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Book of Abstracts

DEWATRA

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TÉCNICO UNIVERSIDADE DE LISBOA

CENTEC

CENTRE FOR MARINE TECHNOLOGY AND OCEAN ENGINEERING

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Trends in decarbonisation of waterborne transportation

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Extended Abstract

The shipping fleet, both deep-sea and inland waters, makes a significant contribution to the Greenhouse Gas (GHG) emissions, even though shipping is a less environmentally damaging mode of transport than road and air transportation. The world fleet continues increasing, and the large number of existing ships forced the IMO, which is mainly concerned with maritime safety, to adopt, through the Marine Environment Protection Committee (MEPC), a wide range of measures to control the shipping industry's pollution in support of the global action towards climate change mitigation. Therefore, the shipping industry is under large pressure to decarbonise waterborne transportation within a relatively short time frame.

The "green shipping" or "sustainable shipping" is a long-term objective for the shipping industry to transport goods without GHG emissions. This could be achieved by developing new fuels such as liquid natural gas (LNG), methanol, hydrogen, or ammonia, alongside the simultaneous development of maritime engines to operate with these fuels and the creation of infrastructure in major ports to supply these fuels to the shipping industry. Present forecasts suggest that this may only occur after 2040. In the meantime, the industry has identified several short- and medium-term measures to reduce GHG emissions.

The current situation of GHG emissions can be assessed through several local monitoring programs that can validate simulation models. To estimate ship emissions, the current methodologies range from top-down to bottom-up approaches. In the bottom-up approach, the emission rate by each ship in its specific position and during a specific activity is calculated. Nowadays, AIS data are used to study the impact of ship emissions on the air quality of the sea and coastal areas.

Improving the ship design process is an important short-term initiative to enhance the optimisation of the ship's hull shape, systems, and components, reducing fuel consumption. These components encompass hull structures, propulsion systems, energy systems, control systems, and operational protocols. The goal is to achieve the best possible performance across speed range, fuel consumption, emissions, safety, and reliability, whilst meeting competitive performance indicators.

Optimising the hull shape is essential for reducing hull resistance and, thus, the power required for ship propulsion. It is a main effective step to minimise the Energy Efficiency Design Index (EEDI) towards green shipping. Investigation of several hydrodynamic enhancement models for specific devices, including propeller and rudder devices, air lubrication, hull vortex generators, specialised hull coatings, innovative rudder designs, Becker Flaps, twists, twin and dual-fin configurations, and flapping foil thrusters, among others, has been performed.

Regarding the propulsion system, this has included developing engine technologies to minimise fuel consumption and ensure combustion with alternative fuels. This improvement is achieved through optimisation of combustion by modifying fuel injection, combustion chamber shape and geometry, and engine operating parameters. The concept of a dual-fuel engine became widely adopted, with LNG as the alternative fuel used in areas where low emissions are required. A significant number of retrofitted ships and new builds can already be found in the world fleet. Waste energy recovery is also an important strategy for use with different propulsion systems.

As an alternative to conventional engines, fuel cells can reach higher efficiencies, especially with bottoming cycles. Electric propulsion has been more widely used, particularly for ship types that can take advantage of its emissions-free operation. Significant efficiency gains and emission reductions can be achieved by replacing conventional direct drive mechanical transmission systems with either hybrid or complete electrical transmission, as in the "all-electric ship". Electric transmission is also an important enabler, permitting multiple different energy suppliers (engines, fuel cells, Flettner rotors, for example) and consumers (propulsion, hotel load) to be integrated.

Renewable energy devices based on wind or solar energy have been increasingly used as a complementary means of propulsion, to reduce fuel consumption, or to reduce overall onboard energy consumption. Achieving optimised, energy-efficient performance in ship operations is an enormous challenge that requires a robust decision-support system to balance energy supply and consumption across various sources. For these systems, AI models can be very useful in properly handling the large volume of data produced by sensors across all on-board energy-related activities.

The variables that influence the ship's performance during a sea voyage are numerous. These variables are the ship's ship-specific and vary according to the voyage executed on the seaway. Some of these variables are controllable, like the ship's speed, draught, trim, engine condition, and hull cleanliness, while other variables are uncontrollable, such as weather conditions and shallow water effects close to the coast or harbours. However, weather forecasting and route optimisation techniques can improve ship performance to accommodate these uncontrollable variables. Sometimes the route optimisation system can be integrated with the onboard energy management system, enabling greater coordination and optimisation.

The world fleet is adopting several of these strategies depending on ship type, mode of operation, and shipowner strategy, but the overall trend is a reduction in emissions alongside increased levels of automation and intelligence in onboard systems.

However, for each shipowner, a set of important questions needs to be considered and answered for the specific conditions of each one:

How can they reduce GHG emissions and transition to sustainable shipping practices?

What are the most effective strategies for achieving short-term and long-term reductions in GHG emissions in their fleet?

What technological innovations in ship design and propulsion systems can enhance energy efficiency and reduce emissions in the ship types of their fleet?

Which alternative fuels will they consider for their fleet, given the available onshore supply infrastructure at the ports they normally call?

The DeWaTra COST Action is addressing these questions by developing and providing background material to support shipowners' strategy choices for their fleets. To achieve this objective, five working groups are in operation:

WG1. Assessment of atmospheric emissions from shipping

WG 2. Hydrodynamic hull and propulsor design for energy-efficient performance

WG 3. Operation of ship propulsion systems with alternative fuels

WG 4. Renewable energy contributions to ship energy efficiency

WG 5. Onboard decision support systems for energy-efficient ship operation

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Decarbonising waterborne transportation: assessment and reduction of atmospheric emissions from shipping

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1. GENERAL INTRODUCTION

Maritime transport supports global trade but remains a significant contributor to greenhouse gas emissions, accounting for approximately 2.9–3.3% of global emissions. Achieving decarbonisation requires not only the deployment of low-carbon technologies, but also robust engineering assessment methods capable of quantifying emissions under real operational conditions. This study presents an integrated assessment of engineering improvements, renewable energy technologies, alternative fuels, and electrification strategies, with particular emphasis on data-driven emission modelling and practical implementation pathways.

2. GREEN MARITIME PATHWAY

2.1 Engineering Improvements

Engineering improvements remain the most immediately deployable pathway for reducing fuel consumption across the global fleet. Measures such as hull optimisation, advanced coatings, propeller and rudder improvements, air lubrication, and operational optimisation can collectively deliver fuel savings exceeding 10–20% (Ma et al., 2025).

Accurate assessment of the real-world impact of such measures increasingly relies on Automatic Identification System (AIS) data. AIS provides high-resolution information on vessel specifications, speed, navigation patterns, and operational activity, enabling bottom-up estimation of emissions at ship, route, port, and regional scales (Sun et al., 2025). By combining AIS-derived operational profiles with engine characteristics, emissions of CO_2, NO_x, and SO_x can be estimated under different operational modes, including cruising, manoeuvring, and hoteling, allowing identification of high-emission ship categories, operational hotspots, and port-adjacent pollution zones. Compared with conventional fuel-based inventory approaches, AIS-based methodologies provide significantly improved spatial and temporal resolution and enable validation against port activity records and environmental monitoring data. Their reliability, however, depends on careful preprocessing of incomplete, duplicated, or abnormal trajectory data (He et al., 2025). This data-driven framework provides a robust basis for evaluating the emission reduction potential of emerging decarbonisation technologies under realistic operating conditions.

2.2. Renewable Energy Technologies

Renewable energy technologies provide an important complementary pathway by harnessing natural energy sources such as wind and solar radiation. Wind-assisted propulsion systems (WASP), including Flettner rotors, rigid and deployable sails, and kite systems, have demonstrated considerable potential for reducing fuel consumption. Full-scale studies and operational data indicate that Flettner rotors can achieve fuel savings of 5-20%, depending on vessel type and route conditions (Ammar & Seddiek, 2022). Similarly, kite systems can reduce fuel consumption by up to 20% under favourable wind conditions. Solar photovoltaic (PV) systems, while limited by power density, can contribute to auxiliary energy demand, particularly when integrated into deck and superstructure areas. The effectiveness of renewable technologies is highly dependent on environmental conditions, including wind speed, wind direction, solar availability, and vessel routing. As such, these systems are most effective when incorporated into hybrid configurations rather than as standalone solutions.

2.3. Alternative Fuels

Alternative fuels represent the most critical pathway for achieving deep decarbonisation in maritime transport. The environmental performance of these fuels must be evaluated using a Well-to-Wake (WtW) approach, as upstream production processes significantly influence overall emissions. Liquefied natural gas (LNG) offers a transitional solution with lower emissions compared to conventional fuels, although methane slip reduces its long-term sustainability benefits. Methanol has emerged as a promising near-term option due to its liquid state and compatibility with existing infrastructure. At the same time, hydrogen and ammonia offer the potential for near-zero emissions when produced from renewable sources (Zamboni et al., 2024). However, these fuels pose significant challenges in storage, safety, bunkering infrastructure, and cost. Therefore, their adoption will depend on the development of global supply chains and regulatory frameworks.

2.4. Electrification and Hybridisation

Electrification and hybridisation technologies play a key role in improving energy efficiency and enabling the integration of renewable energy systems. Battery-electric systems are particularly suitable for short-sea shipping and port operations, offering zero emissions at the point of use. Hybrid-electric configurations, which combine conventional engines with energy storage systems, are currently the most mature and widely applied solution, providing operational flexibility and improved efficiency (Wang et al., 2025). Fuel cell systems, powered by hydrogen or hydrogen-derived fuels, offer high efficiency and zero-emission potential but are constrained by cost and infrastructure limitations. The integration of electrification with renewable energy and alternative fuels represents a critical step towards achieving a flexible and resilient maritime energy system.

3. HYBRID SYSTEMS AS A RECOMMENDED PATHWAY

Hybrid energy systems are increasingly recognised as the most practical pathway for maritime decarbonisation, combining conventional propulsion with batteries, fuel cells, and renewable energy sources to optimise energy use under varying operational conditions. Their flexibility makes them a key enabler for the transition towards low- and zero-carbon shipping.

4. CONCLUSIONS

In conclusion, decarbonising shipping requires a combined engineering and assessment framework in which efficiency improvements, renewable assistance, alternative fuels, and hybrid-electric systems are evaluated together rather than in isolation. Green engineering measures remain the most practical first step because they reduce baseline fuel demand. Renewable technologies can provide auxiliary or route-dependent propulsion support, while methanol offers a feasible near-term fuel pathway and hydrogen and ammonia remain important longer-term options. In parallel, AIS-based emission assessment provides a technically robust foundation for quantifying real-world emissions, identifying operational hotspots, and evaluating the actual impact of mitigation strategies. This integrated approach is therefore essential for both engineering design decisions and evidence-based emission control policy.

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Hydrodynamic hull design for energy-efficient performance

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EXTENDED ABSTRACT

In order to address the challenge of global warming and its connection to rising Earth temperatures, with a particular emphasis on the role of the shipping industry in international trade, DeWaTra project (https://dewatra.eu/) contributes to the decarbonization of maritime transportation by bringing together research groups with activities in the following directions: (i) in the assessment of atmospheric emissions from shipping, (ii) the hydrodynamic hull design for energy-efficient performance, (iii) alternative fuels for ship propulsion, (iv) renewable energy contributions to ship energy efficiency, and (v) onboard decision support systems for energy-efficient ship operation.

In particular, Working Group 2 of DeWaTra focuses on the hydrodynamic hull design for energy-efficient performance. In this connection, important parameters dealing with ship design and optimization, such as selection of the main dimensions of new vessels that play an important role in the energy efficiency characteristics are reviewed. Following traditional approaches, the main dimensions are chosen based on analyses from a database of previous successful designs, preventing potential innovative improvements whilst providing a safe solution. A measurable amount of improvement in hydrodynamic characteristics may be obtained with an initial study on the main dimensions of a vessel when the performance is investigated for multiple performance criteria. For modern commercial ship design, a modified initial design approach investigating the relationship between main dimension combinations with cargo capacity and energy efficiency measures should be incorporated into the design process for better compliance with modern requirements. Before the hydrodynamic hull form optimization utilizing RANS CFD, an initial study will be conducted to provide a better starting point for the optimization process.

To achieve an optimal design, parametric hull form optimization is coupled with modern RANS CFD solvers. Hull lines adjust based on parameters, guided by an optimization routine to meet operational requirements while adhering to hydrodynamic constraints set by the customer. WG2 discusses the ship design model combined with CFD for hydrodynamic ship hull optimization. Traditionally, geometrical parameters define the hull, with tension splines and nurbs used for generating shape modifications. Optimized hull forms will be obtained and compared to the base form to demonstrate the procedure's effectiveness and validity.

1.1 *DeWaTra WG2 subgroups and directions of research review*

The following key areas have been indentified as DeWaTra WG2 subgroups

Group 1: Hydrodynamic hull form parametric design methods and tools
Group 2: RANS CFD and other models for ship hull hydrodynamic analysis (calm water/real conditions)
Group 3: Optimizers for ship hull design for best performance
Group 4: Test cases (model scale/full scale) and demonstration
Group 5: Other methods to reduce ship resistance and improve performance

1.2 *DeWaTra WG2 Progress*

Results by the first two subgroups have been presented and discussed. In detailed presentations by the WG2 members, including the traditional approach based on the design spiral, with stages: Preliminary design phase primarily focuses on: Selection of “optimal” main characteristics, Internal layout, volumes & weights, Hullform, Hydrodynamic performance, Safety, Operational & Economic viability. On the other hand, the holistic ship design approach (see, e.g. Papanicolaou 2019, 2021) allows the simultaneous assessment of the most important aspects of numerous designs, as an alternative to the traditional design spiral, Depending on the available resources and time constraints, different levels of detail can be incorporated in the parametric model, used in the optimization process (Kanellopoulou 2023). In the case of the 3D geometric model design evaluation is based on the analysis using high-fidelity methods to account for design details (e.g., CFD) with higher accuracy, but not practical for large scale optimization, and computational efficiency can be achieved by opting for surrogate models or machine learning concepts (as e.g., ANNs),

Moreover, comprehensive review presented by Sulovsky et al (2026) examines the application of Reynolds-Averaged Navier-Stokes (RANS) modelling in computational ship hydrodynamics, starting from fundamental theory, numerical implementation, validation procedures, and diverse practical applications. The rationale behind these methods is to retain the computational efficiency of RANS near walls and in attached boundary layers, while resolving the larger, more energetic turbulent eddies in wakes, stern flows, and propeller slipstreams through LES-like formulations. Also, integration of machine learning with RANS simulations is explored as an emerging frontier for accelerated design optimization, with particular focus on resistance prediction, hull optimization, and wake field analysis; see Fig.1.

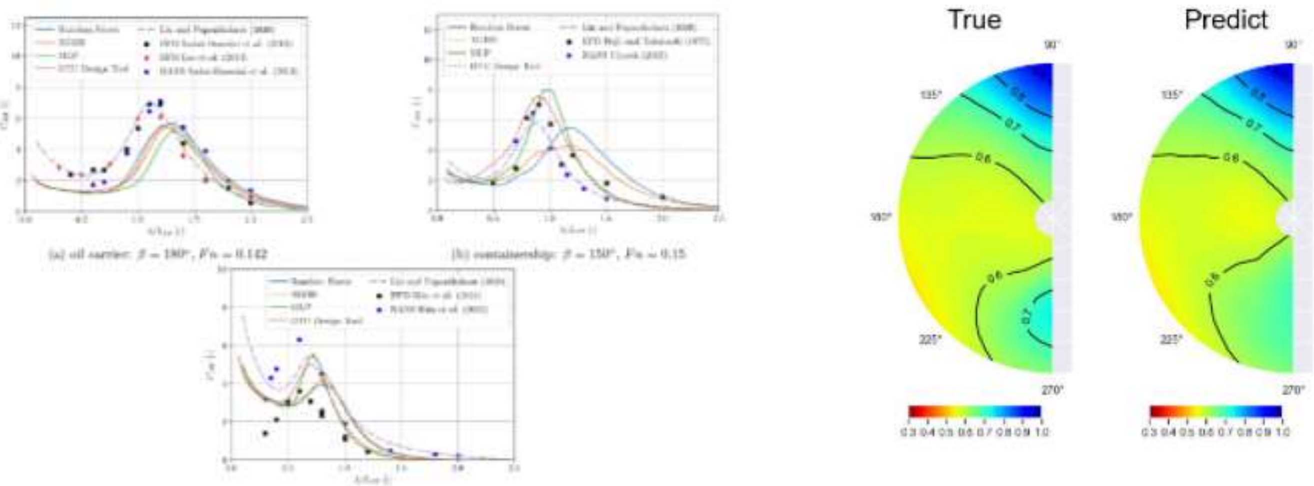

Figure 1: Comparison of ML predicted results and reference results for exemplary cases for (a) added wave resistance coefficient, and (b) ship wakefield on the propeller plane.

Future perspectives on hybrid RANS-LES approaches, increased availability of CFD services and ultimately, AI-augmented ship design workflows, providing a comprehensive reference for researchers and engineers in computational ship hydrodynamics. Hybrid RANS–LES (Reynolds-Averaged Navier–Stokes – Large Eddy Simulation) approaches represent one of the most promising frontiers in ship CFD.

1.3 *DeWaTra WG2 Future tasks*

In the next phase, WG2 will review work and Test cases (model scale/full scale) and demonstration and other methods to reduce ship resistance and improve performance.

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Alternative fuel ship propulsion: Challenges and future directions

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Extended Abstract

Maritime shipping is entering an implementation phase of decarbonisation. In the European Union, FuelEU Maritime has applied since January 1, 2025. At the global level, the International Maritime Organization approved the draft IMO Net-Zero Framework in April 2025, while formal adoption discussions continued into 2026. Under these conditions, propulsion choices can no longer be assessed independently of fuel availability, storage penalties, safety requirements, vessel duty cycles, and compliance exposure. Working Group 3 (WG3) of the DeWaTra COST Action addresses this challenge by examining the operation of ship propulsion systems under alternative fuels, with attention to internal combustion engines (ICEs), fuel cells, hybrid architectures, gas turbines, and digital support tools. This extended abstract argues that decarbonising ship propulsion is no longer primarily a fuel substitution exercise. It is a system architecture problem in which fuel characteristics, conversion technologies, onboard integration, and operational context must be designed together (DeWaTra COST Action CA23159, n.d.; European Commission, n.d.; IMO, 2025).

