fuel consumption and emissions under suitable operating conditions, particularly on routes with consistent favorable wind climates, *Elg et al. (2025), Sandberg et al. (2023)*. However, reported performance varies significantly depending on vessel type, operational profile, route geometry, and prevailing metocean conditions, highlighting the importance of voyage-specific assessment rather than generalized performance assumptions, *Ma et al. (2023), Mason (2021)*.

2.2. Overview of Wind-Assisted Propulsion Technologies

Modern WAPS technologies include rotor sails, wing sails, suction wings, kites, and other sail-assisted systems, *Tillig and Ringsberg (2020)*. These technologies use wind to provide additional thrust and reduce engine power demand. Some systems, such as rotor sails, are already installed on commercial vessels including tankers, RoRo ships, and ferries, *DNV (2025)*. The performance of WAPS depends mainly on wind conditions, vessel speed, and route characteristics, *Ma et al. (2023)*.

Previous studies show that fuel savings from WAPS can vary significantly between different ships and operating routes, *Tillig and Ringsberg (2020)*. Better performance is usually achieved on routes with stable and favorable wind conditions, while coastal operations and changing weather can reduce the overall benefit, *Rehmatulla et al. (2017)*. Therefore, the effectiveness of WAPS should be evaluated using real operational and environmental data over complete voyages rather than ideal operating conditions alone, *Mason (2021)*.

2.3. Challenges in WAPS Assessment

A major challenge in evaluating wind-assisted propulsion systems is the difference between theoretical performance estimates and actual operational results. Previous studies have shown that simplified approaches often overestimate fuel savings because they do not fully account for realistic operating conditions, *Ma et al. (2023), Tillig and Ringsberg (2020)*. In many cases, average wind statistics are used instead of route-specific weather data, while operational factors such as seasonal variations, ship loading condition, slow steaming, and port operations are also simplified. In addition, the interaction between aerodynamic forces, ship resistance, and propulsion performance can reduce the net benefit of WAPS under real sailing conditions.

Several studies have demonstrated that WAPS performance depends strongly on vessel type, operating profile, and trade route. Routes with stable and favorable wind conditions generally show higher savings potential, while constrained coastal routes or unfavorable wind directions can significantly reduce effectiveness. These findings highlight the importance of using realistic operational and environmental data when evaluating WAPS performance, *Mason (2021)*. Based on these considerations, the present study applies a voyage-based assessment approach using measured operational data together with detailed weather and sea-state conditions along the route. Rather than relying on idealized assumptions, the methodology evaluates WAPS performance under realistic tanker operating conditions, including varying wind environments, ship speed, and propulsion demand throughout the voyage.

3. Methodology

3.1. Weather Data Methodology and Challenges

Modern meteorological and oceanographic reanalysis datasets, such as ERA5 *ECMWF (2018)* for atmospheric conditions 0and Copernicus Marine for marine conditions, provide long-term global coverage over several decades. They include key environmental variables such as wind, waves, air and sea temperature, and ocean currents at relatively high spatial and temporal resolution.

Because these datasets cover the entire globe and are stored at frequent time intervals, typically hourly or three-hourly, they generate very large data volumes. Even a single year of data can consist of millions of grid points and thousands of time steps, and when multiple variables are combined, the total storage requirement can reach several terabytes. As a result, using these datasets for engineering applications such as voyage simulation or performance analysis requires significant computational resources.

This scale of data introduces practical limitations in terms of storage, data transfer, and processing. Full-resolution global datasets are often difficult to handle on standard computing systems, and conventional sequential processing methods are inefficient for such large inputs. To address these challenges, our study uses an automated data processing method that splits the global data into smaller spatial and temporal parts, Fig.1. This makes it possible to process the information more efficiently while keeping enough detail for voyage-level analysis.

In practice, the global domain is divided into predefined geographic zones using polygon boundaries. Each zone covers a specific region of the world on a regional scale. For each zone and data source, the relevant historical wind, wave, and ocean data are pre-processed and stored in separate zone-based datasets.