Adapted and dual-fuel ICEs remain the most deployable near-term solution because they build on established machinery platforms, existing maintenance ecosystems, and familiar operational practice. This gives them a practical advantage for both newbuilds and retrofits, particularly in segments where reliability, serviceability, and crew familiarity remain decisive. Their extension to ammonia and hydrogen is technically feasible, but it is constrained by combustion instability, emissions formation, material compatibility, and fuel handling requirements. In most cases, the transition involves much more than modifying the engine itself, since storage arrangements, fuel supply systems, safety barriers, ventilation, and exhaust aftertreatment must also be reconsidered at vessel level. For ammonia, recent work confirms that efficiency gains remain closely tied to difficult trade-offs involving NOx, N2O, and ammonia slip, which complicates optimisation and regulatory compliance. For hydrogen, storage and volumetric energy density remain decisive system-level constraints that directly affect ship layout, payload, range, and, in some cases, commercial viability on longer routes (Diamantakis et al., 2026).

Fuel cells offer a structurally different pathway because of their high conversion efficiency and, in some cases, wider fuel flexibility. They are particularly attractive in decarbonisation strategies that prioritise high efficiency, low local emissions, and closer integration with electrified onboard power architectures. Solid oxide fuel cell systems are especially promising for marine applications, but their preference for steady operation, thermal inertia, start-up constraints, and degradation sensitivity limit direct compatibility with variable ship duty cycles. This makes hybridisation increasingly important, and in many cases necessary, rather than simply advantageous. Hybrid systems can combine engines, fuel cells, batteries, and power electronics to distribute loads more effectively, improve part-load performance, absorb transient demand, and accommodate operational variability. Within such architectures, batteries can buffer rapid load changes, while fuel cells can operate closer to stable high-efficiency conditions. In parallel, digital twins and advanced supervisory control systems are moving from supporting tools to core integration layers because they enable optimisation, condition monitoring, fault diagnosis, and lifecycle-informed decision-making in increasingly complex onboard energy systems (Elkafas & Attar, 2026).

The figure below (Fig. 1) indicates that alternative-fuel propulsion decisions are increasingly shaped by a layered system of logic in which regulation, fuel characteristics, conversion technologies, and vessel operation jointly determine the feasible propulsion architecture. Recent market evidence indicates that the sector is diversifying rather than converging. Alternative-fuel vessel orders now span LNG, methanol, LPG, hydrogen, ammonia, biofuels, and other emerging options, with adoption patterns varying across vessel classes and route profiles (Lloyd's Register, 2026). This fragmentation points to five structural challenges. First, fuel penalties are system-defining. Storage volume, pressure, cryogenic requirements, toxicity, and bunkering procedures can reshape vessel arrangement and economic performance. Second, the efficiency-emissions trade-off remains unresolved in several combustion-based pathways, especially for ammonia and hydrogen engines. Third, integration complexity is often underestimated. Once multiple energy sources, storage systems, converters, and control layers are combined, nonlinear interactions become central to system behaviour. Fourth, dynamic operation remains a critical gap because many high-efficiency technologies perform best in quasi-steady conditions rather than under realistic marine load profiles. Fifth, durability and degradation remain insufficiently validated under marine conditions at full-system level, particularly where components with different technology readiness levels are integrated into the same architecture (Diamantakis et al., 2026; Elkafas & Attar, 2026).

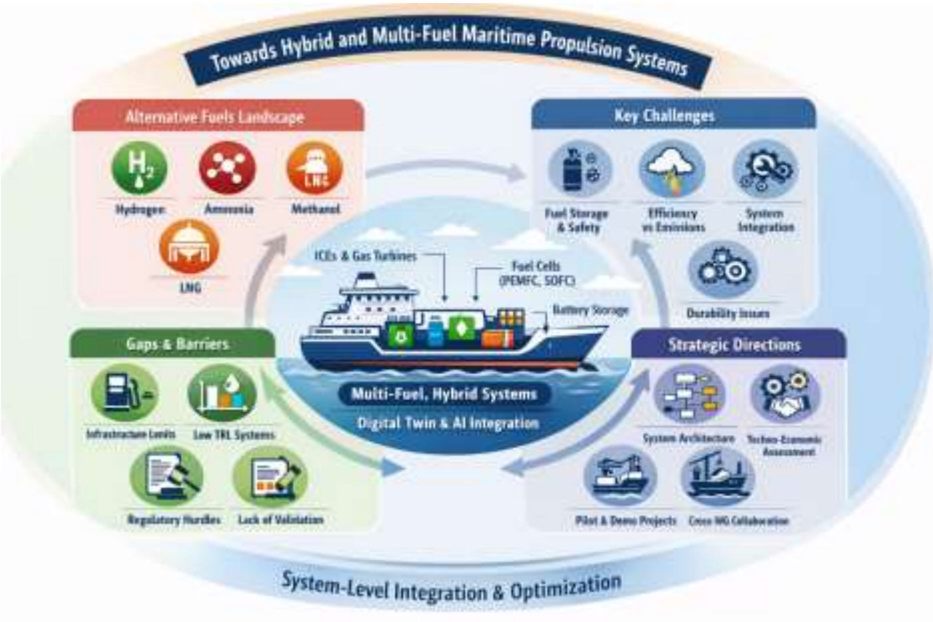

Figure 1 - Hybrid and Multi-Fuel Maritime Propulsion: Challenges and future pathways

The main gap in the field is no longer the absence of technical options. It is the absence of sufficiently coherent methods for comparing and integrating them. WG3 can contribute by moving from technology mapping to system structuring. Priority actions include defining reference propulsion architectures for representative ship types, developing harmonised assessment frameworks that jointly evaluate efficiency, emissions, safety, space claim, durability, and compliance, embedding digital twins in both design and operation, and promoting system-level demonstrations that integrate fuel, storage, conversion, control, and mission profile within one validated framework. Stronger interaction with fuel production, infrastructure, and regulatory workstreams will also be essential because propulsion decisions are increasingly shaped by factors beyond the machinery space itself.

Alternative-fuel ship propulsion should be understood as a constrained integration problem rather than a search for a single winning technology. The absence of one dominant solution is likely to remain a structural feature of the transition. Near- and medium-term progress will depend on hybrid, segment-specific, and digitally managed energy systems whose performance is determined by integration quality as much as by component efficiency. In this context, WG3 is well placed to support the transition by defining comparable architectures, realistic evaluation methods, and system-level research priorities for maritime decarbonisation (IMO, 2025; Lloyd's Register, 2026).

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Integration of renewable energy in ship energy systems as a means for maritime decarbonization

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1 INTRODUCTION

The global shipping industry is intensifying its efforts to reduce dependence on fossil fuels as part of the broader transition toward maritime decarbonization. Although ships are already among the most energy-efficient modes of transport, significant opportunities remain to enhance their operational efficiency and thereby further decrease fossil-fuel consumption. Within this context, Working Group 4 of the DeWaTra project examines how renewable energy sources can contribute to improved ship energy performance. This presentation synthesizes the group's activities, addressing wind-assisted propulsion systems (WAPS), solar-energy integration, energy-storage and management solutions, ship-performance modelling for technology assessment and retrofitting, as well as the associated economic, environmental, regulatory, and safety considerations, including human-factor dimensions in ship operations.

2 RENEWABLE ENERGY CONTRIBUTIONS TO SHIP ENERGY EFFICIENCY

The DeWaTra project contributes to advancing the analysis and understanding of how renewable energy can be more effectively integrated into ship operations to enhance energy efficiency and reduce reliance on fossil fuels. Working Group 4 is organized into five subgroups, each responsible for coordinating research activities, webinars, ongoing collaborative projects, new joint project proposals, and benchmarking studies: (SG1) wind-assist technology, (SG2) solar panels and energy storage systems, (SG3) other renewable energy solutions, (SG4) ship performance models and economic aspects, and (SG5) rules, regulations, safety and human factors. The presentation will provide an overview of the outcomes from five webinars, completed activities, and planned initiatives across the five subgroups.

2.1 *Hybrid-oriented energy-carrier solutions and energy-management strategies*

A central theme is the importance of integrating complementary technologies within hybrid energy and propulsion architectures. Current assessments indicate that renewable energy can supply approximately 1 to 20% of the total energy demand of a conventional cargo vessel, with WAPS presently representing the only technology capable of delivering substantial contributions at scale. Although the long-term potential of renewable energy harvesting is significant, it remains unlikely that large cargo ships will achieve full energy self-sufficiency solely through onboard renewable sources. Notably, considerable energy savings can be realized through speed reduction: because propulsion power demand scales approximately with the cube of vessel speed, a 10% reduction in speed can yield energy savings of 20 to 30%, surpassing the contributions currently achievable from renewable technologies. As a result, future operational strategies are expected to incorporate route optimization for renewable-energy availability and hybrid energy-supply optimization.

To support this analysis, a taxonomy of en-route renewable energy sources for maritime applications is presented. The taxonomy encompasses mature technologies such as WAPS and solar energy; emerging concepts including thermal, wave, kinetic, osmotic, and atmospheric energy harvesting; and a range of energy-storage solutions, including batteries, thermal and mechanical storage, hydrogen, synthetic fuels, and prospective nuclear-based carriers. Hybrid and integrated systems – combining multiple harvesting mechanisms, hybrid propulsion architectures, and energy-aware route optimization – are identified as the most realistic pathway toward future decarbonized maritime operations.

Overall, the taxonomy and associated analyses highlight that, while wind and solar currently dominate practical maritime renewable-energy applications, a broad spectrum of emerging technologies may contribute incrementally to future low-carbon shipping systems. The most promising trajectory lies in the integration of multiple complementary technologies within hybrid energy and propulsion architectures, rather than reliance on any single renewable-energy source.

2.2 *Solar energy, energy storage and microgrids*

Shipboard microgrids are becoming increasingly significant in maritime engineering due to the growing integration of photovoltaic (PV) systems and battery-energy storage, which enable cleaner and more efficient onboard power generation. However, these hybrid energy systems introduce additional complexity arising from variable environmental conditions and highly dynamic load profiles. Advanced modelling, simulation, and control strategies are therefore essential to ensure reliable, stable, and efficient operation of shipboard microgrids. Real-time simulation platforms such as Typhoon HIL provide a safe and flexible environment for testing control algorithms and energy-management strategies under realistic operating conditions prior to physical implementation. Modern ship systems must manage interactions among distributed generators, propulsion loads, storage units, and auxiliary systems with sub-microsecond precision, underscoring the need for robust control architectures and high-fidelity digital-twin environments.

2.3 *WAPS technologies: similarities, trends, and identifying "the most suitable solution"*

This section presents an overview of the principal WAPS technologies currently under development or in use. It discusses their technological similarities, emerging trends, and the key considerations involved in selecting the most appropriate concept for a given vessel. The discussion is supported by case studies from various projects in which WAPS technologies have been tested at sea and are progressing toward commercial deployment.

2.4 *Benchmark study of ship performance models*

Benchmark study of ship-performance models is introduced by the working group to encourage researchers to systematically compare and evaluate modelling approaches for predicting fossil-fuel savings from renewable-energy technologies. Such models should include, among other elements, velocity-prediction programs tailored to commercial vessels equipped with WAPS, accounting for hydrodynamic behavior under heel and leeway, interactions among multiple renewable-energy technologies, and the vessel's overall energy-storage and energy-management strategy. Several research gaps remain open, including limited transferability of models across different ship types, routes, sensor configurations, and loading conditions; the need for uncertainty-aware predictions rather than single-point fuel-consumption estimates; and the absence of standardized validation datasets and transparent model-reporting practices.

2.5 *Rules, regulations and human factors*

The regulation and implementation of emerging maritime technologies are challenged by the absence of uniform global standards. Integrating multiple energy sources into ship systems further increases complexity, requiring the harmonization of technical solutions, operational procedures, and safety practices. The regulatory framework must therefore evolve continuously to keep pace with technological developments—including wind-assisted propulsion systems (WAPS) and advanced energy-storage technologies—while balancing safety, cost-effectiveness, and sustainability.

Human resources and safety considerations remain central to the operation of increasingly complex ship-energy systems, particularly in the context of accelerating digitalization and the gradual introduction of autonomous vessels. Despite rapid technological progress, the crew continues to play a decisive role in ensuring safe and reliable operations. This underscores the need for continuous education and training to prepare seafarers for working with advanced digital, automated, and hybrid-energy systems. In modern ship operations, the interaction between humans and technology is becoming more prominent, with the human factor remaining indispensable for maintaining operational integrity and safety.

Overview of onboard decision support systems in energy-efficient ship operation for decarbonising waterborne transportation

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Extended Abstract

Working Group 5 (WG5) of the DeWaTra COST Action focuses on onboard decision support systems (DSS) for energy-efficient ship operation, which aim to decarbonise the waterborne transportation (Guedes Soares, 2023), Figure 1. The rationale behind this work is that improvements in ship energy performance cannot rely exclusively on novel technologies (Barreiro et al., 2022; Tadros et al., 2023) or alternative fuels (Wang & Wright, 2021). Considerable gains can also be achieved through better operational decisions on board, provided that ship operators are supported by robust digital tools capable of transforming data into timely and reliable recommendations (Bonvicini et al., 2025). In this context, WG5 addresses onboard DSS as a key enabling mechanism for translating digitalisation into practical support for more efficient ship operations.

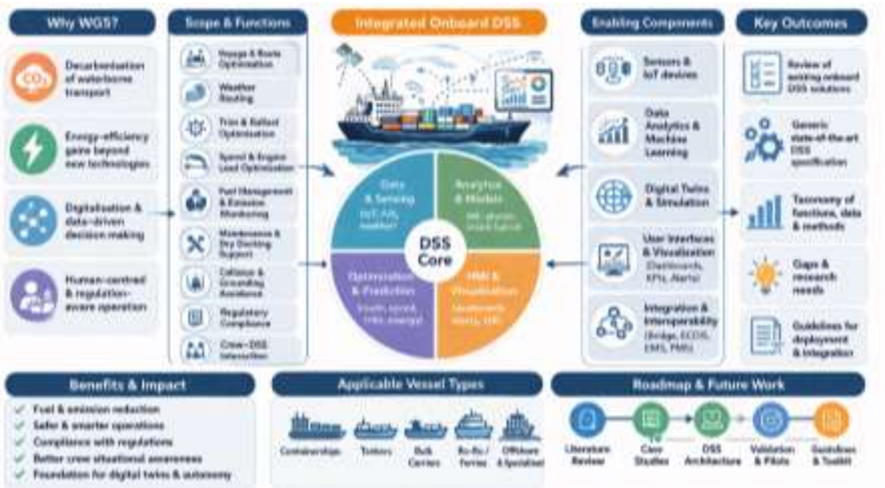

Figure 1. Infographic of WG5 activities in the COST project DeWaTra

The work of WG5 has been organised through a report structure that reflects both the breadth of the field and the main themes emerging from the literature. The report begins by positioning the topic within the broader context of maritime decarbonisation, the importance of energy efficiency in shipping, and the role of digitalisation in achieving these goals. It then reviews the scientific landscape through a bibliometric analysis, clarifies the concept and types of decision support systems, and discusses the main enabling components of energy-efficiency DSS, including sensors and IoT devices, data analytics and machine learning, and user interfaces and visualisation. This structure is important because it frames onboard DSS not as isolated software tools, but as integrated socio-technical systems embedded in real shipboard operations.

At the core of the WG5 work is to identify the principal operational functions of energy-efficiency-related DSS. These include voyage and route optimisation, trim and ballast optimisation, speed and engine load optimisation, fuel management and emission monitoring, weather routing, decision support for dry docking or repairs, collision and grounding avoidance, regulatory compliance, energy flow management, and crew–DSS interaction. Taken together, these topics show that onboard DSS for energy-efficient ship operation is multi-objective. It involves not only minimising fuel use and emissions, but also balancing schedule constraints, ship performance, technical condition, navigational safety, human factors, and compliance with evolving environmental regulations.

A first major thematic cluster within WG5 concerns voyage and operational optimisation. This includes route planning, weather routing, sea-state-aware navigation, speed and engine load optimisation, and infrastructure-related scheduling decisions. These functions represent some of the most immediate operational levers for reducing fuel consumption and greenhouse-gas emissions in existing fleets.

A second thematic cluster relates to ship energy management and technical-operational coordination. Here, the report addresses trim and ballast optimisation, fuel management and emission monitoring, energy flow management, and decision support related to maintenance, repairs, or dry docking. These topics underline that energy-efficiency DSS should not be understood only in navigational terms. They also concern how ship systems are operated, monitored, and maintained over time, and how ship performance can be assessed against suitable baselines. This perspective is closely connected to current developments in digital twins, hybrid physics-based and data-driven modelling, and integrated views of the ship as an energy system. In this respect, WG5 contributes to broadening the understanding of onboard DSS from voyage support alone to more comprehensive energy-performance management.

A third important thematic area concerns safety, regulation, and the human role in decision support. The report explicitly includes collision and grounding avoidance, regulatory compliance, and crew–DSS interaction among the core functions of energy-efficiency DSS. This is a particularly important contribution because it makes clear that energy-efficient operation cannot be treated as an isolated optimisation problem. Recommendations produced by onboard DSS must remain compatible with safe navigation, operator trust, and the regulatory framework governing emissions, energy-efficiency indicators, and maritime operations. In practice, this means that future DSS must be designed as human-centred and regulation-aware systems, rather than purely technical optimisation engines.

The work carried out so far within WG5 also provides an overview of the progress already made in the field. The report includes a review of existing systems, case studies, and demonstrated benefits, including examples from industry and applications across different vessel types. This indicates that onboard DSS has moved beyond a purely conceptual topic and now includes a growing body of applied work. At the same time, the report also identifies important limitations that continue to slow broader implementation. These include issues of data quality and sensor reliability, crew training and confidence in the provided information, and uncertainty related to regulation and interoperability. The value of WG5 lies precisely in bringing these topics together and showing where the field is maturing and where it still remains fragmented.

In conclusion, WG5 addresses a strategically important and rapidly evolving subject area within the DeWaTra COST Action. Its work shows that onboard decision support systems can play a central role in maritime decarbonisation by linking digitalisation with operational decision-making and measurable improvements in ship energy efficiency.

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An Operational Vessel Data Challenge benchmarks predictive performance models to enable verifiable energy-efficiency gains in real operations

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Extended Abstract

1 INTRODUCTION

Maritime decarbonization cannot be achieved by clean fuels alone nor by efficiency measures alone. The sector will need both: (i) accelerated adoption of low- and zero-carbon fuels, and (ii) continuous improvement of energy efficiency and operational performance, including retrofits, and decision support. In the near to medium term, however, the availability of cleaner fuels is expected to be limited, making energy efficiency the primary contributor to emission reductions. Achieving this at scale requires a trusted and standardized ability to measure, model, and verify vessel performance under real operational and environmental conditions.
In practice, performance assessment is still fragmented: different fleets use different sensor sets, different pre-processing rules, and different modelling assumptions, which complicates benchmarking, verification, and the transfer of methods between vessels and operators. This is one motivation behind launching a community challenge that compares approaches on a shared, curated dataset and emphasizes transparency and reproducibility.

2 STATE OF THE ART: HOW VESSEL PERFORMANCE IS ANALYSED TODAY

2.1 *What is commonly measured*

Modern vessel performance monitoring typically relies on combinations of (a) operational signals (e.g., speed through water/over ground, drafts, heading, shaft power/rpm), and (b) environmental information (wind, waves, currents, bathymetry/sea temperature), increasingly supported by onboard IoT and dedicated metocean sensors. The practical aim is to quantify the speed–power relation ‘in actual seas’ and separate (i) environmental effects, (ii) technical condition (e.g., hull/propeller state degradation), and (iii) the contribution of technical measures. The latter includes energy-efficiency devices and other retrofit upgrades whose effects should be verified and compared consistently across voyages and conditions.

2.2 *Modelling approaches*

Modelling approaches span a range of methodology:

- High-fidelity physics (CFD, seakeeping, detailed propulsion and engine simulations) used mainly in design and research settings due to complexity and computational cost;
- Semi-empirical / grey-box methods that encode known physics (e.g., propeller law / calm-water curves) with correction terms for wind/waves/currents;
- Data-driven machine learning (ML) models (Artificial Neural Networks (ANNs), gradient boosting, random forests, Gaussian processes) trained on operational data to predict shaft power, speed loss, or fuel consumption;
- Surrogate modelling and digital-twin concepts that combine models with continuous calibration/validation against real voyages, aiming at predictive and prescriptive decision support.

A recurring conclusion in recent reviews is that ML has become dominant in many applied studies (with ANNs frequently used), but successful deployment depends strongly on data preprocessing, feature selection, quality control, and the ability to generalize beyond the training envelope.
Additionally, achieving meaningful energy savings in real operations requires not only the ability to interpret data and support decisions under varying conditions. Studies indicate that significant efficiency gains (≤16%) can be unlocked through improved monitoring, optimization, and operational awareness, and decision support systems (DSS) play a central role by linking data to actionable insights, with energy efficiency modelling acting as the key enabler that converts data into performance predictions for decision-making.

3 THE VESSEL EFFICIENCY DATA CHALLENGE

3.1 *Objective*

DNV, together with the vessel data provider, proposes an open modelling challenge where participants develop models that (i) reproduce vessel performance (speed–power behaviour) from operational + metocean data; and (ii) demonstrate predictive capability for future behaviour (forecasting/generalization). The broader intent is to compare modelling methodologies (physics-guided, purely data-driven, hybrid) on a common dataset and identify key requirements for robustness and transparency in real-world performance verification.

3.2 *Timeline and eligibility*

Registration for the challenge opens on 25 May 2026 via the link on DeWaTra webpage, with data made available from 15 June 2026. The submission deadline for solutions is 31 August 2027, and the winners will be announced in the 4th quarter of 2027. Participation is open to industrial and academic contributors affiliated with the DeWaTra COST Action.

3.3 *Dataset*

Participants will receive several months of time-synchronized data containing the following:
Timestamp; Displacement; Speed Through Water (STW); Draft fore/aft; Significant wave height; wave peak period & direction; Speed over ground; Shaft power; Depth; True and relative wind direction/speed; Shaft speed (rpm); Vessel heading; current direction/speed; wave directional spectrum; swell and wind-sea periods/heights; sea surface temperature; salinity. In addition, a limited set of vessel metadata will be provided to support modelling (e.g., vessel type/segment and selected principal particulars), subject to anonymization constraints.
Access control & anonymization: The dataset is shared in anonymized form for competition purposes, with distribution controlled via registration/sign-up webpage leading to data access on DNV Veracity platform, as agreed with the data partner. The challenge rules explicitly prohibit participants from republishing raw/derived data that could enable re-identification. Authors are free to publish the solutions after the challenge deadline.

3.4 *Potential modelling strategies*

Participants are free to experiment with different modelling approaches (e.g. data-driven, physics-guided, hybrid), which will be compared on a common evaluation framework.

3.5 *Evaluation criteria and additional considerations*

Solutions will be evaluated based on (i) quality of modelling, (ii) originality of approach, and (iii) clarity of the solution and documentation. Modelling quality will be assessed based on: predictive performance and generalization capability; robustness to transients; uncertainty awareness; sensitivity and interpretability. Submissions shall include a method description and results; code may be provided optionally/when possible. Participants shall briefly document how their approach accounts for environmental factors, technical conditions (e.g., hull/propeller degradation), and measurement/data uncertainty.

The challenge is designed to surface practical lessons: which inputs are truly necessary, what preprocessing/quality checks dominate accuracy, how to prevent leakage and overfitting in time series, and how to communicate uncertainty and limitations. In the medium term, the outcomes can support a more standardized approach to measurement-model-verification workflows for vessel efficiency, enabling more trustworthy benchmarking of operational measures (routing, speed management), technical measures (cleaning, propeller polishing), and retrofit effects.

3.6 *Award and collaboration opportunity*

The winning authors will be invited to spend one week immersed in DNV's research and business development environment in partnership with Vessel data provider, with the dual aim of (i) transferring the winning approach into a more generalizable framework and (ii) exploring pathways for real-world deployment.
Following the challenge, the submitted solutions will be analysed collectively to extract methodological insights, with the intention to synthesize the results in a joint publication covering performance, strengths, and limitations of the different approaches.

Working Group 1 on Assessment of atmospheric emissions from shipping

Energy system optimization and emissions pricing - Comparing alternative generation concepts

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Extended Abstract

1 INTRODUCTION

Maritime transport is the backbone of global trade, representing a highly efficient mode of transport in terms of energy per ton-kilometer. However, due to the massive scale of the industry and a projected continuous increase in shipping volume, it remains a significant contributor to global anthropogenic greenhouse gas (GHG) emissions. In response to the escalating climate crisis, regulatory bodies have introduced increasingly stringent environmental targets. Most notably, the International Maritime Organization (IMO) has revised its strategy, setting a clear trajectory towards net-zero GHG emissions from international shipping by 2050.

European Union regulations, such as the inclusion of shipping in the EU Emissions Trading System (EU-ETS), further intensify the pressure on ship operators to reduce their carbon footprint.

A vast array of measures for direct efficiency improvements is available to ship designers and operators, ranging from alternative carbon-neutral fuels and hybrid-electric propulsion concepts to energy storage implementation and extensive sector coupling on board [Bouman2017]. While the integration of these technologies significantly expands the design space and offers immense potential for drastic efficiency gains, it also increases the complexity of the ship design process dramatically and creates an interconnected architecture where isolated component optimization is no longer sufficient.

Ships designed today will have to operate efficiently throughout a 40+ year lifespan, necessitating a design process that effectively navigates the complex, highly interconnected solution space while accounting for future developments in fuel pricing, emission pricing, and component costs.

While contemporary literature provides rigorous component-level analyses, these often isolate specific technologies without accounting for the interconnectedness or cost uncertainty. Recent studies evaluating Solid Oxide Fuel Cell (SOFC) and Internal Combustion Engine (ICE) hybrids demonstrate significant fuel reductions but highlight that capital cost remains the primary economic barrier [Elkafas2026]. Similarly, investigations into the life-cycle cost (LCC) and environmental performance of alternative marine fuels—such as methanol and liquefied natural gas (LNG) compared to conventional fuel oils—emphasize that volatile future fuel prices and carbon pricing drastically affect architectural viability [He2025].

Furthermore, research explicitly addressing cruise ship environments highlights the necessity of optimizing both system topology and energy management strategies to handle highly variable load demands effectively, yet frequently relies on fixed battery storage without considering long-term degradation and capital replacement costs concurrently with component configuration [Cao2023]. Moreover, while studies have investigated waste heat recovery (WHR) and hybrid battery/fuel cell plants using long-term economic forecasting to demonstrate substantial decarbonization potential [Yuksel2025], integrating these models and combining diverse gensets, multiple fuel cells, variable thermal and electrical storage, and alternative fuels—into a unified decision-making optimizer remains a critical gap.

Consequently, this paper proposes the use of the MESO [Molinski2024], a holistic framework designed for the automated optimization of complex ship energy system architectures, to bridge this gap.

2 OPTIMIZATION SETUP

The goal of this study is to investigate the effect of emission taxation, fuel price volatility and component cost variations on both the process of ship energy system optimization and the resulting optimal configurations. Optimization is done with MESO, a modular Python platform designed to optimize the architecture, dimensioning, and operation of sector-coupled ship energy systems.

The proposed investigation bases its technical parameters on contemporary studies from literature and use demand data from measurements on an existing cruise ship with the fundamental assumption of using electric propulsion. The configuration options include:

- Generators of different size ranges with various fuels (Diesel, HFO, LNG, methanol, ammonia, hydrogen), each with different performance parameters - e.g. partial-load efficiency curves, start-up time, ramping capabilities, waste-heat recovery potential,etc.
- High-temperature fuel cells of different types (SOFC, MCFC, HT-PEMFC) with different fuel options and performance parameters.
- Renewable energy sources, mainly PV, since WASP is not viable without route optimization.
- Different types of thermal and electrical energy storage, parameters include e.g. charge/discharge power and efficiency, capacity ranges, degradation and self-discharge rates, etc.
- Shore power connection for zero-emission port operations, with different power ratings and availability profiles.

The variation of economic parameters includes a range of fuel price scenarios, emission taxation levels, and component cost variations, based on projections from literature and market analyses. MESO is used to optimize the energy system configuration for each scenario, evaluating the resulting configurations based on performance indicators such as total cost of ownership, fuel consumption, emissions, and system reliability. The effect of varying the economic parameters on the optimized configurations is then analyzed to identify trends and thresholds where certain technologies or configurations become more favorable. This analysis provides insights into how future economic conditions could influence ship energy system design and the potential for different technologies to contribute to decarbonization efforts under varying market conditions (see Figure 1).

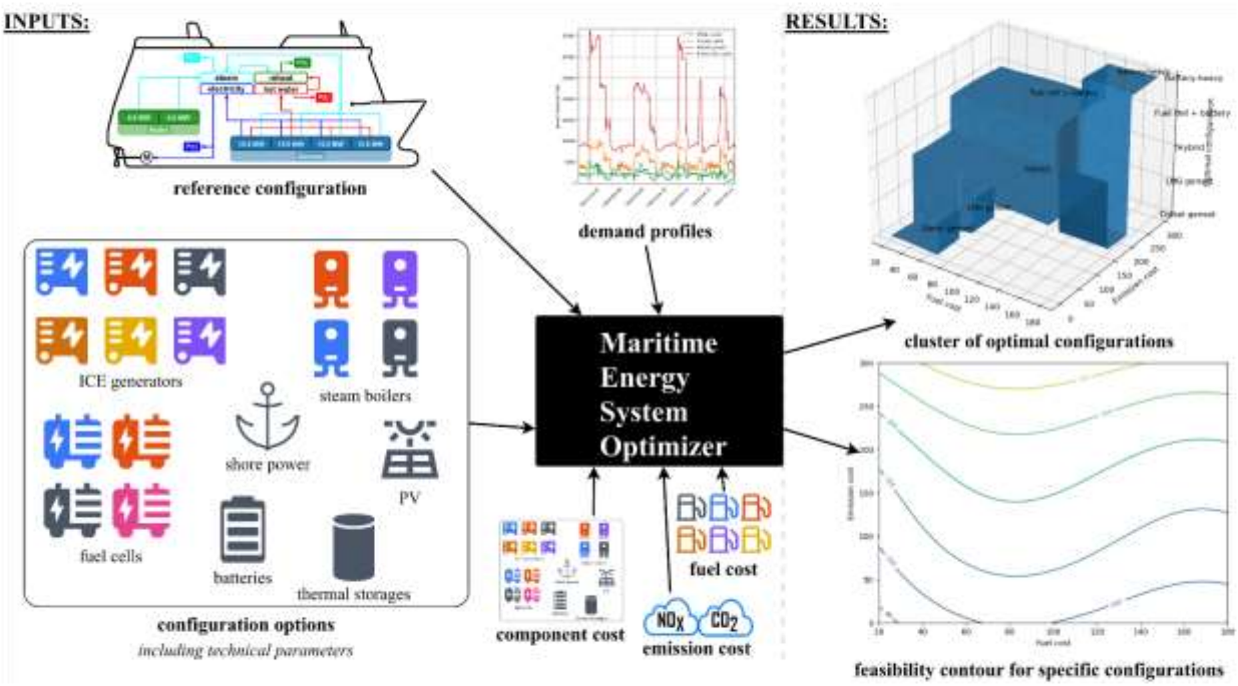

Figure 1: Concept of the proposed study: investigating the effect of emission pricing, fuel price volatility and component cost variations on ship energy system optimization

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Assessing global atmospheric emissions from shipping: A meta-review and best practices for future work

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Extended Abstract

1 INTRODUCTION

Shipping-related air pollution, which accounts for approximately 2–3% of global greenhouse gas (GHG) emissions depending on the scope and methodology applied, has increasingly become the subject of focused attention by the international shipping community and regulators. Global emission inventories are needed to quantify, compare, and track emissions from shipping worldwide, support climate and air quality modelling, inform international policy, and assess the health and environmental impacts of maritime activities.

This paper presents a meta-review of the existing literature reviews on ship emissions, with a primary emphasis on global emission inventories, as these are relevant to the discussion on Climate Change.

The rest of the paper is organized as follows. Section 2 directs the reader to the main systematic literature reviews on ship emission inventories and discusses, in separate subsections, the emission estimates reported by the International Maritime Organization (IMO) and the Intergovernmental Panel on Climate Change (IPCC). Section 3 concludes by outlining potential extensions and additional applications of ship emission inventories.

2 GLOBAL EMISSION INVENTORIES AND PROJECTIONS

A substantial body of literature has examined methods for estimating shipping emissions. In this section, we highlight key review studies that synthesize this literature, with a particular emphasis on global emission inventories. While individual studies are not discussed in detail here, it is worth noting that global ship emission inventories were reported as early as 1997. Corbett and Fischbeck (1997) presented global estimates of NOx and SOx emissions (excluding CO_2), reflecting their relevance to air quality and the fact that these pollutants were already central to discussions at the IMO. Most early studies (e.g., Corbett and Fischbeck, 1997) primarily employed top-down approaches, relying largely on international marine fuel consumption statistics published by the U.S. Energy Information Administration (EIA). The relevant studies have examined in various review studies; the interested reader is referred to the below for more details. Miola and Ciuffo (2011) provided a comprehensive meta-analysis of both top-down and bottom-up modelling approaches and the data sources used in early shipping emission studies. Their analysis highlighted the uncertainties associated with different methodologies and attributed these uncertainties to variations in input data quality and availability. Most recently, Yan et al. (2025) presented an extensive review of 78 academic studies published between 2009 and 2024, with a particular focus on inventories using AIS data as the primary data source.

3 GLIMPSE INTO THE FUTURE OF GLOBAL EMISSION INVENTORIES

The review studies discussed in Section 2.1 highlight several persistent challenges in ship emission modeling. Many of these challenges are expected to be progressively addressed through improvements in modeling techniques, and, critically, the systematic validation and calibration of emission models using real-world datasets such as those provided by the EU MRV and the IMO Data Collection System (DCS).

The Terms of Reference for upcoming IMO studies (see Section 2.3) further identify key priorities for future work. A central requirement is the comprehensive calculation of all relevant greenhouse gas (GHG) emissions from shipping, but also other pollutants. In this context, the increasing uptake of alternative fuels such as ammonia, methanol, and hydrogen necessitates explicit consideration of associated non-CO_2 emissions and fuel-specific slips, including methane (CH_4) and nitrous oxide (N_2O). In addition, hydrogen fuel use may be associated with hydrogen slip; while hydrogen itself is not a greenhouse gas, it exerts an indirect warming effect through atmospheric chemical interactions.At the same time, ship emission inventories have long quantified emissions of sulphur oxides (SO_x) and nitrogen oxides (NO_x), which, although not greenhouse gases, have well-established impacts on the climate system. This climate interaction has been widely discussed in the literature (e.g. Sofiev et al., 2018; Kontovas, 2020). Against this background, we recommend that future ship emission inventories aim to quantify as broad a range of relevant emissions as possible, including both greenhouse and non-greenhouse species. This should include the calculation of well-to-wake emissions, as increasingly emphasized in policy discussions, as well as an assessment of the total climate impacts of different emission species.

3.1 Future Elements: Beyond emissions

One might argue that, as increasingly accurate operational data become available, the need for emission inventories will diminish. For example, the IMO DCS provides reported fuel consumption data (note here: reported and not real) that, in principle, could be used directly to estimate emissions without relying on modeling. While such datasets represent a major improvement over earlier assumptions-based approaches, this view overlooks several fundamental reasons why ship emission inventories (and ship activity models more broadly) remain essential.

First, emission inventories are indispensable for future-oriented analysis. Reported data describe historical or current conditions, whereas inventories embedded within activity-based models allow emissions to be projected under alternative future scenarios. These models are built on transparent assumptions that can be systematically adjusted to assess the effects of changing market conditions, fleet evolution, fuel/energy pathways, operational measures (such as speed optimization and WASP), and policy interventions. Examples include the evaluation of regional measures such as the EU Emissions Trading System (EU ETS), fuel carbon intensity standards (FuelEU or IMO GHG Fuel Intensity), and other market-based measures (i.e. regional or global “taxes”). Without emission inventories, it would not be possible to consistently explore counterfactual scenarios or assess the long-term impacts of prospective regulations.

Second, emission inventories enable detailed spatiotemporal characterization of shipping emissions, which cannot be derived directly from aggregated reporting systems such as the IMO DCS. Ship activity models are required to allocate emissions geographically and temporally—at the level of coastal zones, ports, or sensitive regions such as the Arctic. They also allow emissions to be differentiated by voyage type such as international versus domestic shipping. This spatial and temporal resolution is, more importantly, essential for air quality modeling, as dispersion and chemical transport models require geographically resolved emission inputs to simulate pollutant concentrations accurately.

Furthermore, equity and distributional analysis and integrated assessment modeling also rely critically on ship emission inventories. Spatially resolved inventories make it possible to assess how the environmental and health impacts of shipping emissions are distributed across countries, regions, and population groups, including coastal and port communities, developing countries or Small Island Developing States (SIDS), that may experience disproportionate consequences despite limited economic benefits from maritime transport. In addition, ship emission inventories provide essential inputs to integrated assessment models (IAMs), where they are used to represent the maritime sector within economy–energy–climate systems. In this context, inventories support the evaluation of long-term decarbonization pathways, interactions between shipping and other sectors, and the economy-wide implications of alternative climate and air pollution policies.