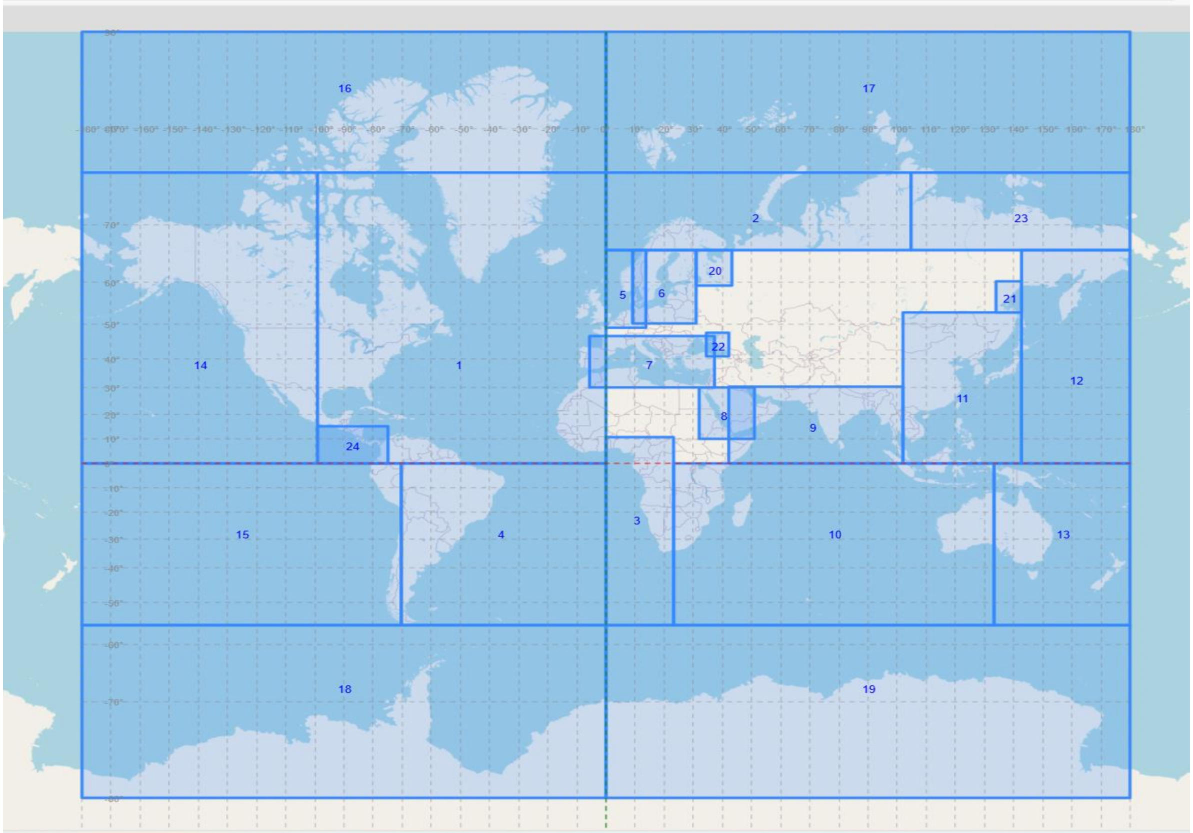


Fig.1: The segmentation of the world into 24 zones

This approach improves efficiency by allowing the data to be processed in parallel, reduces computational load, and makes the workflow scalable when adding new regions. It also simplifies data storage and is well suited for multi-zone vessel routes, where voyages pass through different environmental regions.

3.2. Data Sources and Characteristics

3.2.1. Oceanographic Data: CMEMS Global Wave Analysis and Forecast

Wave conditions are obtained from the Copernicus Marine Environment Monitoring Service (CMEMS) product GLOBAL_ANALYSISFORECAST_WAV_001_027. This dataset provides globally consistent wave information derived from numerical wave modelling. It has a spatial resolution of approximately 1/12° (about 8–9 km) and a daily temporal resolution. The key variables used in this study include significant wave height (VHM0), mean wave direction (VMDR), and peak wave period (VTPK). These parameters are used to describe the prevailing sea state along the vessel routes and are essential for estimating wave-induced added resistance, which significantly contributes to total propulsion power demand in open-ocean conditions.

3.3. Atmospheric Data: ERA5 Reanalysis

Atmospheric conditions are taken from the ERA5 reanalysis dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), covering the period from 1940 to present. ERA5 provides globally consistent hourly weather data at a spatial resolution of 0.25° (approximately 31 km). The main variables used in this study are the 10 m zonal and meridional wind components (u10 and v10), the 2 m air temperature (t2m), and the sea surface temperature (sst). Wind data is used to compute apparent wind conditions, aerodynamic resistance, and the potential performance benefits of wind-assisted propulsion systems, while temperature data provides additional environmental context for operational and route analysis.

4. DeltaSeas Hydrodynamic and Aerodynamic Modeling Framework

DeltaSeas is Deltamarin's in-house propulsion modelling tool, developed specifically for the analysis of ship performance under real sea conditions. The hydrodynamic and aerodynamic performance calculations in this publication were carried out using the DeltaSeas framework, which combines calm-water resistance, wave-added resistance, aerodynamic effects, and rudder dynamics to estimate the vessel's required propulsion power under realistic operating conditions. Calm-water performance was derived from baseline speed–power curves obtained from towing tank and CFD data, while environmental effects were incorporated using measured operational and metocean conditions. Wave-added resistance was estimated using the STAWAVE-II method, which evaluates the increase in ship resistance caused by wave conditions and vessel motions in seaways. Depending on wave severity and operational conditions, wave-induced resistance can significantly increase the required propulsion power compared to calm-water operation.

In addition to hydrodynamic resistance, the model also considers aerodynamic forces generated by wind acting on the hull, superstructure, and wind-assisted propulsion systems. Apparent wind conditions were used to calculate air resistance and sail-related forces, including the effects of wind angle and sail operating conditions. The framework iteratively balances hydrodynamic and aerodynamic forces and moments to determine the resulting drift angle, rudder response, and effective thrust requirement at each timestep. This approach enables dynamic estimation of voyage-specific power demand and sea margin while avoiding unnecessary complexity in the present study, where the primary focus is operational and performance assessment rather than detailed hydrodynamic modeling.

5. Energy System Modelling: DeltaKey

The propulsion power results from DeltaSeas are passed to DeltaKey, Deltamarin's full-ship energy system model. DeltaKey represents the entire onboard energy system, including main and auxiliary engines, waste heat recovery, shaft generators, batteries, boilers, and hotel loads.
For each time step along the voyage, the model calculates fuel consumption, emissions, heat recovery, and electrical power balance. When wind-assisted propulsion reduces the required main engine power, this effect is carried through the entire energy system, influencing fuel consumption, waste heat recovery, and auxiliary engine loading. DeltaKey can also evaluate different combinations of onboard technologies and machinery configurations.

The iterative nature of the process allows the designer to update the vessel's energy model as WAPS system parameters are refined, ensuring that the optimal technology combination is identified not in isolation but in the context of the full vessel design. This is particularly important for newbuild assessments where WAPS sizing, placement, and fuel system design are interdependent.

Finally, total fuel use, CO_2 emissions, and energy costs are calculated for the full voyage. From these results, key regulatory indicators such as CII and FuelEU Maritime intensity are derived, allowing comparison of different design and operational options against regulatory limits.

6. Case Study

6.1. Tanker in Deep Sea Trade

The study considers a tanker operating on long-range intercontinental trade routes, as illustrated by the voyage tracks shown in Fig.2. The vessel operates primarily between Northwestern Europe, the Mediterranean and Suez corridor, and destinations in the Arabian Sea and Indian Ocean region, with additional transits along the West African coast and around the Cape of Good Hope on certain legs. The resulting route network includes both direct Suez passages and longer Cape routes depending on operational conditions and scheduling.

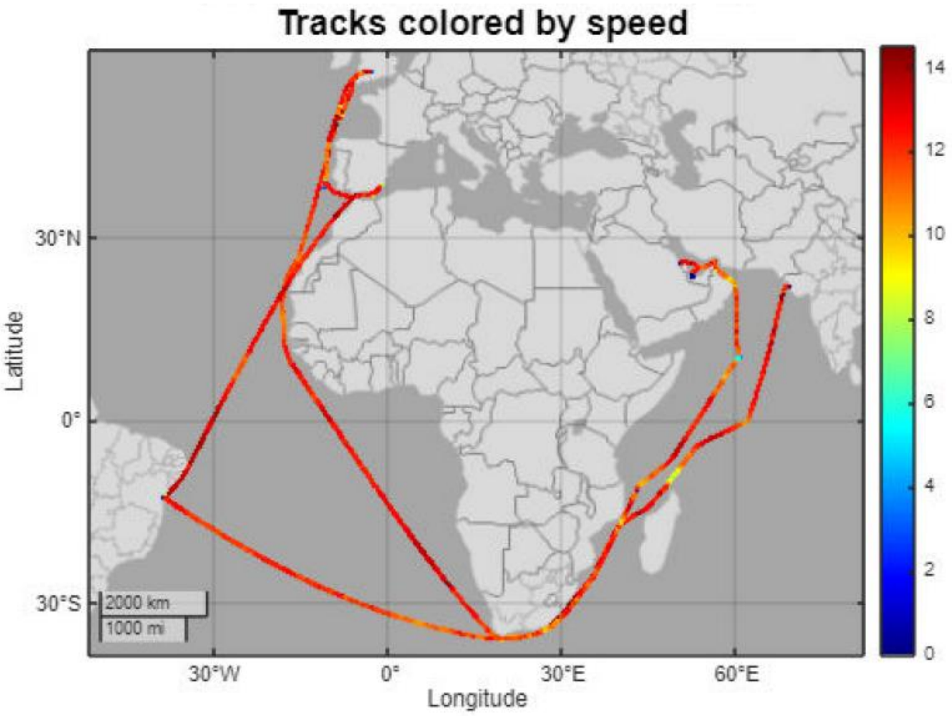


Fig.2: Case vessel route

These trading patterns include a combination of open-ocean segments and geographically constrained waters, particularly in coastal regions such as the European shelf seas, the Mediterranean, the Red Sea, and near-port approaches along the African coastline. This mix of operating environments is important for the analysis, as WAPS performance is generally higher in open-ocean segments with steady wind exposure, while sheltered and constrained waters reduce the availability of favorable wind angles and wind speeds, limiting the effective contribution of wind-assisted propulsion.

The principal design characteristics of the vessel are as follows: length between perpendiculars (Lpp) of 224 m, breadth of 36 m, and a scantling draught of 14.5 m. The hull form is relatively full with a block coefficient (Cb) of 0.840, consistent with tanker-type vessels optimized for cargo capacity and operational efficiency at moderate speeds. The propulsion system is equipped with an 8 m diameter propeller and a propulsion shaft line efficiency of 99%, reflecting a high-efficiency mechanical transmission setup typical of modern deep-sea tanker designs.

6.2. Multi-Departure Methodology

For each departure, the integrated methodology produces a detailed dataset covering both environmental conditions and vessel performance over the full voyage. Fig.3 shows the range of parameters extracted from one representative departure, including time series of: (a) wind direction and wind speed (b) significant wave height and (c) peak wave period obtained and (d) sea and air temperature statistics. Each parameter reflects a different part of the metocean environment encountered during the voyage. Wave conditions are used to estimate added resistance, apparent wind speed and angle control the force that can be generated by wind-assisted propulsion systems. Temperature-related parameters, including sea surface temperature and 2-meter air temperature (t2m), show how sea and air temperatures change throughout the voyage. These datasets help identify regions with stable weather conditions as well as areas with rapidly changing atmospheric behavior. Overall, the extraction of this wide range of parameters for a single departure demonstrates the detailed and data-driven nature of the methodology and establishes the basis for comparison across multiple departures and seasonal conditions.