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Sustainable legislation: Perfect storm or perfect opportunities

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Extended Abstract

Shipyards are facing legislation from many different directions. IMO and the EU are pushing for GHG reductions in ships. Within the EU, Corporate Sustainabily Reporting Directive (CSRD) (EU, Corporate sustainability reporting, 2025) is forcing companies and their suppliers to disclose their broader Environmental, Social and Governance (ESG) impacts. While the Digital Product Passport (DPP) (EU, Digital Product Passport, 2025) is providing insights in impacts of the production of products (steel and batteries for now). Finally, the Circular Economy Action Plan (CEAP) (EU, Circular economy action plan, 2025) acts as a driver for circularity and the Critical Raw Material Act (EU, Critical Raw Material Act, 2025) forces outside suppliers to provide the same information and pay taxes on them.

While dealing with all this can be daunting for shipyards, CirclesofLife proposes a set of three measurements that use and could serve as input to all of these legislations. A Ship Circular Material Passport (SCMP) to capture the materials and their history, a Ship Lifecycle Passport (SLP) capturing impacts from materials and processes linked to the vessel and a Shipyard Environmental Process Indicator (SEPI) to capture the impact of shipyard processes, both absolute and relevant to each other.

The Ship Circular Materials Passport (SCMP) is a Passport on the individual materials, parts, and components of the Bill of Materials of a ship (BOM) (used in the maritime value chain). These passports are related or like the Environmental Product Declaration (EPD + ISO 14025) and Product Circularity Data Sheet (PCDC - ISO 59040) and are used to trace circularity and environmental impact of individual parts, materials, and components. For sustainability score, for example, the SCMP helps to compare and select suppliers with the lowest environmental impact and work as a mechanism to drive the supply chain to develop materials and components with the lowest impact. The SCMP also discloses what the circular performance of the material or component is, stating what materials are incorporated and how they can be recovered (including location) or re-used at the end of life and thus bridging that information gap while also optimizing circularity.

The Ship Lifecycle Passport (SLP) is to cover more than just a report of used materials and in how far they are sourced in a circular manner. The goal of the passport is to cover the environmental performance of the ship throughout its lifecycle wherein the concept of circularity brings a significant potential reduction of environmental and societal costs. A key challenge is to balance the non-operational impact related to the material application and reusability against the operational benefits of having a lighter and thus more energy efficient ship; this can only be properly answered by taking into account the full lifecycle of the ship and its materials (re-)use. Furthermore, it should support decision-making about yard and supplier selection and yard processes both for newbuilding as well as life-cycle support, extension, or termination. The SLP will also serve as a statement of the residual value of the ship throughout its lifecycle, including the Inventory of Hazardous Materials (IHM). In this way, the SLP supports decision-making during the design, production, and operation & maintenance of the ship but it also helps to identify retrofit and lifetime extension possibilities, i.e. the increase of residual value, or decisions regarding decommissioning, monetising on residual value and transparency on the vessel content. The connection between these different life cycle phases including the true value and costs (incorporating economic, environmental, and social costs) and the connection to external regulatory requirements are unique in the SLP.

The goal of the SEPI to supply input for reporting towards (upcoming) legislation (e.g. CSRD) and most importantly to provide insight into impacts and impact hotspots to the shipyard itself. As a result, SEPI currently focuses on the Environmental topics of ESRS (E's). However, this does not mean that the other ESG categories are out of focus. The core rationale behind ESRS standards is that social and environmental impacts cannot be

considered separately. Even when a standard primarily addresses environmental issues, it must do so while considering the social externalities resulting from environmental decisions. The SEPI includes a generic yard model for mapping of emissions and a maturity level to indicate the detail of measurements. A low maturity means data is collected at yard level, while the highest maturity measures data a tool level and aggregates this into yard level impacts.

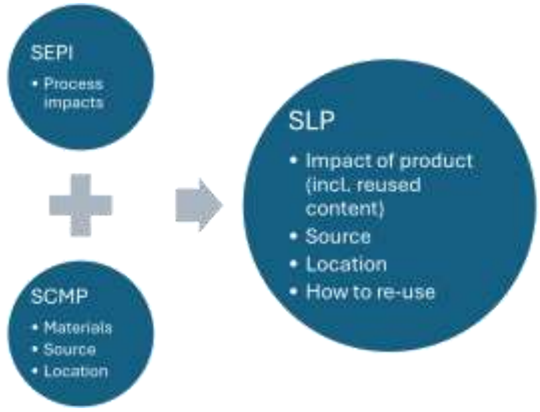

Figure 1: Relation between SEPI, SLP and SCMP

As shown in Figure 1, the three components do not operate independently as material and process impacts combined form the life cycle impact. Also this approach should be considered for upstream suppliers as well. The emissions linked to the materials bought, are the result of the materials and processes applied to these materials. So although focussed on ships, the model could be cascaded up the supply chain as well. However, without one element, the other elements will also not function, showing the precarious balance between these three elements and the need to incorporate all in legislation and not only one or two.

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Competitive, sustainable and resilient shipping pathways

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Extended Abstract

Maritime transport remains a fundamental pillar of the global economy, accounting for more than 80% of international trade and facilitating the movement of energy, food, manufactured goods, and critical raw materials. At the same time, the sector is undergoing a multifaceted transition, where decarbonisation pressures, freight-rate volatility, geopolitical rerouting, climate-related disruptions, and increasing digital and cyber risks do not evolve independently but interact (sometimes reinforcing each other in ways that are not always predictable).

A clear regulatory direction is provided by FuelEU Maritime, which mandates progressively lower lifecycle greenhouse gas intensity for energy used onboard ships above 5,000 GT calling at EU ports, starting with a 2% reduction in 2025 and reaching 80% by 2050. It also introduces zero-emission requirements at berth for containerships and passenger ships from 2030 in AFIR-designated ports. In parallel, the EU Industrial Maritime Strategy (European Commission, 2026), together with the evolving IMO Net-Zero Framework, reinforces the need to consider competitiveness, sustainability, and resilience not as separate policy tracks, but as interconnected objectives (European Union, 2023; International Maritime Organization, 2026).

The argument developed in this paper is that the perceived tension among these objectives is, to a considerable extent, the result of a rather narrow interpretation of competitiveness; one that focuses primarily on short-term cost minimisation. If, instead, competitiveness is understood more dynamically, as the ability to deliver reliable, compliant, low-emission and disruption-tolerant transport at an acceptable total system cost, then sustainability and resilience begin to appear less as constraints and more as enabling factors.

A central limitation in much of the existing literature (and, arguably, in parts of the policy discourse) is the fragmented treatment of fuel transition, digital transformation, industrial capability, and resilience. In practice, maritime decision-making brings these elements together through cost structures, regulatory exposure, fleet renewal cycles, infrastructure constraints, interoperability, and safety considerations. Yet, many quantitative analyses still assess fuels or technologies in isolation, often under a single baseline scenario, which inevitably simplifies the decision space.

To address this gap, the paper introduces two main contributions. First, it evaluates integrated transition pathways rather than isolated technologies or fuels. Second, it assesses these pathways across multiple scenarios, explicitly incorporating uncertainty and disruption effects. The analysis therefore moves away from the question of “which fuel is best” in isolation and instead considers which transition pathways remain robust when cost, lifecycle emissions, and resilience are examined jointly.

The proposed methodology combines assessment, scenario analysis, and prioritization, treating the transition pathway as the primary unit of analysis. Each pathway is defined as a portfolio that includes fuel selection, technical retrofits, operational measures, port-interface solutions, and digital capabilities. An indicator system is developed across three pillars. Competitiveness is captured through generalized transport cost, schedule reliability, asset utilisation, and regulatory cost dependence. Sustainability is measured through well-to-wake greenhouse gas intensity, lifecycle emissions per transport work, the share of low- or zero-emission energy, and compliance with at-berth requirements. Resilience, somewhat more difficult to quantify in a consistent way, is evaluated using normalized route diversity, fuel supply diversity, chokepoint exposure, recovery time, and performance degradation under disruption.

Each pathway is stress-tested under six scenarios: baseline transition, policy acceleration, EU–IMO policy fragmentation, geopolitical disruption, climate stress, and technology acceleration. Indicators are normalized against fixed benchmark bounds and aggregated through a hybrid weighting approach combining expert judgement with entropy-based weighting. This allows the calculation of pillar-specific scores and, ultimately, an overall trilemma of performance index. Robust prioritization is then carried out using scenario-weighted mean performance and downside semi-deviation, enabling a distinction between no-regret, conditional, and longer-term strategic measures. The methodology is illustrated through an application to EU-related container shipping

above 5,000 GT, within a normalized multi-criteria framework that combines data-driven and expert-informed weights.

Building on the work of Mallouppas & Yfantis (2021), which reviews a broad set of technological and operational decarbonisation pathways (including alternative fuels, fuel cells, wind assistance, and efficiency measures such as slow steaming and hull optimisation) three analytical propositions are advanced. First, efficiency-first decarbonisation appears to be the most robust, no-regret strategy. Measures such as weather routing, just-in-time arrival, propulsion improvements, and voyage optimisation can reduce fuel consumption, emissions, and exposure to fuel price volatility simultaneously, although their effectiveness may vary depending on operational context. Second, fuel pluralism seems more defensible than reliance on a single dominant fuel. No alternative fuel is universally optimal across vessel types, routes, and infrastructure conditions, which supports a more technology-neutral and lifecycle-based approach. Lifecycle evidence suggests strong potential for fuels such as green hydrogen, waste-derived biodiesel, and bio-methanol, whereas ammonia and e-methanol remain sensitive to upstream production pathways and emission assumptions (Tomos et al., 2024). Third, fuel transition alone is unlikely to be sufficient. Effective decarbonisation requires parallel investments—not only in retrofits and fleet renewal, but also in port electrification, fuel supply chains, cybersecurity, maintenance capacity, and workforce development. Some of these elements tend to receive less attention, yet they can become critical bottlenecks.

Resilience must therefore be treated as an economic variable rather than a secondary consideration or an external insurance premium. Recent evidence indicates that maritime trade growth has slowed, voyage distances have increased due to rerouting, and greenhouse gas emissions rose in 2024 as disruptions persisted (UNCTAD, 2025). Application of the proposed framework suggests that the most robust transition pathways are those that combine efficiency-oriented operations, selective retrofits, digital optimisation, and gradual fuel flexibility. Such portfolios tend to perform more consistently across scenarios by reducing costs, lowering emissions, and limiting exposure to fuel price volatility, chokepoint disruption, and regulatory uncertainty. By contrast, strategies centred primarily on single-fuel substitution—especially when not accompanied by corresponding investments in infrastructure, port readiness, and institutional support—appear more sensitive to fragmentation and implementation risks. Preliminary results indicate that integrated pathways can reduce lifecycle greenhouse gas emissions by approximately 25–40%, while maintaining generalized transport costs within a ±10% range under most scenarios, although this remains dependent on several assumptions.

The contribution of this paper is both analytical and practical. From a scientific perspective, it translates the competitiveness–sustainability–resilience nexus into a measurable decision framework suitable for comparative scenario analysis and robust prioritization. From a policy and industry standpoint, it outlines a structured hierarchy of actions, ranging from no-regret measures—such as efficiency improvements, digital optimisation, cybersecurity, and skills development—to conditional and longer-term strategic investments, including fuel pathways, port electrification, green corridors, and resilient bunkering networks. The central conclusion is that the maritime sector should not approach competitiveness, sustainability, and resilience as inherently conflicting objectives. Rather, competitiveness needs to be redefined through lifecycle efficiency, regulatory readiness, and operational continuity under uncertainty. The fleets and logistics systems most likely to lead in the coming decades will be those that integrate efficiency, fuel flexibility, digital capability, and resilience—not perfectly, but deliberately—into their design and operation.

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Cruise ship emissions in urban ports within the DeWaTra Framework: A bottom-up assessment for the 2024 season at Istanbul Galataport

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1. INTRODUCTION

Within the framework of DeWaTra – *Decarbonization of Water Transportation*, the transition toward low-carbon maritime systems requires robust and harmonized methodologies capable of quantifying emissions at both global and local scales. Although maritime transport is widely recognized as one of the most energy-efficient modes of freight movement, it remains a relevant source of greenhouse gases and air pollutants, particularly in coastal and port environments where shipping activities take place in close proximity to urban populations. While international decarbonization strategies mainly focus on reducing greenhouse gas emissions at fleet level, port–city interfaces represent critical hotspots in which maritime traffic generates localized environmental pressures with direct implications for air quality, human exposure, and urban sustainability (Corbett et al. 1977; Eyring et al. 2010; Viana et al. 2010). In this context, reliable emission inventories are essential not only for improving the understanding of shipping-related impacts but also for supporting the design, comparison, and evaluation of mitigation measures. In this perspective, the Working Group "Assessment of atmospheric emissions from ships" promotes the development of standardized bottom-up approaches to support comparable inventories, mitigation assessment, and evidence-based decision-making. Such approaches are particularly valuable because they allow emissions to be estimated from vessel activity, technical characteristics, and operational patterns, thereby offering a transparent and transferable framework for port-level analyses. By linking methodological consistency to site-specific applications, this line of work helps bridge the gap between broad decarbonization objectives and the practical needs of ports, local authorities, and policymakers managing complex urban-maritime environments. The present study contributes to these objectives by developing a detailed emission inventory for cruise ship operations at Istanbul Galataport during the 2024 cruise season. In port–city interfaces, where terminals are located close to residential and commercial districts, localized emission inventories become essential to support mitigation planning and policy decisions.

1.1 *Contextual Framework*

In this context, cruise shipping represents a particularly energy-intensive segment of maritime transport (IPCC 2021). In addition to propulsion requirements, cruise vessels demand substantial auxiliary power to sustain onboard hotel services such as air conditioning, catering, lighting, water supply, entertainment systems, and other passenger-related functions. Unlike other ship types, these energy demands remain significant even when vessels are berthed, as onboard services must continue throughout the port stay. As a result, the hotelling phase often becomes one of the main contributors to total emissions in port areas, especially in the case of large cruise ships characterized by high passenger capacity and prolonged berthing times. This makes cruise activity particularly relevant from both an environmental and an urban management perspective. Given the location of Galataport in close proximity to densely populated residential and commercial districts, the accurate quantification of cruise-related emissions is essential for assessing potential impacts on local air quality and for supporting effective decarbonization and mitigation planning. Situated in Istanbul, Türkiye overlooks the Sea of Marmara and occupies a strategic position within the Turkish Straits system, which connects the Black Sea to the Mediterranean and represents one of the most intensively used maritime corridors in the region (Mocerino et al. 2026). This location has long supported the city's role as a major crossroads of trade, mobility, and tourism between Europe and Asia, while also concentrating intense maritime activity in close proximity to densely populated urban areas. Within this geographical and economic framework, Galataport has emerged as a key cruise port and waterfront redevelopment project, combining maritime functions with commercial, cultural, and public-space uses. Opened as part of a broader urban regeneration process, the project has transformed a historically significant port area into a contemporary hub for cruise operations and urban activities. As such, it has further strengthened Istanbul's role in regional maritime connectivity and tourism development, while also increasing the relevance of assessing cruise-related emissions in a complex port–city interface.

2. METHODS AND PRELIMINARY RESULTS

A bottom-up methodology was adopted to ensure transparency, reproducibility, and alignment with DeWaTra objectives. Vessel-specific technical data, including installed main and auxiliary engine power, engine category, and construction year, were integrated with detailed port call records reporting arrival and departure times. Emissions were calculated for manoeuvring and hotelling phases using phase-specific load factors applied to installed power, combined with pollutant-dependent emission factors derived from internationally recognized sources. The analysis focused on carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter (PM), with fuel sulfur content assumptions consistent with the applicable regulatory framework during the 2024 season. The inventory covers 164 cruise calls performed by 53 different vessels during the 2024 cruise season. Preliminary results indicate that the hotelling phase constitutes the dominant share of total port-related emissions. In particular, more than 90% of total CO_2 emissions were generated during at-berth operations, confirming the importance of prolonged berthing times and sustained auxiliary engine demand. Total annual emissions were estimated at approximately 31,360 t of CO_2, 370 t of NO_x, 350 t of SO_x, and 44 t of PM. Although manoeuvring involves higher propulsion loads, its shorter duration limits its overall contribution to total emissions. Conversely, prolonged berthing times coupled with sustained auxiliary engine operation generate significant cumulative emissions, particularly for NO_x, SO_x, and PM. Carbon dioxide emissions were found to correlate strongly with installed auxiliary power and duration of stay, highlighting the influence of vessel size and onboard energy demand. Larger cruise vessels exhibited disproportionately higher per-call emissions, emphasizing the importance of fleet composition in shaping seasonal emission profiles. From a decarbonization perspective, these findings confirm that strategies focusing exclusively on propulsion efficiency are insufficient to substantially reduce emissions in urban port contexts. The dominance of hotelling emissions highlights the critical importance of port-based energy management strategies. Interventions targeting auxiliary energy supply during berthing—such as shore-side electricity, alternative fuels, hybridization of onboard systems, and improved auxiliary engine efficiency—emerge as potentially high-impact mitigation measures. In urban cruise ports embedded within densely populated metropolitan areas, emission reduction is not only an environmental priority but also a relevant public health objective. By providing a detailed and transferable methodological framework, this case study supports the objectives of DeWaTra in bridging the gap between high-level decarbonization targets and site-specific implementation strategies. The results highlight the relevance of localized emission inventories in guiding port authorities and policymakers toward effective mitigation actions within complex urban maritime environments. Future research should expand the analysis through emission intensity indicators, such as emissions per ship call, per gross tonnage, or per passenger, and through scenario-based evaluation of mitigation options. Overall, the findings provide a technical basis for evidence-based policymaking and more sustainable cruise port management in Türkiye and in comparable Mediterranean port contexts.