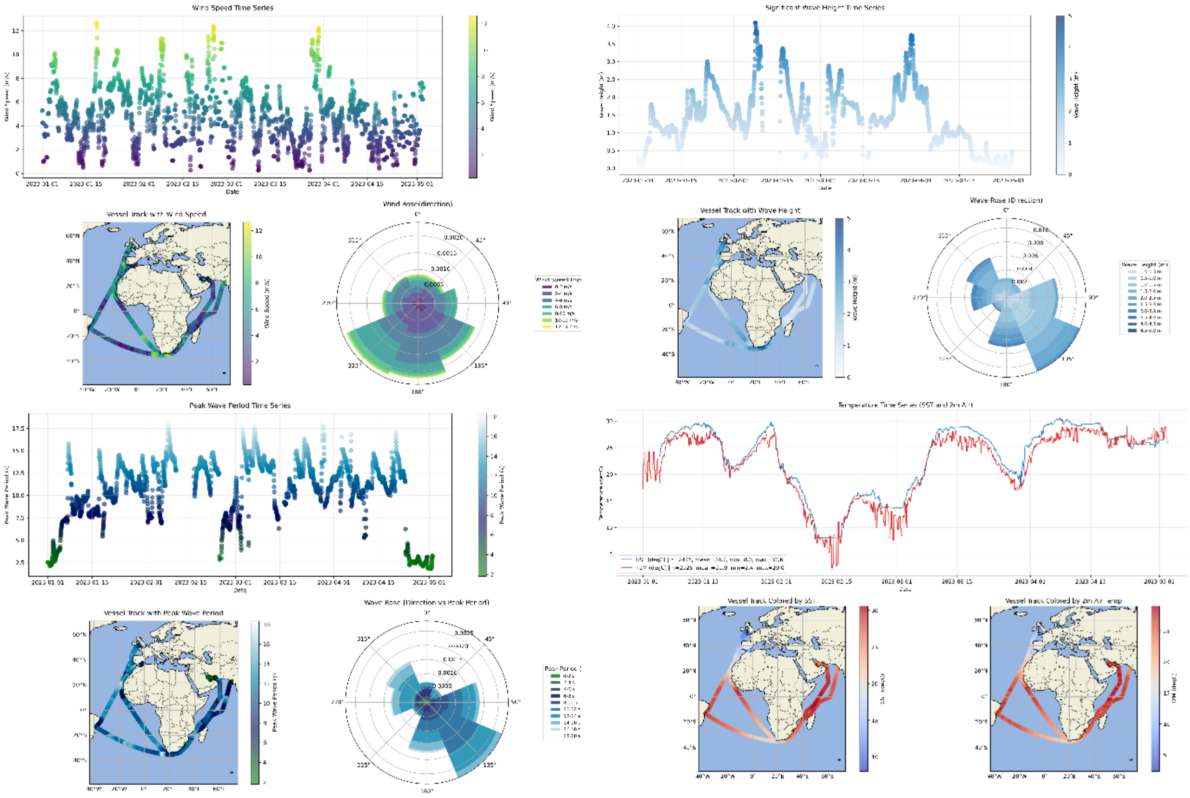


Fig.3: Single-departure environmental parameters

To capture operational weather variability that a single voyage snapshot cannot represent, we analyse four distinct departure dates distributed across the year: January, April, July, and October 2023. Each departure is used to define a corresponding voyage of approximately four months, during which metocean conditions are interpolated along the vessel route. The voyage of about 120 days at sea covers a wide range of seasonal weather conditions throughout the year. For each departure, we reconstruct the along-track time series of metocean fields, sea surface and air temperature, significant wave height, peak wave period, and wind speed and direction, and summarise them using the same diagnostic layout as Fig.3, time series, route-coloured maps, and directional roses.

As shown in Fig.4, the apparent wind speed and wind direction change significantly between departures. Each row represents one departure month (January, April, July, and October 2023).

- Left panels: Time series of true wind speed (m/s) during the four-month voyage, with colors indicating wind intensity.
- Center panels: Spatial distribution of wind speed along the vessel route, showing differences between open-ocean and coastal/constrained waters.
- Right panels: Wind rose diagrams showing the frequency and direction of encountered winds.

The true wind data were obtained from the Copernicus Marine reanalysis dataset at 10 m reference height and matched to vessel positions using the zone-based method. Fig.4 clearly shows strong seasonal differences in wind speed, wind range, and wind direction across departures. When combined with vessel speed and heading from AIS data, these differences create distinct apparent wind conditions and different levels of WAPS operational potential.

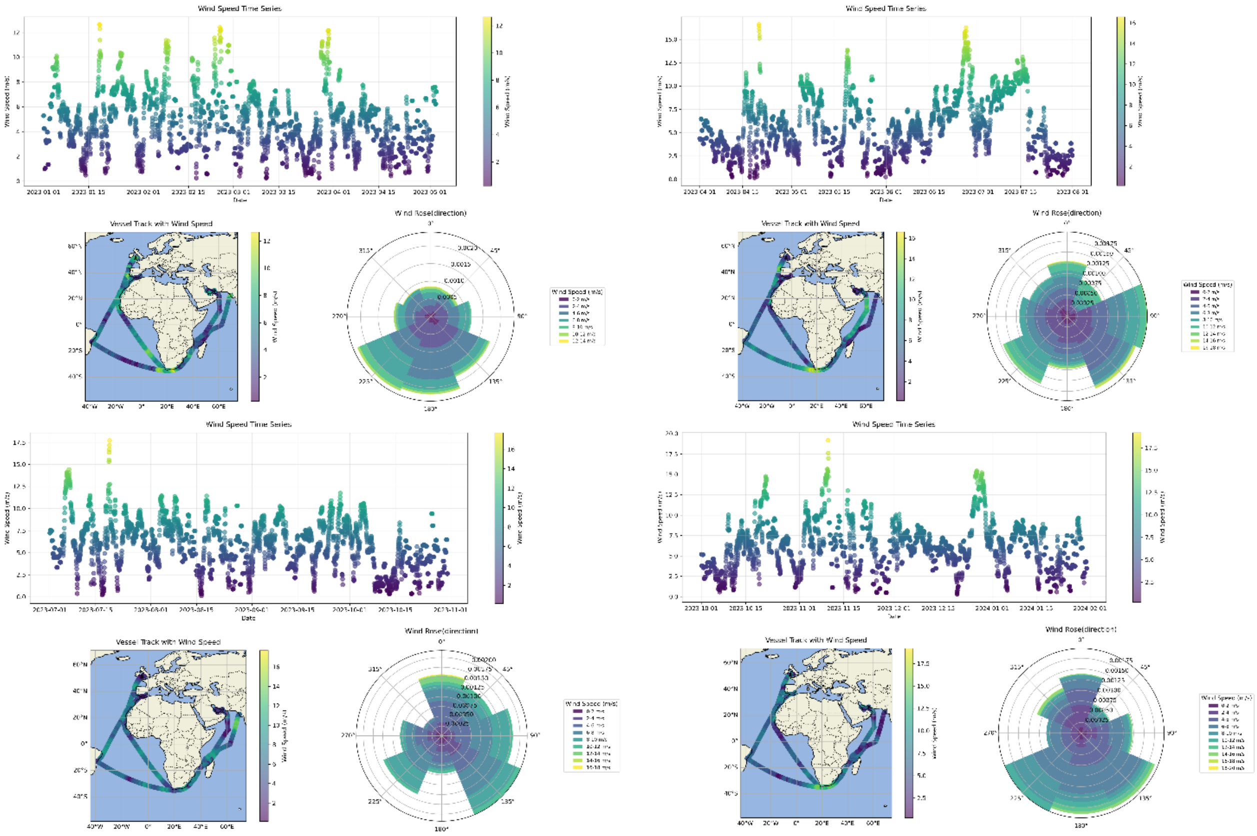


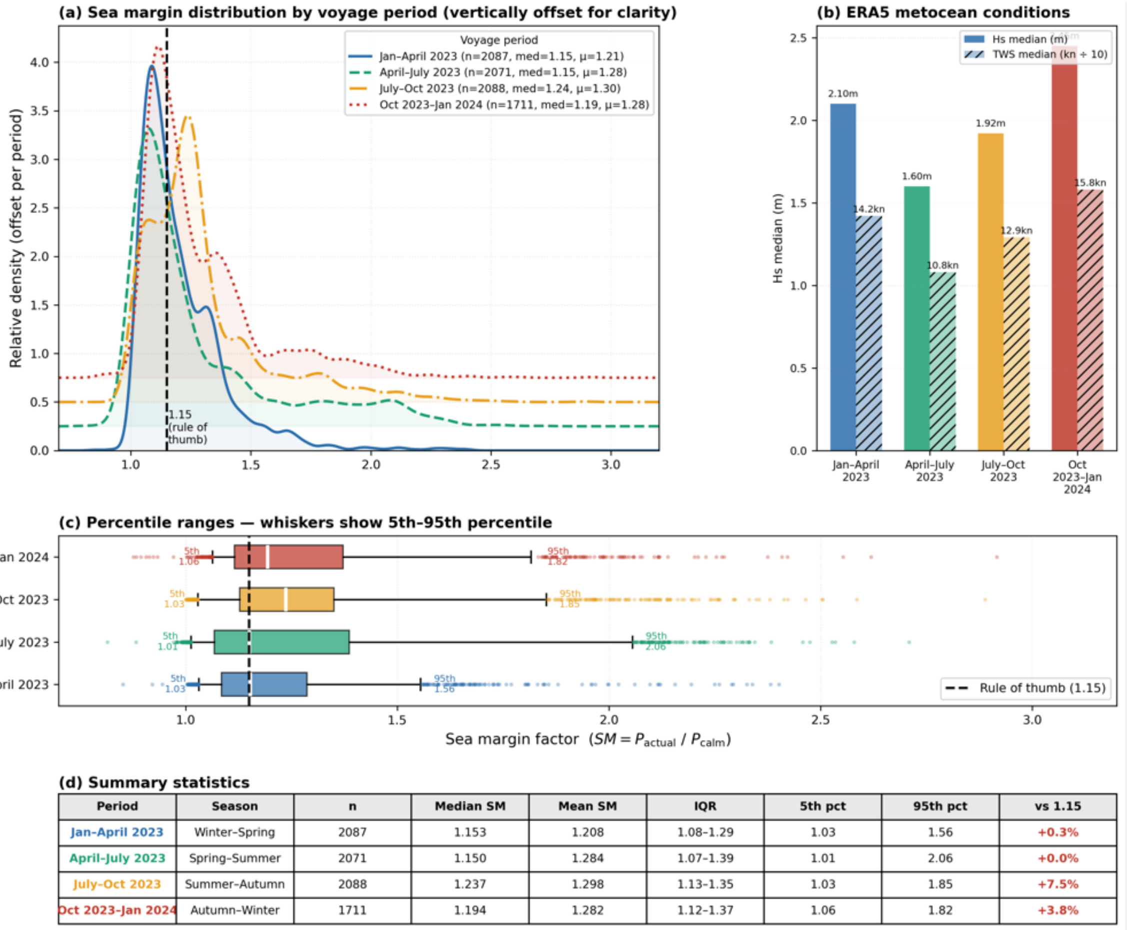
Fig.4: True wind speed and wind direction for four seasonal departures

7. Dynamic Sea Margin Definition

By combining departure-specific weather and ocean data with the DeltaSeas force-balance model, different sea margin results are obtained for each departure period. Fig.5 presents statistical summaries of dynamic sea margin, ratio of seaway power to calm-water power, across all four departures, including median, mean, interquartile range (IQR), and percentile limits.

Under typical conditions, the January-April 2023 departure, representing the winter-to-spring transition, shows a median sea margin of 1.153, which is only 0.3% above the industry-standard 15% margin (sea margin factor of 1.15). This indicates that for the majority of the voyage, roughly half the time, the sea margin requirement aligns closely with conventional design practices. However, this median value masks important variability in actual conditions. To understand the full operational envelope, we examine the range of sea margin values encountered: while typical conditions cluster around 1.15, occasional rough-weather events push sea margin considerably higher.

The percentile-based analysis reveals the critical design challenge. The 95th percentile sea margin, a statistical measure indicating the value exceeded only 5% of the time during the four-month voyage, reaches 1.56 for January-April, Fig.5 table d.



Period	Season	n	Median SM	Mean SM	IQR	5th pct	95th pct	vs 1.15
Jan-April 2023	Winter-Spring	2087	1.153	1.208	1.08-1.29	1.03	1.56	+0.3%
April-July 2023	Spring-Summer	2071	1.150	1.284	1.07-1.39	1.01	2.06	+0.0%
July-Oct 2023	Summer-Autumn	2088	1.237	1.298	1.13-1.35	1.03	1.85	+7.5%
Oct 2023-Jan 2024	Autumn-Winter	1711	1.194	1.282	1.12-1.37	1.06	1.82	+3.8%

Fig.5: Dynamic Sea Margin Analysis

July-October 2023 departure, representing the summer-to-autumn transition, gives the highest sea margin values. The median reaches 1.237 and the mean increases to 1.298, which is about 7.5% above the reference margin. The interquartile range widens to 1.13-1.35, while the 95th percentile reaches 1.85. These higher values indicate frequent exposure to severe weather conditions, mainly due to tropical storm activity and monsoon effects encountered in the Indian Ocean during the voyage.

April-July shows the widest extremal range driven by its combination of highest mean wind speeds and highly variable sea states, which we will see in Table II. Sustained strong winds create both favorable propulsion conditions (reducing relative resistance) and occasional extreme wave events (increasing resistance sharply).

The October 2023-January 2024 departure, corresponding to the autumn-to-winter transition, has a median sea margin of 1.194 and a mean of 1.282. This is 3.8% above the reference margin. The 95th percentile reaches 1.82, showing the influence of developing winter storm systems in the North Atlantic and persistent harsh weather conditions during the vessel's return voyage to Northern Europe.

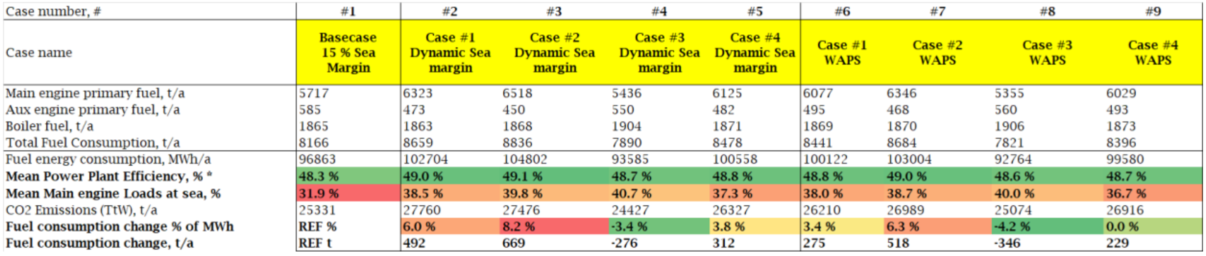
Although all four cases use the same vessel characteristics and operational assumptions, the sea margin distributions differ significantly because each voyage experiences different environmental conditions over the four-month route. This demonstrates that sea margins are strongly influenced by departure timing and weather exposure. Across the four departures, sea margins vary from 0% changes to 7.5% above the standard reference value of 1.15. These differences directly affect fuel consumption prediction, and operational speed planning.