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Assessing AIS fitness for port-anchorage emission inventory modelling

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Extended Abstract

Reliable baseline emissions are essential for decarbonising waterborne transportation. In many national contexts, however, the key bottleneck is not the emission equation itself, but whether available AIS data are sufficiently reliable for reconstructing vessel activity in port-anchorage environments, where signal gaps, low-speed stop-and-go movements, and ambiguous transitions between berthing and anchoring are especially challenging (Johansson et al. 2017; Yi et al. 2025). This study therefore asks a prior methodological question: under what data-quality conditions can AIS support stable and interpretable emission inventory modelling in port-anchorage areas, and which uncertainty sources most strongly affect the resulting estimates? Focusing on pilot-port applications in Vietnam and the Philippines, the study develops a feasibility-first, AIS-driven inventory module for operational-mode identification (at sea, manoeuvring, at berth, anchorage) and tank-to-wake (TTW) CO_2 estimation. The aim is not only to generate pilot estimates, but also to establish a transparent and transferable framework for judging whether AIS is fit for purpose in data-constrained inventory settings (Grigoriadis et al. 2026).

AIS messages are first cleaned and assembled into vessel trajectories, and then linked to basic vessel attributes, including ship type, size class, and IMO number where available. This supports vessel grouping and proxy assignment for missing technical parameters. Operational modes are identified using a combined rule set based on speed thresholds, proximity to port and anchorage polygons, stop-event detection, and temporal consistency checks. This procedure enables the derivation of mode-resolved time and activity metrics at both vessel and port scales (Johansson et al. 2017; Yi et al. 2025). TTW CO_2 emissions are then estimated using an activity-based, power-driven formulation combining engine power, load factors, time in mode, and fuel-specific CO_2 emission factors. Missing technical parameters are addressed through transparent proxy rules, and their influence is propagated into uncertainty ranges in line with recent methodological recommendations for improving inventory robustness (Grigoriadis et al. 2026).

The study adopts a staged pilot design around one or two representative ports or anchorages. Its central methodological contribution is to operationalise AIS fitness through a set of diagnostic indicators and threshold-based checks, including message-interval distributions, spatial coverage differences between offshore and port waters, missingness rates, trajectory-break frequency, and the temporal stability of berth and anchorage detection. Sensitivity tests are further used to evaluate how mode shares and CO_2 estimates respond to key classification thresholds and proxy assumptions, thereby identifying dominant error pathways and minimum data requirements for stable modelling. Where available, port-call records, throughput indicators, or fuel statistics are used as independent plausibility checks to assess whether estimated activity and emissions remain within a reasonable range.

Expected outputs include: (i) a practical AIS feasibility checklist for port-anchorage emission inventory applications; (ii) threshold-based guidance on when AIS-derived modelling is reliable, conditionally usable, or unsuitable; (iii) mode-resolved TTW CO_2 estimates for pilot areas; and (iv) a transparent set of assumptions, sensitivity ranges, and uncertainty bounds that can inform later scaling to a full-year national baseline. In this way, the study contributes to the DEWATRA topic “Assessment of atmospheric emissions from shipping” by shifting attention from inventory construction alone to the more fundamental question of whether the underlying AIS data are sufficient to support it in data-constrained national contexts. As a later extension, the module may be expanded from a TTW baseline to a well-to-wake perspective when upstream fuel-cycle impacts become relevant (Kramel et al. 2021; Liu et al. 2016).

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Port related ship emissions and decarbonization strategies: The case of the Port of Augusta

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Extended Abstract

Port areas are strategic hubs but at the same time critical from an environmental point of view, as they are heavily affected by greenhouse gas emissions and air pollutants associated with maritime transport. The operational activities of ships in ports – including docking and undocking manoeuvres, the operation of auxiliary engines and the use of on-board generators while berthed – contribute significantly to local concentrations of carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur oxides (SO_x) and particulate matter (PM). These emissions have a direct impact on air quality and the health of people living and working in port areas, making them one of the main environmental challenges facing the maritime sector. Consequently, reducing the emissions impact of ports is a key lever for achieving the decarbonisation and environmental sustainability goals promoted at international and local level.

In this context, the International Maritime Organisation (IMO) GHG Strategy, updated in 2023, marked a significant acceleration in the transition to low-carbon maritime transport. The strategy sets the goal of achieving net-zero emissions by or around 2050, with ambitious interim targets, including a reduction in the carbon intensity of maritime transport of at least 40% by 2030 compared to baseline levels [Govindan et al., 2024; Alamoush et al., 2022]. These targets imply not only the adoption of alternative fuels and more efficient propulsion technologies, but also a rethinking of port infrastructure and the operating modes of ships in port.
At European level, the "Fit for 55" legislative package represents the most advanced regulatory framework for climate and emissions reduction policies. A key element of this package is the extension of the European Emissions Trading System (EU ETS) to the maritime sector. From 2024 onwards, shipping companies will be required to internalise the environmental costs associated with their CO_2 emissions, with a progressive obligation that will lead to 100% coverage of verified emissions by 2026 [Regulation (EU) 2023/1804; Regulation (EU) 2023/1805]. The inclusion of maritime transport in the ETS sends a strong economic signal aimed at encouraging energy efficiency, technological innovation and the use of lower-carbon solutions.

At the same time, the FuelEU Maritime Regulation and the Alternative Fuels Infrastructure Regulation (AFIR) are promoting a profound technological renewal of port infrastructure. These regulatory instruments provide for a progressive reduction in the greenhouse gas intensity of the energy used on board ships and require the main ports belonging to the TEN-T network to provide shore-side electricity (cold ironing) to passenger ships and container ships by 2030 [Xiao et al., 2024; Peddi et al., 2024]. The adoption of cold ironing allows on-board engines to be switched off while moored, drastically reducing local emissions and contributing to improved air quality in port areas, with significant environmental and health benefits.

This study therefore focuses on analysing ship emissions while in port, with the aim of quantifying their impact and identifying effective strategies for reducing them. Emissions are estimated using available data on the technical characteristics of ships, such as gross tonnage and engine power, and on port operations, including arrival and departure times and length of stay. The estimate is based on empirical models and considers general variables, such as the level of ship utilisation and average emission factors for different pollutants.

The data used comes from case study analysis, on-site surveys and public databases, such as the Automatic Identification System (AIS), as well as international studies.

The results indicate that emissions from ships in port contribute significantly to the overall pollution load in urban port areas, with significant peaks during loading and unloading operations. Among the possible solutions for reducing emissions in port, the project evaluates in particular the possibility of using shore-side

electricity (cold ironing), whereby ships switch off their auxiliary engines while moored and connect to low-emission port electricity networks.

This solution is applied to the case study of the container terminal at the port of Augusta, located in the province of Syracuse, in eastern Sicily. The port of Augusta is included in the TEN-T “Core” Network as a Strategic Port of the European Union, thanks to its central location along international traffic routes. In 2024, it handled 22,996,066 tonnes of goods, while in 2025 it recorded strong growth in traffic, particularly in the container sector, with an increase of +21.6% in the first four months. This growth is supported by the transfer of container traffic from Catania to Augusta, consolidating the port as a strategic hub in the Mediterranean and confirming its key role in the port system of eastern Sicily. This growth is supported by the transfer of container traffic from Catania to Augusta, consolidating the port as a strategic hub in the Mediterranean and confirming its key role in the port system of eastern Sicily, which handled a total of over 43 million tonnes of goods in 2025. Work is currently underway to expand the container terminal and electrify the quays, with the aim of bringing the port up to international standards and significantly reducing its local environmental impact.

The approach adopted provides concrete guidance for decision-makers, port managers and shipping operators, highlighting how targeted technological interventions and sustainable energy infrastructure can significantly reduce emissions from ships in port. The study also emphasises the importance of an integrated approach that simultaneously considers technical, managerial and regulatory aspects, promoting the definition of guidelines and policies for more sustainable and environmentally responsible port management.

In conclusion, ship emissions in port are a critical element in the decarbonisation of the maritime sector. Understanding the factors that influence these emissions, combined with the adoption of clean technologies and sustainable operating practices, such as cold ironing applied to the Augusta container terminal, can contribute significantly to reducing the overall environmental impact of maritime transport, improving air quality in port areas and promoting public health.

Comparative Analysis of Environmental Footprint Assessment Methods in Ports

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Extended Abstract

1 INTRODUCTION

Maritime transport is the primary mode for global freight, making ports crucial hubs for economic activity. However, port operations generate significant environmental impacts, especially in terms of air pollution and CO_2 emissions (Książkiewicz 2020). Growing awareness of these impacts has led to stringent international regulations, such as those established by the International Maritime Organisation (IMO) and the European Union (Bach & Hansen 2023), which promote strategies such as the use of alternative fuels and dock electrification (cold ironing) (Canepa et al. 2023, Panagou 2024). In this context, quantifying, evaluating, and estimating emissions is essential to understanding and reducing the port-related environmental footprint. This paper presents an integrative literature review and comparative analysis of methodological approaches for assessing the environmental footprint of port activities, focusing on advanced techniques, models, and sensors used to measure and estimate pollutants such as CO_2, NOx, SOx, and particulate matter (PM).

2 METHODOLOGICAL APPROACH

The study adopts an integrative review methodology, allowing for the analysis of a wide range of models, comparing operational data with predictive and monitoring tools. The selection process was guided by a specific objective: to identify studies analysing the environmental impact of port activities through various methodologies, searching the literature using the keywords ‘shipping’, ‘environmental’ and ‘ports’, and selecting studies that employ empirical research, theoretical models and technical reports. The integrative review adopted in this study is notable for its ability to collate and analyse approaches and models for estimating and assessing emissions in ports. The review categorises the research into four main pillars based on the applied methodology:

- Bottom-up data analysis: this method relies on the collection of detailed operational data to obtain accurate emission estimates.
- Regression models: these allow the study of the relationship between port activities and air pollutant concentrations; are particularly effective in identifying correlations and trends over time.
- Emission inventories: these constitute a fundamental methodology for the overall estimation of emissions produced in port areas. it is based on the collection of aggregated data.
- Sensor monitoring: this method uses sensor networks for the direct measurement of air pollutant concentrations in real time.

The selected studies are categorised according to the methodology used, examining how the choice of model and input data influences the results and subsequent applications in environmental policy.

3 ANALYSIS OF MAIN AIR POLLUTANTS

The review identifies key environmental parameters generated by ship engines, cargo handling equipment, and land traffic, such as CO_2, that are the primary greenhouse gas emitted by ships and handling equipment; NOx, that generated during high-temperature combustion in engines, contributing to smog and acid rain; Sox, related to the sulphur content in fuels; its emissions are strictly regulated in port areas, and PM, which have significant effects on public health and local ecosystems.

Accurate data classification is essential for precise analysis of port emissions. Key indicators include vessel movements (routes, speed, and dwell times), technical characteristics (size, power, and fuel type), and fuel consumption during various operational phases. These are supplemented by data on emissions, the use of port equipment, and land traffic flows linked to the port. Finally, air quality analyses and meteorological data enable estimates to be verified and interpreted correctly. These indicators are essential for supporting the most effective methodologies for quantifying the environmental impact of ports.

4 DISCUSSIONS

The choice of methodology involves a trade-off between accuracy, resource availability, and the scope of the analysis. The main features of these methodologies are summarised and compared in Table 1.

Table 1. Comparative analysis of advantages and disadvantages of the main methodologies for port emission quantification, evaluation, and estimation.

Methodology	Advantages	Limits
Bottom-up approach	High accuracy; identifies targeted interventions such as dock electrification	Requires highly detailed data (AIS/VTS) and significant technical expertise.
Regression models	Isolates port impact from other urban sources; adaptable to various contexts.	Dependent on high-quality air quality data; provides less operational detail.
Emission inventories	Provides a macro-scale view; useful for external cost assessment and policy-making.	Less accurate at the local level; relies on standardised factors that may miss specific conditions.
Sensor monitoring	Real-time, granular data; allows for quick detection of concentration changes.	Requires continuous maintenance and calibration; needs dispersion models for a complete picture.

The study offers clear comparisons of the strengths and limitations of each approach and highlights key research gaps, especially the need to better integrate different methodologies and develop hybrid assessment frameworks. The findings can help practitioners and policymakers choose more suitable methods for environmental management in ports.

5 CONCLUSIONS

The integrative review concludes there is no single ideal methodology: effectiveness lies in a flexible approach that integrates analytical estimates, historical data and real-time monitoring, tailored to the specific characteristics of each port. In this regard, collaboration and the exchange of methodologies between ports are crucial for addressing the shortcomings of individual models and optimising overall mitigation strategies. Future research should emphasise adapting these tools to different port contexts, ensuring that implementation decisions for sustainability (e.g., cold ironing, alternative fuels) are based on solid and reliable port data.

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A roadmap towards Energy Efficiency and Emissions Reduction in Maritime Transport

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Extended Abstract

The growing urgency of climate change has led to the introduction of strict regulations aimed at reducing greenhouse gas (GHG) emissions across all industries. The maritime industry, responsible for approximately 3% of global emissions and 13.5% of transport emissions within the European Union (EU), is under increasing pressure to enhance its environmental performance. This sector must comply with decarbonization strategies set by the International Maritime Organisation (IMO) and the EU, which impose both technical and operational requirements. Currently, the FuelEU Maritime Regulation targets to lower the GHG intensity of energy used aboard ships over 5,000 GT, requiring for both EU and non-EU flagged vessels calling at European ports a reduction from 6% by 2030 to 80% by 2050.

In response to these targets, the maritime industry is pursuing the development of alternative fuels, innovative technologies, and updated technical standards to ensure compliance and safety. Achieving these goals necessitates a comprehensive design strategy; however, progress has been hindered by technological neutrality and uncertainty regarding the best investment choices. Temporary gaps in technical regulations further complicate the sector's transition towards greener operations.

A central aspect of the maritime industry's transition involves evaluating the feasibility of Energy Efficiency Technologies (EETs) across various ship types and operational contexts (DNV, 2025). This study reviews a wide range of promising EETs for six representative vessel categories: bulk carrier, tanker, containership, LPG carrier, Ro-Pax and general cargo vessels considering applications for both new builds and retrofits. The technologies assessed include sustainable low-emission fuel power systems, electrification solutions, carbon-capture systems, advanced propeller-hull energy saving systems, hydrodynamic improvements, wind-assisted propulsion, and operational measures.

In this work, a screening methodology for proposing EETs-vessel type combinations is presented, developed through a technical workshop conducted by academia, engineering and design experts. The technologies are evaluated in terms of technical feasibility, readiness level, relevance and alignment with vessel-type constraints, operational profile and age. The technologies were categorised as viable, potential, or non-feasible. To address the multivariate attributes of each energy system, different screening criteria were considered. HVAC system upgrades were allocated to passenger ships which exhibit extensive cooling requirements. Shaft generator selection conditioned upon shaft system length, electric power requirements and sailing loads (Everllence, 2026). Batteries were proposed in combination with electrification-promoting technologies. Fuel cell (FC) systems

were appraised according to energy demand and power generation capabilities of current products (Elkafas et al., 2022). Onshore power supply (OPS) implementation depended on regulatory mandates, on the adequacy of time at berth and on the compatibility with cargo handling operations (Najihah et al., 2023). Air lubrication systems (ALS) were recommended for U-shaped hulls and low to medium Froude numbers (EMSA, 2026). Wind assisted propulsion systems (WAPS) were considered appropriate for ships with adequate available space on deck sailing on routes without navigational restrictions (bridge clearances) (Wang et al., 2026). Carbon capture systems (CCS) selection was based on the availability of space on deck, ship energy requirements and operational profile (EMSA, 2024). Waste heat recovery (WHR) upgrades were deemed potential for all ships, with respect to combinations with CCS and FC, while steam system improvements were targeted for all ships with increased steam production. Finally, hydrodynamic solutions and devices were evaluated based on the fundamental principles of ship resistance and propulsion.

This methodology offers guidance on the adoption of energy efficiency technologies throughout the global fleet. By directly combining technologies to vessel types and taking to consideration vessel characteristics and the evolving regulatory requirements, it supports informed decision-making for short-, medium-, and long-term GHG reduction. Ultimately, it promotes the accelerated adoption of energy-efficiency technologies and provides a solid foundation for a coherent decarbonisation roadmap for the maritime sector.

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Combined top-down and bottom-up Mediterranean fuel demand mapping

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1 INTRODUCTION

Maritime decarbonisation remains a major challenge, particularly with respect to the transition towards low- and zero-carbon fuels. In this respect, a robust understanding of the current state of fuel consumption and supply is essential. This requires structured and transparent data frameworks capable of supporting both the quantification and the spatial interpretation of fuel demand, enabling realistic pathway design and informed decisions on fleet adaptation and infrastructure development. Existing regulatory frameworks (e.g., IMO DCS, EU MRV) provide valuable insights into fuel consumption and emissions at an aggregated level, supporting the implementation of policy measures (e.g., EU ETS, FuelEU Maritime) (Annetis, et al. 2025). At the same time, increasing availability of operational data, including AIS-derived data, port call records and bunkering activity, offers new opportunities for analysing shipping patterns and localising fuel demand (Fuentes 2021). However, these datasets differ in structure, resolution and level of verification, creating challenges in their combined use.

In this context, this study -as part of the EU-funded GreenMED project- aims to estimate and spatially allocate marine fuel demand across the Mediterranean Sea by combining bottom-up and top-down methods. The bottom-up approach relies on AIS-derived ship-to-ship (STS) bunkering events to estimate and localise fuel demand, while a top-down approach based on aggregated bunker sales data is used for validation purposes. The analysis focuses on conventional marine fuels -mainly Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO)/Marine Gas Oil (MGO)- which currently dominate maritime energy use (Campbell, et al. 2023). The Mediterranean Sea is selected as the study area, as it represents a highly relevant case for regional energy transition planning. The proposed approach contributes to the development of more robust data frameworks, supporting the design of decarbonisation pathways and the strategic deployment of fuel supply chains.

2 METHODS

The bottom-up approach is based on the identification and analysis of STS bunkering operations derived from AIS data, which provide high-frequency spatiotemporal information on vessel movements. In particular, bunkering events are detected through the identification of prolonged close-proximity encounters between vessels, combined with low-speed or near-zero-speed conditions, consistent with operational practices observed in STS fuel transfer activities (Watanabe & Shibasaki 2023). Following that, a structured filtering and classification procedure is applied to ensure the reliability of detected events. For each STS event, fuel transfer quantities are estimated using a set of operational assumptions.

To ensure the consistency and robustness of the bottom-up estimates, a top-down validation approach is applied using aggregated bunker sales data, as identified per country through reliable databases, excluding non-Mediterranean sales through expert judgement and historic data analysis. This approach provides an independent reference for total fuel demand at national and regional (i.e., Mediterranean), allowing the comparison of estimated quantities with observed market data (IMO 2020). Rather than producing independent estimates, the top-down approach functions as a verification mechanism, highlighting potential discrepancies and supporting the calibration of the bottom-up methodology.