The results also suggest that while a fixed reference sea margin may remain suitable for general design practice, a dynamic sea margin approach can provide additional accuracy when more weather-sensitive performance assessments are required. For example, the lowest-margin departure (April-July) experiences milder conditions than assumed by the fixed reference margin, while the highest-margin departures (July-October and October-January) encounter significantly harsher weather conditions. Therefore, using weather data specific to each departure can make WAPS performance evaluations more realistic and better suited for cases where conditions change over time. This can also support more flexible and accurate use of decarbonization tools such as CII and FuelEU Maritime.

7. Energy and Emissions Results

Building on the departure-specific sea margin results, we now incorporate them into a full energy balance model to estimate fuel consumption, power demand, and CO_2 emissions.

Table I: Simulation Analysis for all departures



Case number, #	#1	#2	#3	#4	#5	#6	#7	#8	#9
Case name	**Basecase 15 % Sea Margin**	**Case #1 Dynamic Sea margin**	**Case #2 Dynamic Sea margin**	**Case #3 Dynamic Sea margin**	**Case #4 Dynamic Sea margin**	**Case #1 WAPS**	**Case #2 WAPS**	**Case #3 WAPS**	**Case #4 WAPS**
Main engine primary fuel, t/a	5717	6323	6518	5436	6125	6077	6346	5355	6029
Aux engine primary fuel, t/a	585	473	450	550	482	495	468	560	493
Boiler fuel, t/a	1865	1863	1868	1904	1871	1869	1870	1906	1873
Total Fuel Consumption, t/a	8166	8659	8836	7890	8478	8441	8684	7821	8396
Fuel energy consumption, MWh/a	96863	102704	104802	93585	100558	100122	103004	92764	99580
Mean Power Plant Efficiency, % *	**48.3 %**	**49.0 %**	**49.1 %**	**48.7 %**	**48.8 %**	**48.8 %**	**49.0 %**	**48.6 %**	**48.7 %**
Mean Main engine Loads at sea, %	**31.9 %**	**38.5 %**	**39.8 %**	**40.7 %**	**37.3 %**	**38.0 %**	**38.7 %**	**40.0 %**	**36.7 %**
CO2 Emissions (TtW), t/a	25331	27760	27476	24427	26327	26210	26989	25074	26916
Fuel consumption change % of MWh	**REF %**	**6.0 %**	**8.2 %**	**-3.4 %**	**3.8 %**	**3.4 %**	**6.3 %**	**-4.2 %**	**0.0 %**
Fuel consumption change, t/a	**REF t**	**492**	**669**	**-276**	**312**	**275**	**518**	**-346**	**229**

The purpose of Table is to examine the effect of departure timing under realistic weather conditions. In all simulations, the vessel model, route, and calculation method remain unchanged, while only the departure period varies throughout the year using metocean-based wind and wave data. The results show that different departure periods lead to different dynamic sea margin values, which then affect annual fuel consumption, power demand, and emissions.

Using the fixed 15% sea margin case as reference, the dynamic sea margin cases show both higher and lower fuel consumption depending on the departure period. This indicates that voyage performance is sensitive to the timing of departure and the associated weather conditions. For our tanker case, some dynamic departures resulted in higher fuel use than the fixed margin baseline, while others produced lower values. Similar trends were observed for average engine load and CO_2 emissions, showing that weather-related variations directly affect ship resistance, propulsion demand, and overall energy performance.

The WAPS performance presented in Table I represents the specific conditions of this tanker route and should not be generalized as typical WAPS capability. A common misconception is that departure-specific sea margin analysis implies variable machinery sizing. This is not the case. The vessel is designed with fixed main engine power, selected to meet specified service speed under a reference sea margin condition, conventionally either a design departure, seasonal average, or worst-case scenario. This power rating is immutable once the ship is built.

The value of dynamic sea margin analysis lies not in changing machinery, but in understanding how the fixed machinery operates under real conditions. The energy simulation results, I, Cases #1-9 demonstrate this principle. Each studied voyage represents approximately 120 days of continuous at-sea operation (4-month intercontinental transit). The annualized fuel consumption values (t/a) represent the projected annual fuel consumption if the vessel were to undertake this same route repeatedly throughout the year, a standard methodology for comparing seasonal route performance.

Case #1, employing the conventional 15% fixed sea margin, shows a baseline fuel consumption of 8,166 t/a on this annualized basis. Cases #2–5, employing dynamic sea margin derived from actual voyage conditions, yield annualized fuel consumptions ranging from 7,890 to 8,836 t/a, a spread of 950 tonnes annually (11.6% variability). This variability is not due to changing the engine; it reflects how the same fixed engine operates under different seasonal loading regimes when undertaking this route in different seasons. These results demonstrate that seasonal variations in operational envelope, not changes to machinery design, are the primary driver of annual fuel consumption variability.

8. Favorable Wind Angles and Head-Wind Dominance

Analysis of at-sea wind conditions (filtered dataset: n = 2,071–2,088 hours per departure, representing all hours with speed >5 knots and sea margin within operational bounds) reveals that favorable apparent wind angles (40°–170°) occur in only 29–44% of the voyage duration, with head-wind dominance (apparent wind angle <40°) persisting for 55–70% of the time, Fig.5, Table II.

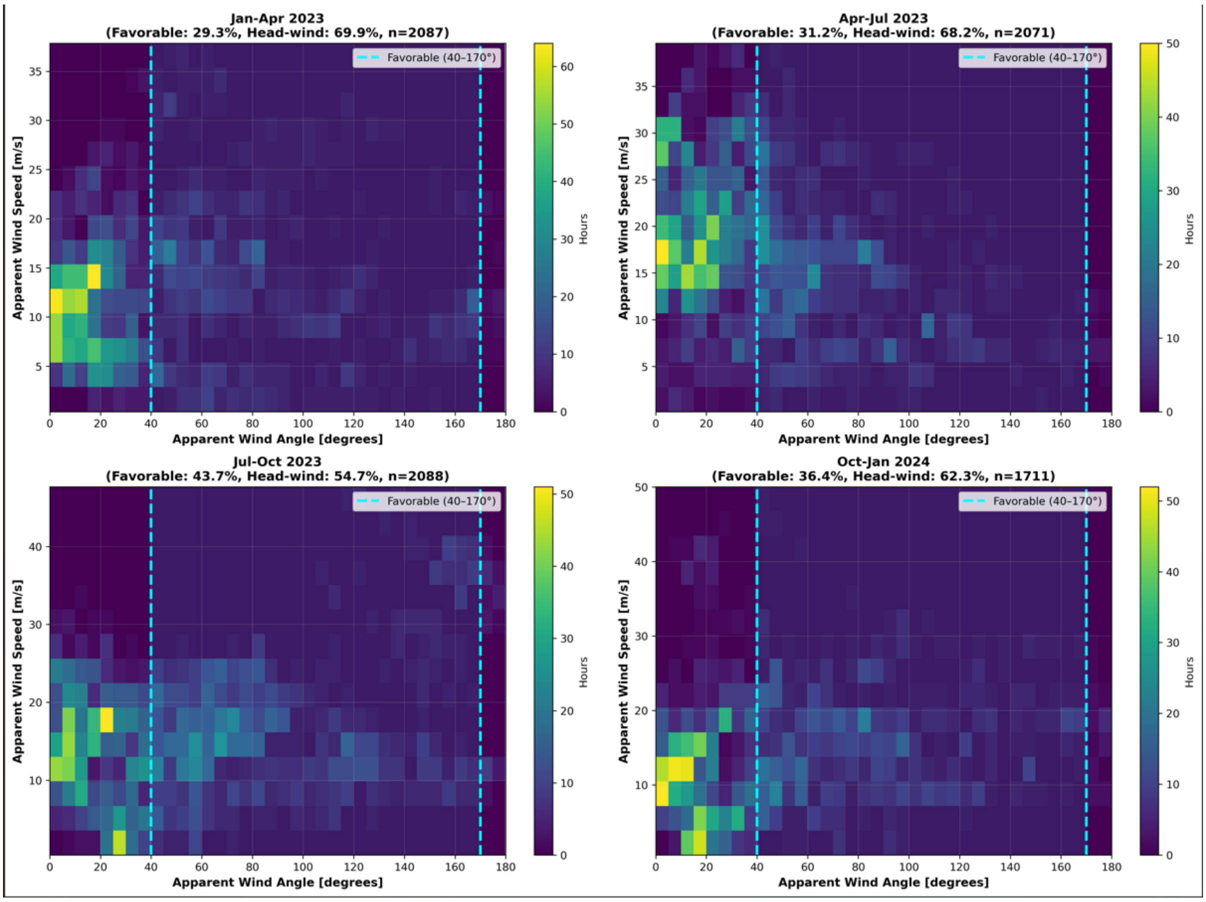


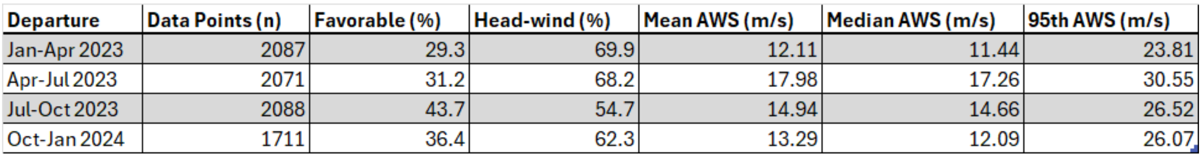
Fig.6:Wind Analysis Heatmaps of four departures

For this tanker route, the apparent wind-angle and apparent wind-speed distributions indicate that a significant share of time is outside favorable sail-propulsion conditions (including frequent head-wind sectors and many low-wind-speed hours). In addition, route proximity to coasts and constrained legs reduces sustained exposure to favorable open-ocean wind geometry. These factors lower effective sail utilization and explain why average savings remain modest in this tanker case.

An important finding is that April-July exhibits the highest mean apparent wind speed (17.98 m/s) but only 31.2% favorable angles, lower than July-October's 43.7%. This decoupling of wind speed and wind-angle favorability is visible in the heatmaps, Fig.6. The April-Jul heatmap shows concentrated intensity in the low-angle regions (0°-40°), indicating frequent strong head winds. Conversely, the July-Oct heatmap shows a broader, more distributed pattern with significant intensity across the favorable 40°-170° envelope, but at lower overall wind speeds.

This distinction is critical for WAPS assessment: high wind speed does not guarantee high WAPS utilization if the wind predominantly arrives from unfavorable angles. April-July's 17.98 m/s mean wind speed drives high air resistance (increasing sea margin, discussed below) and some WAPS benefit (2.80%, the highest among departures), but the majority of this wind arrives in head-wind configurations where sails cannot be deployed efficiently. In contrast, July-October's more favorable angle distribution (43.7%) would typically favor WAPS, yet the overall WAPS savings (1.58%) are the lowest. This apparent contradiction is explained by sea state effects (higher median sea margin 1.237) and the lower mean wind speed (14.94 m/s) in July-October.