The spatial distribution of fuel demand is derived from the geographical coordinates of STS bunkering events. Each event is assigned to a port or hub location based on proximity criteria, using distance-based algorithms applied to predefined port datasets. For events occurring in open sea areas, additional assumptions and expert judgement are applied to allocate demand to the most relevant nearby port or operational hub. This process enables the aggregation of fuel demand at port level, supporting the identification of key bunkering locations and regional demand patterns.

3 DATA AND ANALYSIS

For the bottom-up method, the analysis is based on a dataset of 80,373 STS bunkering events recorded across the Mediterranean Sea for the reference year 2022. The dataset was originally extracted from the S&P Global

Sea-web™ database, for the entire Mediterranean Sea basin, as defined by the Suez Canal, the Gibraltar straight and the Bosporus straight. To form the dataset, a multi-step filtering procedure is applied to improve the reliability of the data and to exclude implausible or non-representative events: i) operator-based filtering is applied to exclude events involving vessels under the same operator, ii) vessel-classification filtering in order to retain events only if at least one participating vessel can reasonably be identified as a bunkering vessel, and iii) time-based filtering to remove events with unrealistic duration, excluding operations shorter than 1.5 hours or longer than 24 hours. Then, fuel transfer quantities are estimated using a rule-based calculation framework combining operational assumptions with vessel-specific characteristics. For each event, the effective bunkering duration is derived by excluding one hour from the reported interaction time, accounting for preparatory and finalisation processes. Representative fuel flow rates are assigned by fuel type (i.e., 250 m^3/h for HFO and 400 m^3/h for MDO). For vessels operating with multiple fuel types, the estimation accounts for both main and secondary fuels. The transferred quantity of the main fuel is calculated as described, while the quantity of the secondary fuel is estimated proportionally, based on the ratio of respective fuel tank capacities.

For the top-down method, fuel demand estimates are derived from aggregated international marine bunkers, as well as domestic navigation and fishing fleet bunkers, obtained from the International Energy Agency (IEA). The analysis goes beyond the country-level marine bunkers data to estimate the overall marine fuel demand in the Mediterranean region by excluding quantities assumed to be bunkered outside the region based on expert judgement and statistics from historic data.

4 RESULTS

Results provide a detailed mapping of conventional marine fuel demand across the Mediterranean Sea, including the spatial distribution of STS bunkering activity and the estimated transferred quantities of HFO and MDO/MGO per port area. Indicatively, in aggregates, the bottom-up approach estimates 16,273 kt of HFO and 6,796 kt of MDO, while the top-down approach estimates 16,100 kt of HFO and 7,025 kt of MDO. Thus, the comparison between them demonstrates a satisfactory level of consistency, supporting the validity of the proposed methodological framework while also revealing discrepancies linked to data availability, operational assumptions and the limitations of aggregated statistics. Further, the analysis highlights the concentration of bunkering activity around major Mediterranean hubs and strategic maritime corridors, while also identifying offshore and non-traditional bunkering locations associated with operational shipping patterns.

5 DISCUSSION & CONCLUSIONS

The proposed method demonstrates the potential of combining AIS-derived operational data with aggregated market statistics to support fuel-demand estimation and localisation at regional scale. Beyond methodological validation, the results contribute to the broader objectives of the GreenMED project and the development of Mediterranean Shipping Strategy Observatory (MSSO), supporting evidence-based planning for maritime decarbonisation and alternative fuel infrastructure deployment (Annetis, et al. 2025). At the same time, the analysis highlights the importance of structured, transparent and interoperable data frameworks, as well as the need for further improvement in the availability and harmonisation of bunkering-related datasets. Overall, the study confirms that combining bottom-up and top-down approaches can provide a robust basis for understanding current fuel demand patterns and supporting the design of realistic shipping energy transition pathways in the Mediterranean region.

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Calculation and impact on shipping of the new GHG Intensity concept

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Extended Abstract

The maritime sector is responsible for approximately 3% of global greenhouse gas emissions and for the transport of 90% of goods worldwide. As such a large industry, it is necessary to keep emissions under control, working towards the goal of total decarbonization. To achieve this, international and European regulatory requirements are being tightened year after year to reduce environmental impact.

In this context, the choice of fuel used on board ships has become a strategic and technically complex decision, influenced by direct emissions, lifecycle GHG Intensity, and regulatory compliance mechanisms.

This study assesses the effectiveness of different alternative fuels in complying with the limits on GHG emissions, focusing on two case studies: an Ultra Large Container Vessel sailing between China and Northern Europe, and a Feeder Container vessel, which operates between Northern European ports.

Since it is a highly relevant issue impacting the future of the maritime sector, the decarbonization of maritime transport has already been addressed at both the international and regional levels. The International Maritime Organization, through the Fourth IMO Greenhouse Gas Study 2020 (IMO, 2020), provides statistics, data collections, and comprehensive global analyses of emissions and future projections, highlighting the urgent need for low-carbon fuels. More recently, the IMO 2024 Guidelines on Greenhouse Gas Intensity in the Life Cycle of Marine Fuels (IMO, 2024) defined new methods for calculating emissions, focusing on a broader approach: Well-to-Wake, which includes Well-to-Tank and Tank-to-Wake, and as analysed during this study, this new method of calculating emissions significantly impacts fuel choice and allows for a broader view regarding the issue of emissions. At the international level, the International Maritime Organization has proposed new measures to take into account and limit emissions through the IMO Net-Zero Framework (IMO, 2025a), which introduces progressive limits on GHG emissions from ships and economic penalties for non-compliant vessels. However, the framework has not yet entered into force, as its potential economic implications for global trade and the shipping industry are still being debated among member states (IMO, 2025b).

At the European level, the EU has also introduced new rules and regulatory systems, such as FuelEU Maritime (EC, 2025) and the inclusion of maritime transport in the Emissions Trading System (ETS), creating new economic incentives and compliance mechanisms for companies and shipowners.

The new regulations require lower emissions in all the different sectors related to maritime transport, and hence all areas of research are influenced to improve technical and managerial performance on board ships, as well as during production and transportation.

Although there has been extensive research on alternative fuels, life-cycle emissions, and the economic implications of decarbonization policies, most studies examine these aspects in isolation or by combining two of them, focusing only on technical performance, environmental assessment, or cost impacts.

For this reason, the study was conducted with the aim of combining technical aspects of the ship, economic aspects, and the current regulatory landscape, to understand which terms influence the GHG Intensity indicator and show the impact that the introduction of this new concept could have in the maritime field at the European and international level.

The scope of the study was to assess the GHG Intensity of a ship operating on various marine fuels, in order to evaluate how each fuel's GHG Intensity constant affects the total emissions produced by the ship over the course of a year, and thus understand how fuel choice impacts emissions and costs. The fuels used for propulsion engines in this analysis are VLSFO, LNG, ammonia, methanol, and hydrogen. MDO is used in 5 cases as fuel for power generation. Moreover, an additional case has been analysed in which LNG is used both for propulsion and for power generation, in order to understand how much the emissions from onboard generators affect the total. For this study, a worst-case scenario was considered for unconventional fuels such as ammonia, methanol, and hydrogen by using the highest GHG Intensity values reported in the available sources, in order to avoid

favouring these fuels by default. This assumption is necessary because, for these fuels, there is no single default GHG Intensity value. Upstream emissions in the Well-to-Tank phase can vary significantly depending on the production pathway, as well as on the extraction, refining, and transport processes involved.

As a result, the same fuel can present very different GHG Intensity depending on how it is produced, ranging from highly polluting pathways to low-carbon alternatives.

The analysis is based on average data of commercial routes, energy consumption, and emissions, using a Well-to-Wake approach to assess the environmental impact along the entire fuel life cycle. Estimation and decisions were taken starting from the choice of two different types of container ships, a Feeder Container Vessel and an Ultra Large Container Vessel (ULCV). Then, the ship's main characteristics, including on-board systems, were specified, taking into account realistic examples. Given these data, the routes and cargo loading conditions were hypothesized, which were ultimately useful for determining the load on the engines and thus estimating fuel consumption. As regards costs, CAPEX and OPEX costs were estimated, also taking into account the FuelEU Maritime penalties. Although the IMO Net-Zero Framework proposes a similar penalty mechanism for emissions exceeding future limits, it was not included in the calculations since the framework has not yet entered into force. However, the study briefly discusses its potential implications and the main criticisms raised by the industry. Indeed, the results of the GHG Intensity values of ships in the various scenarios have been compared with the limits set by FuelEU Maritime.

From the point of view of emissions and costs, results show that LNG is the best transition solution, as it allows emissions to be reduced without significantly increasing costs On the other hand, the unconventional fuels such as ammonia, methanol and hydrogen, require significant investments in the production pathway to become more competitive. The comparison between the two different case studies shows how the new measures impact differently the Feeder ship operating only in Europe, and the ULCV traveling between China and Europe, considering that the larger ship is responsible for the emissions it produces only for a small part of its journey, as it follows the European regulation, and this highlights a critical limitation of the current regulatory framework until global regulations, such as the proposed IMO Net-Zero Framework, are implemented.

In conclusion, the study results show significant economic differences between the various case studies, emphasizing that, until IMO regulations are applied globally, the European market risks being hampered by FuelEU Maritime penalties. At the same time, however, when the time comes, Europe could be ahead of other continents.

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Analysis of Maritime Emissions and Their Influence on Public Health in Port Regions

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Extended Abstract

Maritime shipping relies heavily on fossil fuels that generate significant environmental and public health impacts. Previously, the maritime sector used low-cost fuels, such as heavy fuel oil, resulting in high emissions of sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM), particularly in busy port areas. As land-based emission sources, such as road traffic and domestic heating, continue to decrease due to stricter urban regulations, the contribution of shipping emissions to urban air pollution is expected to grow, making it an increasingly serious concern for environmental quality and human health (Contini & Merico, 2020).

The environmental footprint of a vessel is not uniform throughout its journey but varies significantly by operational phase, typically categorized as cruising, maneuvering, and hoteling (Yoon et al., 2023). While cruising or navigating at sea produces the highest total volume of emissions, these emissions are often dispersed far from human settlements. Conversely, maneuvering and hoteling operations are conducted in proximity to densely populated coastal regions. Maneuvering occurs when a ship approaches or departs from a berth at reduced speed, a phase that often results in poor combustion in marine diesel propulsion engines due to low engine load (Roy & Chakraborty, 2025). Once at berth, the vessel enters the hoteling phase, during which the main propulsion engines are typically shut down, but auxiliary engines and generators remain active to provide electricity for onboard systems, cargo handling, and climate control (Yoon et al., 2023). In a study by Toscano et al., it was found that emissions during the hoteling phase can account for up to 95% of total port-related emissions, while navigation within the port accounts for only a small fraction (Toscano et al., 2021). This concentration of emissions at the dock is particularly hazardous as modern container and passenger terminals are frequently located immediately adjacent to residential neighborhoods.

The quantity and type of pollutants emitted are directly determined by the engine type, fuel quality, and the specific load factor required for each operation. Emission factors (EF) quantify these relationships, usually expressed in grams of pollutant per kilowatt-hour (g/kWh). For a representative 2010-standard fleet, NO_x EFs for maneuvering and hoteling using slow-speed diesel engines range from 12.7 to 13.5 g/kWh. In comparison, cruising NO_x EFs are slightly higher, ranging from 15.8 to 16.9 g/kWh, due to higher service loads. However, PM EFs are significantly higher during maneuvering and hoteling, reaching 0.9 to 2.4 g/kWh, compared to only 0.3 to 1.7 g/kWh during cruising. This is largely because auxiliary engines, which handle the hoteling load, often have different emission profiles than the main engines, with NO_x factors ranging from 10.2 to 13.7 g/kWh across all phases (Toscano et al., 2021).

Shipping emissions contribute substantially to the ambient concentrations of toxic pollutants in local port environments. In medium-sized harbor cities, SO_x emissions from ships are often larger than those from road traffic, while NO_x and PM concentrations are frequently comparable. Studies indicate that shipping contributes between 1% and 14% of ambient fine PM levels in European coastal areas, while in some Asian ports this contribution can reach 7% to 26% (Contini & Merico, 2020; Roy & Chakraborty, 2025). In specific hub ports, such as Busan, South Korea, vessels have been found responsible for up to 71% of total SO_x emissions (Song et al., 2022). In Gothenburg, local shipping contributes approximately 14% of the annual mean NO_x concentration, with even higher peaks during the summer months due to increased vessel activity (Ramacher et al., 2020). The dispersion of these pollutants is highly sensitive to meteorological factors; for instance, strong coastal winds can carry fine PM away from the immediate port area, while temperature inversions can trap pollutants near the ground, worsening their impact on residents. Furthermore, shipping emissions are major precursors for secondary air pollutants (e.g., ground-level ozone), potentially impacting air quality hundreds of kilometers downwind (Roy & Chakraborty, 2025).

The public health implications of maritime emissions are severe and well-documented. Pollutants from shipping emissions can increase asthma rates, particularly in children, and cause lung inflammation and aggravated cardiovascular symptoms. Global estimates from the early 2010s attributed approximately 60,000 to 90,000 annual premature deaths to PM emissions from shipping (Roy & Chakraborty, 2025; Zhu & Wang,

2021). In the Pearl River Delta of China alone, shipping-related pollution is estimated to result in between 14,500 and 37,500 early deaths per year (Roy & Chakraborty, 2025). Beyond mortality, the economic burden of these health impacts is immense; for example, the social cost of excessive SO_x exposure in Beijing was estimated at 384.89 million RMB per year, and the health benefits of reducing shipping emissions in the Iberian Peninsula were valued at over 267 million Euros due to avoided hospital admissions and deaths (Borges et al., 2023; Song et al., 2022). Interestingly, while larger cities see the greatest absolute reduction in mortality from emission controls, the relative health benefits are often most pronounced in smaller port towns where shipping is the predominant industrial activity (Ducruet et al., 2024).

The regulatory landscape is undergoing a significant shift to address these challenges through international and regional frameworks. The International Maritime Organization (IMO) 2020 Sulfur Cap is a landmark regulation that reduced the global sulfur limit for ship fuel from 3.5% to 0.5%. This single measure has achieved an estimated 75% reduction in global SO_x emissions relative to previous peaks (Borges et al., 2023). In the Bosphorus Strait, implementation of the 2020 cap reduced modeled SO_x concentrations from 6.65 $\mu g/m^3$ to 1.48 $\mu g/m^3$ (Ekmekcioglu et al., 2023). Furthermore, Emission Control Areas (ECAs), such as those in the North Sea, Baltic Sea, and along the North American coasts, enforce even stricter limits of 0.1% sulfur and require new ships to comply with Tier III NO_x standards, which target an 80% reduction in nitrogen oxide emissions (Ramacher et al., 2020). Research in China's ECAs has shown that implementing fuel-content regulations at the Shanghai Port resulted in significant pollution mitigation, reaching areas more than 200 km away, potentially avoiding 23,800 premature deaths in the year following implementation (Zhu & Wang, 2021). These regulations are often most effective when targeted at densely populated port waters, maximizing public health benefits relative to the high cost of low-sulfur fuels

Technological advancements are further augmenting regulatory efforts to achieve a "green port" transition. Onshore Power Supply (OPS) allows vessels at berth to shut down their auxiliary engines and connect to the local electrical grid. Large-scale implementation of OPS in the Port of Gothenburg is projected to reduce local NO_x concentrations by up to 30% and SO_x by up to 12% (Ramacher et al., 2020). On the propulsion side, the industry is gradually adopting alternative fuels such as LNG, which can reduce CO2 emissions by ~30% and NO_x emissions by ~87% while virtually eliminating SO_x and PM emissions. Looking further ahead, the adoption of ammonia or hydrogen as fuels could reduce life-cycle greenhouse gas emissions by 28% to 39%, respectively, compared with heavy fuel oil (Roy & Chakraborty, 2025)

These analyses show that while significant progress has been made through the IMO 2020 sulfur cap and the establishment of regional ECAs, NO_x and fine PM emissions remain critical challenges for port-city air quality and, by extension, public health. Thus, this paper aims to provide a comprehensive assessment of the correlation between maritime fossil fuel consumption and localized public health outcomes based on the results of the associated studies available in the open literature, specifically arguing that the environmental burden is not uniform but varies significantly across different operational phases: cruising, maneuvering, and hoteling. This paper also aims to provide a detailed comparative analysis of the vessels' operational emission factors, demonstrating that hoteling and maneuvering contribute disproportionately to local air quality degradation and the subsequent effects on the health of port-side residents.

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Accuracy of bridge simulators for predicting ship manoeuvring emissions

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Extended Abstract

This study investigates the operational validity of maritime bridge simulators in estimating carbon dioxide emissions during port berthing manoeuvres through a comparative evaluation against real world ship operation data. The research is grounded in the growing need for reliable and practical methods to quantify ship emissions during manoeuvring phases, which remain among the most difficult operational segments to assess with precision. While sailing emissions can often be estimated with greater consistency through voyage-based datasets and standard operational profiles, port approach and berthing phases involve rapidly changing engine loads, frequent propulsion adjustments, tug interactions, and vessel specific manoeuvring decisions. These characteristics make direct emission measurement particularly challenging and introduce uncertainty into conventional estimation approaches. In this context, the study explores whether high fidelity maritime bridge simulators can provide a dependable platform for emission estimation during these complex operational periods. The motivation for the study stems from both methodological and practical concerns. From a methodological perspective, the literature has increasingly emphasized the importance of activity based and operation specific emission assessment in maritime transport, especially in relation to port operations and short duration high intensity manoeuvres. However, access to sufficiently detailed real world datasets remain limited. Fuel consumption records are not always available at the required temporal resolution, and direct onboard measurement during manoeuvring is difficult to standardize across ship types and operating conditions. From a practical perspective, ports, ship operators, and researchers need replicable tools that can support environmental assessment without relying exclusively on expensive or logistically difficult field measurements. Bridge simulators, if shown to generate sufficiently accurate emission estimates, may fill this gap by enabling controlled and repeatable analyses of vessel behaviour under realistic operational scenarios (Şenol & Seyhan, 2024).