Table II: Wind statistics table

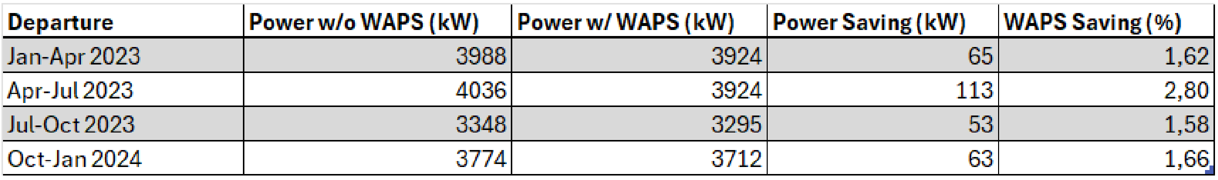


Departure	Data Points (n)	Favorable (%)	Head-wind (%)	Mean AWS (m/s)	Median AWS (m/s)	95th AWS (m/s)
Jan-Apr 2023	2087	29.3	69.9	12.11	11.44	23.81
Apr-Jul 2023	2071	31.2	68.2	17.98	17.26	30.55
Jul-Oct 2023	2088	43.7	54.7	14.94	14.66	26.52
Oct-Jan 2024	1711	36.4	62.3	13.29	12.09	26.07

9. WAPS Power Savings and Seasonal Variability

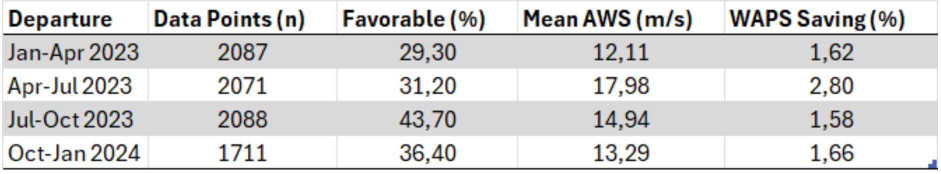
Wind-assisted propulsion system savings range from 1.58% to 2.80% across the four departures, Table III, with the highest benefit occurring in April–July, the period of maximum mean apparent wind speed (17.98 m/s) and highest overall wind intensity. The energy simulation, Table I, Cases #6–9, corroborates these findings: WAPS-equipped variants show power savings of 53–113 kW, translating to 1.58–2.80% fuel efficiency gains.

Table III:Power without WAPS and with WAPS



Departure	Power w/o WAPS (kW)	Power w/ WAPS (kW)	Power Saving (kW)	WAPS Saving (%)
Jan-Apr 2023	3988	3924	65	1,62
Apr-Jul 2023	4036	3924	113	2,80
Jul-Oct 2023	3348	3295	53	1,58
Oct-Jan 2024	3774	3712	63	1,66

Table IV: WAPS saving summary with different favorable winds



Departure	Data Points (n)	Favorable (%)	Mean AWS (m/s)	WAPS Saving (%)
Jan-Apr 2023	2087	29,30	12,11	1,62
Apr-Jul 2023	2071	31,20	17,98	2,80
Jul-Oct 2023	2088	43,70	14,94	1,58
Oct-Jan 2024	1711	36,40	13,29	1,66

The Table IV results are not a limitation of the method, but a reflection of the vessel's assigned operational environment. Three factors explain this pattern and distinguish this tanker from vessels operating on more favorable routes:

- Across all departures, 55-70% of at-sea operating time occurs in head-wind conditions (apparent wind angle <40°), rendering sails aerodynamically inefficient or inactive
- Multiple passages through coastal waters and straits restrict sustained open-ocean wind exposure.
- These findings differ from an earlier case on a bulk carrier, *Elg et al. (2025)*, where significantly larger WAPS benefits were observed. The difference reflects fundamental differences in route

characteristics and wind exposure. Bulk carriers typically operate on longer ocean transits with more stable wind conditions and fewer geographic restrictions, allowing sustained use of wind propulsion. The tanker examined here operates roughly four-month voyages with multiple constrained segments, which limits the cumulative contribution of wind-assist systems.

10. Conclusion

Today, when new ships are designed, they must be designed to consider tightening demands for environmental performance, which typically means including great flexibility in energy sources and high energy efficiency in operation. This includes the growing relevance of wind and other renewable energy sources as part of the propulsion concept. This paper illustrates an important principle: WAPS effectiveness is voyage-specific and cannot be reliably transferred between different vessel types or routes. Realistic savings estimates require analysis of the actual wind patterns and operational constraints for the specific service profile being evaluated.

The integration of WAPS into ship design must begin at a very early stage, as these systems require dedicated space allocation, structural reinforcement, and careful consideration of their impact on the vessel’s overall energy architecture, cargo capacity, and lifecycle economics. In addition, the number and type of sails installed can significantly influence the selection and configuration of the main propulsion machinery. However, the time and resources for ship conceptual design (whether it is a question of a newbuilding or a retrofit study) are always more or less limited. Therefore, performing the analysis of WAPS performance in realistic operational conditions as a part of the entire ship conceptual design brings considerable value to the process, however it has been a challenge earlier for Deltamarin to make the analysis fast enough and robust enough to serve real, fast-paced conceptual projects.

The results of this study lead to two practical recommendations. First, when actual weather and AIS data are available, sea margin calculations should account for specific departure dates and seasonal variations, as these materially affect predicted performance. Second, the WAPS assessment must incorporate route-specific wind availability and operational limitations

Nevertheless, the approach which was presented in this paper also has limitations. Overall, it is a simplified assumption to utilize a pre-determined speed- or voyage pattern to describe the ship operation. In reality, weather conditions can directly influence operational decision-making, including engine settings and speed optimization strategies. Many cargo vessels are also operated at fixed engine rpm setting, rather than fixed ship speed over ground. Furthermore, various kinds of voyage optimization is an important energy management means for any ship, and including WAPS, weather routing has been recognized as a highly beneficial combination to optimize further ship fuel performance.

Therefore, the next steps in Deltamarin’s development also involve more flexibility towards voyage optimization. However, assuming a more or less fixed route as the basis of design is still an important approach and a starting point for a ship designer, since the design approach includes also comparison of various machinery components, including analysis of various sail types. Adding voyage and weather optimization in the process too early might also make apple-to-apple comparison of different solutions difficult. Utilizing a fixed sea margin is a traditional way to dimension or ensure a certain capacity for the ship main engine, which might still be a relevant approach to ensure adequate margin in certain specified conditions.

In conclusion, the data-driven framework for supporting especially wind-assisted propulsion design is a valuable addition to ship designer's conceptual design toolbox both even as a stand-alone methodology for obtaining a fast and flexible outlook to environmental conditions on a given route anywhere around the globe. In practice, it may give indication even as such for considering various types of WAPS for a given project. Nevertheless, the biggest value in the developed method is in complementing the ship conceptual design process with fast, flexible and integrated approach. The resulting holistic propulsion power analysis is currently a natural part of Deltamarin's early-stage design, where various design- and technical selection is made for the ship.

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