To address this problem, the study adopts a dual methodological framework combining real world operational data and simulator-based emission modelling. The empirical component is based on twelve manoeuvres performed by a maritime pilot across three different vessel categories: Bulk Carrier, Ro Ro, and Container ships. This design was intended to represent variation in vessel handling behaviour and propulsion response during berthing operations while preserving a consistent decision-making framework through the involvement of the same experienced mariner. The preparatory stage of the research involved identifying suitable manoeuvre cases, matching operational phases between actual ship movements and simulated scenarios, and organizing the relevant technical and operational inputs required for comparative analysis. Particular attention was given to ensuring that the simulator scenarios reflected the essential manoeuvring characteristics of the real operations as closely as possible in terms of vessel class, berthing sequence, and propulsion behaviour. Real world emissions were derived from direct fuel consumption logs of the primary vessels using a top-down approach. This enabled the study to anchor its analysis in actual operational records rather than purely theoretical assumptions. In parallel, simulation-based emissions were estimated through a bottom-up approach using instantaneous engine load and revolutions per minute data generated within a Wartsila NTPRO 5000 bridge simulator environment (Kaba et al., 2026). The use of the simulator allowed detailed monitoring of propulsion behaviour throughout the manoeuvring sequence and enabled the conversion of operational activity data into corresponding emission estimates. By integrating engine response and manoeuvre progression at a fine operational level, the bottom-up framework provided a dynamic representation of emission formation during berthing.

The comparative design of the study is one of its principal strengths. Instead of evaluating simulator performance in isolation, the research directly compares simulator-based outputs with empirical emission estimates obtained from real ship operations. This approach makes it possible to assess not only whether the simulator produces plausible values, but also whether it can reproduce the general emission profile of real world manoeuvring activity with sufficient proximity to support scientific and operational use. The comparison was therefore structured around the consistency between real and simulated outputs across the selected manoeuvres and vessel categories.

The results reveal a strong degree of agreement between empirical and simulation-based estimates. The average convergence rate of 92 percent indicates that the simulator environment reproduced the emission behaviour of the observed manoeuvres with a high level of consistency. This finding is significant because it demonstrates that high fidelity bridge simulators are not limited to navigational training and human factor research but can also serve as robust analytical tools for environmental performance assessment. The close alignment between the two datasets suggests that simulator-based modelling can capture the operational dynamics that drive emission formation during berthing, despite the complexity and variability of manoeuvring conditions. The findings also carry broader methodological implications. First, they support the use of simulator derived activity data for emission estimation in contexts where direct real world measurement is constrained or unavailable. Second, they indicate that simulator platforms may provide a standardized environment for comparative studies across ship types, manoeuvring strategies, and operational settings. Third, they open a pathway for integrating bridge simulator outputs into broader environmental monitoring and decision support frameworks for ports and maritime operators. Since manoeuvring emissions are increasingly relevant in discussions of local air quality, port sustainability, and decarbonization planning, a validated simulation-based approach offers clear value for both researchers and practitioners.

In addition, the study contributes to the ongoing discussion on the environmental application of simulation technologies in maritime research. Bridge simulators have traditionally been associated with training, safety analysis, and navigational assessment. This study expands that role by demonstrating their applicability in emission related studies, particularly for operational phases that are otherwise difficult to observe with precision. The ability to reproduce complex port operations in a controlled environment creates opportunities for future analyses of alternative manoeuvring strategies, pilot behaviour, tug assistance patterns, and vessel specific propulsion responses from an emissions perspective. In this respect, the present study not only validates a method, but also establishes a foundation for a wider research agenda linking simulator based maritime operations with environmental performance analysis. In conclusion, the study shows that high fidelity maritime bridge simulators can be effectively used as a primary tool for the detection and calculation of carbon dioxide emissions during port berthing operations. The high level of convergence between real world and simulation-based estimates confirms the operational validity of simulator derived emission modelling for this phase of vessel activity. Accordingly, simulation environments offer a reliable, consistent, and practically valuable platform for evaluating discharge profiles during complex port manoeuvres. Their integration into maritime environmental monitoring systems may significantly strengthen both research capability and operational assessment in the transition toward more sustainable shipping and port management.

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Regulatory Drivers, Energy Efficiency and Alternative Fuel Pathways in Maritime Decarbonization

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1 INTRODUCTION

Maritime transport accounts for nearly 80% of global trade and remains one of the most energy-efficient transport modes. However, it contributes significantly to global greenhouse gas (GHG) emissions, with projections indicating continued growth without additional mitigation measures. Decarbonization efforts are shaped by a dual regulatory structure. The International Maritime Organization (IMO) establishes globally harmonized measures, including the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII), which address both technical (design-related) and operational (performance-based) efficiency improvements (International Maritime Organization, 2020). In parallel, the European Union has introduced regional measures. The Monitoring, Reporting, and Verification (MRV) system serves as a transparency and data-collection framework supporting policy implementation (Adamowicz, 2022). The inclusion of maritime transport in the EU Emissions Trading System (EU ETS) introduces a market-based mechanism, while FuelEU Maritime sets limits on the greenhouse gas intensity of energy used onboard ships, acting primarily as a technical fuel standard (Wang et al., 2021). This paper analyzes how these regulatory approaches influence technological choices, operational strategies, and ship energy system configurations, with particular emphasis on the role of power management systems (PMS) in enabling decarbonization.

The contribution of the paper lies in providing a structured comparison of IMO and EU regulatory frameworks, linking policy instruments with technological pathways, and identifying dominant short- and medium-term decarbonization strategies.

2 METHODOLOGICAL APPROACH

The study adopts a conceptual and qualitative analytical approach, combining comparative analysis of IMO and EU regulatory instruments, literature-based evaluation of technological pathways, and system-level assessment of ship energy systems and power management systems (PMS) integration. The analysis is structured through a conceptual framework linking policy instruments, technological options, operational measures, and emission metrics. This framework enables a systematic evaluation of how regulatory mechanisms influence technological choices, operational strategies, and overall decarbonization pathways in maritime transport. The assessment focuses on identifying dominant short- and medium-term decarbonization strategies and evaluating the role of energy efficiency measures and alternative fuels under different regulatory conditions.

3 REGULATORY INSTRUMENTS AND TECHNOLOGICAL PATHWAYS

Regulatory instruments influence maritime decarbonization indirectly by shaping investment decisions, operational practices, and fuel selection. Their impact is therefore reflected through the adoption of specific technological pathways and operational strategies. IMO short-term measures include EEXI, which addresses technical design efficiency, and CII together with the Ship Energy Efficiency Management Plan (SEEMP), which target operational performance and energy management. These measures jointly address both technical and operational dimensions of energy efficiency, rather than focusing solely on baseline compliance. In addition, IMO is currently developing mid-term measures, expected to include both a technical component (e.g., fuel carbon intensity limits) and an economic component (e.g., carbon pricing mechanism or hybrid solutions). These measures are expected to significantly influence future fuel choices and long-term investment strategies. The

EU approach consists of complementary instruments with distinct roles. The MRV system serves as a transparency and data-collection framework supporting policy implementation. The EU ETS represents the only market-based mechanism, introducing carbon pricing and creating direct economic incentives for emission reduction (Malmborg, 2023). In contrast, FuelEU Maritime acts as a technical regulation targeting the greenhouse gas intensity of fuels used onboard ships. Together, these instruments create both economic pressure (through EU ETS) and technological direction (through FuelEU Maritime), influencing fuel selection and system design. The key difference between the two frameworks lies in their primary decarbonization drivers (Marrero & Martínez-López, 2023).

4 POWER MANAGEMENT SYSTEMS AND OPERATIONAL INTEGRATION

Advanced ship power management systems (PMS) play a critical role in integrating multiple energy sources, including main and auxiliary engines, batteries, and renewable energy systems, while optimizing overall system performance. PMS act as an interface between regulatory requirements and onboard technological implementation, enabling compliance through real-time optimization of energy flows, load distribution, and emission performance (Bacalja Bašić et al., 2023). Energy efficiency improvements are achieved through a combination of operational measures, such as slow steaming and load management, and analytical optimization methods, including linear programming and model predictive control (MPC). In addition, real-time monitoring of energy use and emissions supports both regulatory compliance and operational decision-making. It is important to distinguish between operational measures and analytical methods, as well as between different emission metrics. While CII and EU ETS are based on tank-to-wake emissions, life-cycle approaches such as LCA consider well-to-wake emissions, providing a broader perspective on environmental impact.

5 RESULTS AND DISCUSSION

Energy efficiency technologies, including wind-assist systems, photovoltaic integration, and operational optimization, provide immediate and scalable emission reduction benefits, making them the dominant short-term decarbonization pathway. Alternative fuels face significant constraints related to cost, infrastructure availability, safety requirements, and technological maturity, limiting their short- to medium-term deployment. The EU ETS introduces strong economic signals that influence investment decisions, while FuelEU Maritime primarily acts as a technical compliance driver guiding fuel transition. Finally, IMO measures ensure global consistency and gradual efficiency improvements, but their impact on rapid structural transformation is more limited compared to EU instruments. Overall, the findings indicate that short- to medium-term maritime decarbonization will be driven primarily by energy efficiency improvements, with a gradual transition toward alternative fuels.

6 CONCLUSIONS

Maritime decarbonization depends on the coordinated interaction of regulatory frameworks, technological systems, and operational strategies. IMO measures primarily drive incremental energy efficiency improvements through globally harmonized standards, while EU instruments combine economic incentives and technical regulations to accelerate structural change. Future progress will depend on the alignment between IMO and EU instruments, the integration of emerging IMO mid-term measures, and improved quantification of real (rather than default) efficiency gains achieved through technological and operational measures.

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Green shipping, fragile ecosystems: Is decarbonisation undermining ecological security in waterborne transport

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Extended Abstract

The decarbonisation of waterborne transportation is increasingly positioned at the intersection of climate policy, technological innovation, and sustainable water system management. Within the emerging research landscape shaped by the DEWATRA COST Action, this transition is not only a question of reducing greenhouse gas emissions, but also of ensuring that decarbonisation pathways are compatible with the long-term resilience and integrity of aquatic ecosystems. Yet, despite its strategic importance, the ecological dimension of this transition remains insufficiently integrated into current policy and research frameworks.

This paper addresses this gap by examining whether ongoing efforts to decarbonise maritime and inland water transport may inadvertently undermine ecological security. It argues that prevailing approaches remain largely carbon-centric, prioritising emissions reduction targets while underestimating the complexity of socio-ecological interactions within water-based transport systems. In response, the study advances an interdisciplinary framework that links decarbonisation pathways with ecological security, understood as the capacity of aquatic ecosystems to maintain their structure, functions, and adaptive resilience under multiple and interacting pressures.

The research is guided by three interrelated objectives. First, it seeks to conceptualise ecological security as an operational dimension within waterborne transport decarbonisation, bridging insights from environmental science, transport studies, and sustainability governance. Second, it evaluates the ecological risk profiles of key low-carbon technologies—such as hydrogen, ammonia, biofuels, and electrification—through a lifecycle and systems-based perspective, with particular attention to their implications for water resources, aquatic biodiversity, and pollution dynamics. Third, it assesses the extent to which existing governance frameworks, at international and regional levels, are equipped to address these emerging cross-sectoral risks.

Methodologically, the paper adopts a mixed and multi-scalar approach consistent with DEWATRA's emphasis on integrative research. It combines qualitative analysis of policy and regulatory frameworks with comparative techno-environmental assessment of decarbonisation options. In addition, selected case-based insights from early implementation contexts are used to illustrate how these transitions materialise within specific water systems, including coastal and inland environments. A conceptual model is developed to map the pathways through which ecological risks emerge, accumulate, and interact across different stages of the transition, highlighting feedback loops and potential threshold effects.

The findings reveal a set of systemic trade-offs that challenge the assumption of inherently sustainable decarbonisation. While alternative fuels and electrification offer clear benefits in terms of emissions reduction, they also introduce new ecological pressures. These include increased demand for water and energy resources, risks of chemical leakage and toxicity affecting aquatic life, and lifecycle impacts linked to resource extraction and waste management. Furthermore, the expansion of supporting infrastructure—such as port adaptation and fuel distribution networks—intensifies spatial pressures on already vulnerable ecosystems, contributing to habitat degradation and biodiversity loss.

Crucially, the analysis demonstrates that these risks are not adequately captured within current governance frameworks. Policy approaches remain fragmented across sectors, with limited integration between climate mitigation, water management, and biodiversity protection. This fragmentation creates significant blind spots, particularly in relation to cumulative and long-term ecological impacts. As a result, decarbonisation strategies risk displacing environmental burdens rather than resolving them—an outcome that runs counter to the systemic sustainability objectives underpinning initiatives such as DEWATRA.

In light of these findings, the paper argues for a reframing of waterborne transport decarbonisation as a socio-ecological transition that must be managed holistically. It positions ecological security as a key integrative

concept capable of aligning decarbonisation efforts with the broader goals of sustainable water system governance. This perspective emphasises the need for precautionary approaches, adaptive governance mechanisms, and stronger cross-sectoral coordination.

The paper concludes by proposing an integrated governance framework for ecologically secure decarbonisation, directly aligned with DEWATRA's objectives of advancing sustainable and resilient waterborne systems. Key recommendations include embedding lifecycle ecological risk assessments into decision-making processes, developing indicators that capture ecological impacts within transport systems, and promoting nature-inclusive design in infrastructure planning. The study also highlights the importance of interdisciplinary collaboration and knowledge exchange in addressing the complex challenges at the water–energy–transport nexus.

By explicitly linking decarbonisation with ecological security, this research contributes to a more comprehensive and policy-relevant understanding of sustainability transitions in waterborne transportation. It offers both conceptual and practical insights that support the development of integrated, resilient, and ecologically grounded pathways—fully in line with the ambitions of the DEWATRA COST Action.

This contribution directly supports the COST Action's networking objectives by fostering interdisciplinary exchange across environmental science, transport systems, and policy analysis, while promoting integrated approaches to sustainable waterborne transportation. It also provides a foundation for collaborative research on ecological risk assessment within decarbonisation pathways.

Analysis of GHG emissions reduction in 2024 based on FuelEU regulations

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Extended Abstract

From January 1, 2025, according to FuelEU Maritime Regulation - FEUM (EU, 2023), a greenhouse gas (GHG) intensity limit of 89.3368 (gCO2eq/MJ) came into force, which is a 2 % reduction compared to the reference value of 91.16 (gCO2eq/MJ). The limit will be valid till 2030. This is the European Union's response to the International Maritime Organisation's (IMO) ambitious goal of achieving zero GHG emissions from maritime transport by 2050.

From 2024 onwards, the EU MRV (Monitoring, Reporting, and Verification) regulation covered methane (CH_4) and nitrous oxide (N_2O) emissions, in addition to carbon dioxide (CO_2). This legislation is integrated with the EU Emissions Trading System (ETS) for ships with a gross tonnage of 5,000 tons or more that call at EU ports. The existing FuelEU Regulation is based on the EU-MRV platform.

The analysis of the FuelEU Maritime regulation, based on the authors' previous studies, indicated that the GHG intensity of ships visiting European ports in 2023 does not meet the standards set for 2025-2030. This underscores the urgent need for stronger measures to achieve the ambitious goal of an 80% reduction in emissions by 2050, as outlined in the regulation (Georgiev et al., 2025).

Based on data till 2023, the most energy-efficient ships in terms of greenhouse gas emissions, according to the reference value, are general cargo vessels. In contrast, bulk carriers are identified as the least energy-efficient type of ship.

The present study is based on the most recent 2024 data from THETIS-MRV and considers operational ship characteristics, such as deadweight (t) and ship age (years; Figure 1).

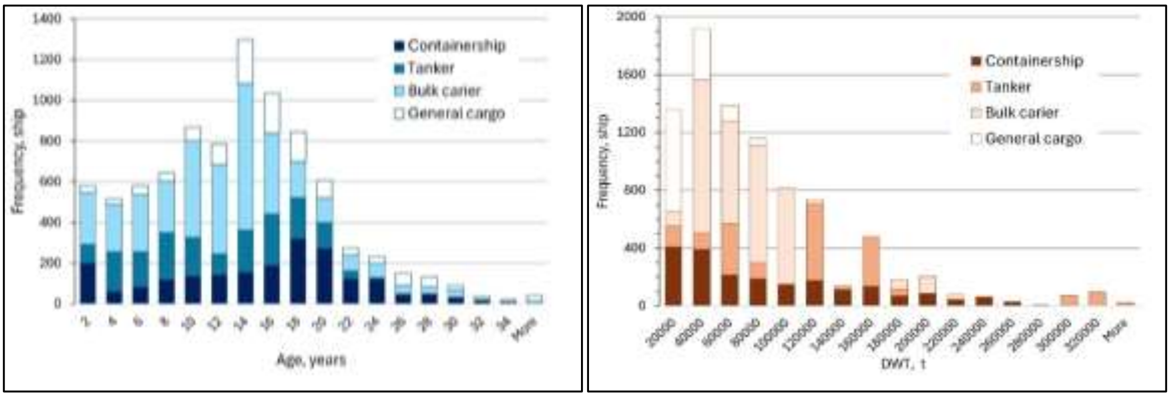

Figure 1. Distribution of Age (left) and DWT (right) of studied ship types

Fuel consumption and CO_{2eq} emissions from the EU-MRV database were used to determine the mass of individual fuels consumed—VLSFO, MGO, LNG, or Methanol for dual-fuelled engines. The greenhouse gas intensity for ships is calculated based on the quantities of the different fuels obtained.

A probabilistic contour line approach (Leira 2008, Winterstein et al. 1993) is used to analyse the operational states of four ship types visiting European ports in 2024 and to estimate the target GHG characteristics. The probabilistic contour lines define the ship age, A_s, and deadweight, DWT, at a given probability of occurrence or exceedance (Figure 2). To set a GHG emission limit, target characteristics should match an annual exceedance probability, q.

The NORSOK Regulation (NORSOK 2007) is applied to control GHG emissions at an annual probability of $q = 10^{-n}$, for ships visiting European ports. where all sources of inherent randomness affecting pollution are considered.

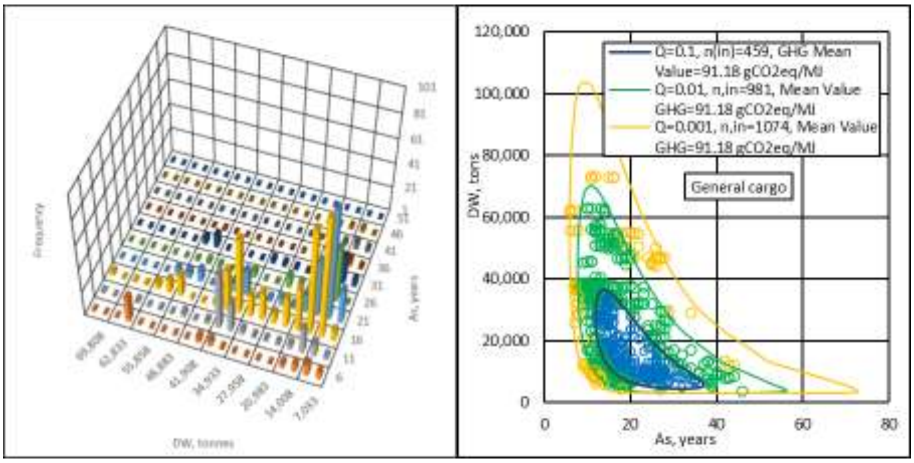

Figure 2. Scatter diagram GHG=f(DW, As) (left) and Contour lines for (right) for general cargo ships

Figure 3 shows the progress in implementing new GHG mitigation activities for the four ship types visiting European ports in 2024. The green line represents the established FuelEU Maritime greenhouse gas reference values of GHG_{EU} = 91.16 gCO_{2eq}/MJ.

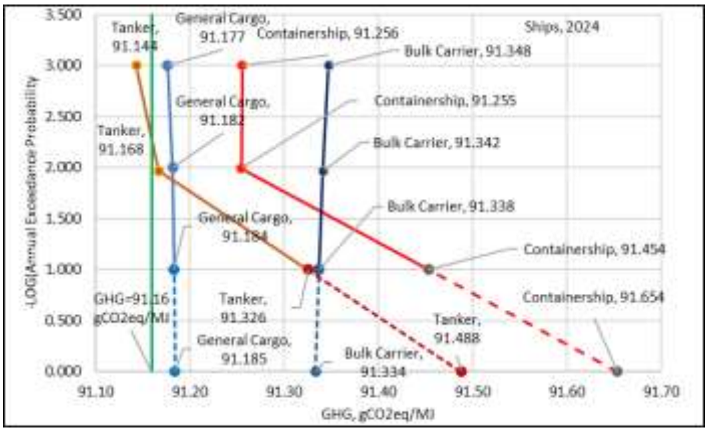

Figure 3. Annual exceedance probability of the mean value of GHG

It is evident that general cargo ships are very close to the target (blue line), and the current mitigation efforts to meet this target appear positive but not satisfactory, with the most likely value in 2024 at 91.2, dropping slightly to 91.184 gCO_{2eq}/MJ at an annual exceedance probability of 10^{-1}. Conversely, for bulk carriers, the opposite trend is observed compared to general cargo ships, where the most probable value in 2024 ranges from 91.334 to 91.338 $gCO2_{eq}$/MJ, with an annual exceedance probability of 10^{-1}, and no efforts to reduce GHG emissions are identified for this type of ship.

The tanker (brawn) and containerships (red) show a noticeable and significant reduction in GHG emissions, starting from 91.488 and 91.654 gCO_{2eq}/MJ as the most likely values for 2024, decreasing to 91.338 and 91.454 $gCO2_{eq}$/MJ, respectively, at an annual exceedance probability of 10^{-1}. Looking at a much longer horizon for the annual exceedance probability, neither ship type meets the EU targets, and the most rigorous mitigation measures need to be applied.

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Operational efficiency and maritime decarbonization through contract innovation

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Extended Abstact

International shipping is under increasing pressure to decarbonise, and much of the current debate focuses on technological solutions such as alternative fuels, wind-assisted propulsion, digital optimisation tools, and energy-efficient vessel design. While these developments are indispensable for long-term decarbonisation, they cannot alone deliver the scale and speed of emissions reductions required in the current decade. Climate harm depends on cumulative emissions rather than distant end-point targets, which makes early and widespread reductions in fuel consumption particularly important. Against this background, operational efficiency has emerged as one of the most immediately available and cost-effective pathways for reducing greenhouse gas emissions across the existing global fleet.

This paper argues that the success of operational efficiency measures is not determined solely by technological capability, but also by legal and behavioural structures that shape how ships are operated in practice. It contends that the green shipping transition is not only a technical challenge, but also a governance problem rooted in private contractual architecture. Despite the increasing sophistication of voyage optimisation tools and the growing availability of real-time operational data, many environmentally beneficial practices, such as speed optimisation, just-in-time arrival, and coordinated port calls, remain difficult to implement consistently. A central reason for this gap between technological potential and operational reality lies in the contractual frameworks that govern commercial shipping.

Contracts of carriage of goods by sea, especially voyage and time charterparties, play a pivotal role in determining how vessels are operated on a day-to-day basis. These contracts allocate rights, obligations, risks, and incentives between shipowners and charterers, and they directly govern operational decisions such as speed, arrival timing, waiting at anchorage, and performance expectations. However, standard charterparty provisions were developed primarily to maximise commercial certainty and allocate financial risk, rather than to promote energy efficiency or emissions reduction. As a result, they often undermine the effective deployment of green shipping technologies and operational practices.

Drawing on doctrinal legal analysis and insights from operational data, including AIS-based studies of vessel behaviour, this paper demonstrates that contractual constraints are a critical but under-examined driver of speed choice, arrival practices, and port congestion. Empirical evidence increasingly shows that vessels frequently sail faster than necessary only to wait at anchorage, even when port congestion is foreseeable and optimisation technologies are available. While this behaviour is often attributed to operational inertia or market pressure, the paper argues that it is more accurately explained by contractual risk allocation mechanisms, such as obligations of reasonable despatch, estimated time of arrival clauses, cancellation dates, and laytime and demurrage regimes. These provisions create strong legal and financial incentives for early arrival and high-speed sailing, discouraging adaptive voyage planning and coordinated arrival strategies.

The paper analyses both voyage and time charterparties from an operational efficiency perspective. Voyage charters are shown to be particularly rigid, prioritising certainty of arrival and risk transfer over flexibility, and thereby reinforcing environmentally inefficient practices such as “sail-fast-then-wait.” Time charterparties, while offering greater theoretical scope for efficiency due to charterer control over employment and fuel costs, are also undermined by split incentives, information asymmetries, and weak coordination between contractual parties. In both cases, contractual structures limit the practical effectiveness of regulatory measures and technological tools designed to improve operational performance.

Against this background, the paper advances the argument that charterparties should be understood not merely as contracts of carriage, but as powerful instruments of private governance. Because they sit at the

intersection of commercial decision-making and vessel operation, charterparties have the capacity either to obstruct or to enable operational efficiency. The paper therefore calls for a rethinking of contractual architecture in the context of maritime decarbonisation. Rather than relying solely on voluntary commitments or external regulation, contract design itself can be used to embed environmental objectives directly into commercial practice by reallocating rights, responsibilities, and incentives in ways that support efficient operation.

The paper concludes by arguing that meaningful progress in maritime decarbonisation requires closer integration between technological innovation and legal governance. Operational efficiency technologies can only deliver their full emissions-reduction potential if contractual frameworks are adapted to accommodate flexibility, data sharing, and collaborative decision-making. By highlighting the central role of private contracts in shaping operational behaviour, this paper contributes an interdisciplinary perspective that complements engineering and policy-focused approaches to green shipping. It suggests that a new contractual architecture, aligned with environmental objectives, is a necessary component of an effective and timely maritime decarbonisation strategy.

Technical and operational characteristics of the Croatian fishing fleet in the context of maritime sector decarbonisation

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Extended Abstract

Maritime decarbonisation policies have predominantly focused on merchant shipping, while fishing vessels remain largely outside international regulatory frameworks despite their cumulative contribution to greenhouse gas emissions, particularly in coastal and semi-enclosed seas such as the Adriatic (Koričan et al., 2023; Perčić et al., 2023). This study addresses this gap by analysing the technical and operational characteristics of the Croatian fishing fleet and quantifying baseline emission profiles for its principal segments.

The assessment is based on the General Fisheries Commission for the Mediterranean (GFCM) classification, distinguishing between Small-Scale Fisheries (SSF) and Large-Scale Fisheries (LSF). The Croatian fleet is characterised by a high number of SSF vessels (typically <12 m), which operate in coastal waters with relatively low installed power and short trips, and a smaller number of LSF vessels (≥12 m), including trawlers and purse seiners, which dominate total landings and fuel consumption, Figure 1. Representative vessel profiles were defined for each segment, incorporating engine power ranges (50–150 kW for SSF, 300–800 kW for LSF) and operational patterns.

Figure 1. GFCM classification of fishing vessels

A bottom-up methodology combining fleet registry data with high-resolution operational measurements (speed, position, and fuel consumption) was applied to reconstruct activity profiles and allocate fuel use across different fishing modes. The results reveal substantial heterogeneity in emission characteristics. Trawlers exhibit the highest fuel intensity due to continuous high-load towing operations, while purse seiners display pronounced variability associated with distinct operational phases. SSF vessels show lower absolute emissions, but significant variability linked to trip frequency and maintenance conditions. When normalised by operational time, LSF segments are the most emission-intensive, whereas efficiency comparisons based on landed catch indicate more complex relationships between energy use and economic output.

The findings underline that fishing vessels cannot be treated as a homogeneous category in decarbonisation strategies. Operational behaviour, such as speed selection, fishing duration, and auxiliary power demand, is identified as a key driver of emissions across all segments. In this context, emission reduction measures include operational optimisation (e.g. speed reduction and route planning), improved maintenance, and gradual integration of alternative energy solutions such as hybrid propulsion systems, electrification of auxiliary loads, and the use of low-carbon fuels (e.g. biofuels and methanol), although their applicability remains segment-dependent.

The study highlights the need for segment-specific emission indicators and integrated environmental–economic performance metrics tailored to fisheries. The presented baseline provides a foundation for evaluating decarbonisation pathways within the GREEN-FISH project, supporting the development of targeted measures for sustainable transformation of the Adriatic fishing sector.

ACKNOWLEDGEMENTS

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Operational Strategies for Strengthening Sustainability in Liner Service Networks

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1 INTRODUCTION

Maritime transport to peripheral island regions faces persistent challenges related to operational efficiency, cost structure, and sustainability. In this work, the sustainability of the existing liner container service network connecting mainland Portugal with the Azores Archipelago is evaluated for a redesigned network, as per studies such as Qi and Song (2012) or Rahmawan and Angelina (2017). This is one possible option, among several currently available, for dealing with sustainability in shipping operations. In fact, shipping companies operating liner networks are facing mounting regulatory pressures, see DNV (2025), as regards sustainability, with strong implications in their cost structure: IMO2020 (0.5% Sulphur fuel), Fit for 55, Emission Trading Scheme (ETS) and Bunker Adjustment Factor (BAF).

There are several technical and operational measures that may be taken to improve sustainability and deal with regulatory pressure, DNV (2025). These include, among others, energy efficiency upgrades for ship's onboard systems, utilization of renewable energies, hull and propeller form modifications, appendages and high performance coatings, hybridization, shore power, optimization of trim and speed, just-in-time arrivals to port, and weather routing. Shipping companies face considerable challenges in identifying the best options for their ships since most measures present various disadvantages. However, in certain cases, it may also be possible to redesign the liner networks in order to obtain improvements in economic efficiency and sustainability. This is particularly important in short sea trades serving ultra-peripheral regions such as islands and archipelagos. This redesign involves several aspects such as changing the fleet size and composition, service rotations and schedules, and ship operating speeds. This is often challenging because of port efficiencies and equipment's and public service requirements.

This paper shows the results of the redesign of the liner network operations that serve the Portuguese islands of Azores and seeks to evaluate its potential benefits in terms of GHG and air pollution. Section 2 shows the methodology used in this study, while section 3 presents the case study parameters, the network redesign and the numerical results (emissions reductions). Section 4 shows the main conclusions and offers recommendations for further study.

2 METHODOLOGY

Figure 1 shows the methodology, which uses models from Ramalho and Santos (2021), adopted for carrying out the analysis of the existing and redesigned liner networks. This approach has been implemented in a generalized numerical tool that performs round-voyage calculations, with different ship speeds and characteristics, while estimating fuel consumption and emissions per voyage. A comparative analysis between the existing and redesigned networks quantifies the environmental footprint of the two networks.

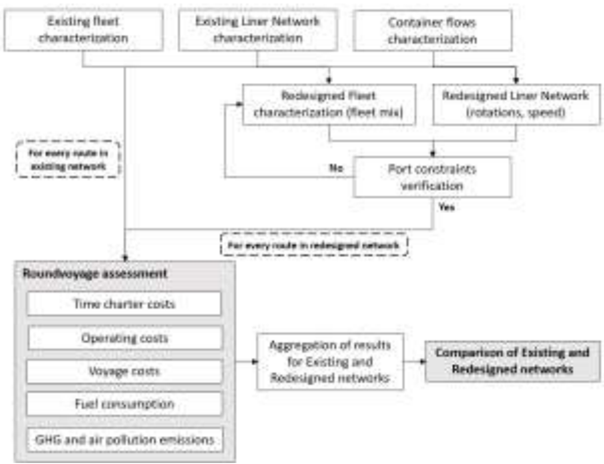

Figure 1 – Methodology for the analysis of existing and redesigned networks.

3 CASE STUDY

The methodology above is applied to the case of the network serving the Azores archipelago. The analysis is focused on a representative two-week peak-season period. Real vessel schedules and containerized cargo volumes were collected from shipping operators and port authorities to analyze the existing services and model a redesigned network. Information was also gathered as regards the ship's characteristics, operational speeds, and time charter rates, with the aim of calculating total operating costs and associated emissions.

The existing liner network has been redesigned into a pure hub-and-spoke network, as shown in Figure 2, using Ponta Delgada and Praia da Vitória as primary distribution hubs, consolidating mainland departures from Lisbon and Leixões into weekly services to both hubs, supported by optimized feeder services (carried out by one ship only) connecting these hubs to the remaining islands. Only the very small island of Corvo has been left out of this network as it is served using very small vessels sailing only from Flores. The required ship sizes for the redesigned services have been estimated based on cargo volumes and commercially available ship sizes.

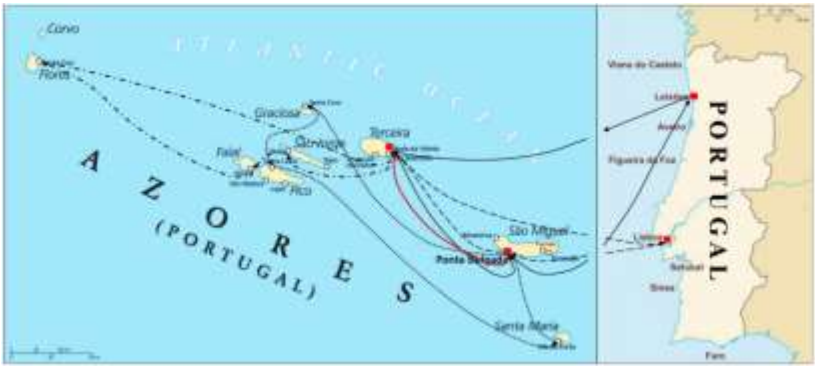

Figure 2 – Redesigned liner network.

Four different scenarios have been considered in this study. The Existing Liner Network scenario represents the as-is situation in the transportation of containerized cargo between the Portuguese mainland and the Azores archipelago, while the Optimized Liner network scenario depicts the redesigned network in Figure 2. Additionally, two other scenarios are considered: replacing the small feeder vessel with an electric feeder; in addition, using shore power for the main ships. The aim is assessing the impact of electrification in improving the sustainability of liner shipping networks. Table 1 displays the emissions in tons for the different scenarios being analyzed and the respective decreases. It can be observed that each successive sustainability upgrades to the liner network yield a clear drop in all measured pollutants. The most comprehensive scenario (redesigned network considering both electric feeders and shore power for main ships) presents the lowest amount of emissions, and displaying savings in the order of 34% for CO_2, 87% for NO_X, 29% for SO_X, PM_{10} and $PM_{2.5}$, representing the potential of electrification for reducing emissions in liner shipping.

Table 1 – Redesigned Network emissions in tons and in percentage for the different scenarios considered.

Scenarios (1-4)	**Emissions in tons**				
	CO2	NOx	SOx	PM10	PM2.5
1 Existing Liner Network	2,294.1	12.3	62.7	0.9	0.8
2 Optimized Liner Network	1,688.1 / *-26.4%*	1.8 / *-85.3%*	47.7 / *-23.9%*	0.7 / *-24.0%*	0.6 / *-24.0%*
3 Optimized liner network with electric feeder	1,584.4 / *-30.9%*	1.7 / *-86.2%*	44.7 / *-28.7%*	0.6 / *-28.7%*	0.6 / *-28.7%*
4 Optimized liner network, electric feeder and shore power for main ships	1,521.6 / *-33.7%*	1.6 / *-86.7%*	44.5 / *-29.1%*	0.6 / *-29.3%*	0.6 / *-29.3%*

4 CONCLUSIONS

Numerical results demonstrate that a redesign of the network and optimized feeder deployment can reduce total emissions significantly (much more than most energy efficiency measures) while maintaining service coverage and schedule feasibility. The findings contribute to a broader discussion on sustainable short-sea shipping and provide a methodological framework applicable to other peripheral island regions.

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The carbon cost of maritime disruptions: Assessing the Impacts of Chokepoint Rerouting in terms of GHG Emissions from chronologic data

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Extended Abstract

INTRODUCTION

Maritime chokepoints, like the Panama or Suez Canals, or the Straits of Malacca and Hormuz, among others) are critical nodes in global shipping networks, channelling a substantial share of maritime freight flows (Rodrigue, 2020). In recent years, the increase of unexpected events affecting those chokepoints resulted on generalized traffic rerouting actions through longer alternative passages, leading to higher costs and travel times. While a growing body of literature examines the «operational and economic consequences» of chokepoint disruptions (Notteboom et al., 2021; Verschuur et al., 2022), little attention has been paid to their *environmental impacts*, specifically the additional greenhouse gas (GHG) emissions generated by forced rerouting. This gap is particularly concerning given the International Maritime Organization's (IMO) ambition to reach net-zero GHG emissions from international shipping by around 2050 (Marine Environmental Protection Committee, 2023) and the increasing frequency of maritime disruptions driven by geopolitical instability and climate change.

On another hand, scientific literature regarding decarbonisation literature in maritime transport has predominantly focused on *technological solutions*, like alternative fuels, ship design or propulsion systems, or on *operational measures and actions*, such as slow steaming, speed optimisation or route planning, as levers for emission reduction (Bouman et al., 2017; Psaraftis and Kontovas, 2013; Lindstad et al., 2015). Most of these studies implicitly assume stable routing patterns and do not consider the extra emissions of alternative routes. Assessing this *carbon cost of disruptions* across multiple events, chokepoints, and vessel types would add both a theoretical and practical insight to anticipate and mitigate the environmental costs of disruptions.

This proposal aims to identify and assess the main environmental costs (mainly related to GHG emissions but not only) related to disruptions of maritime routes at chokepoints, on the basis of a database of disruptive events at chokepoints between 2019 and 2024.

DATA AND METHODOLOGY

The assessment methodology on a unified dataset of daily vessel passages through major maritime chokepoints from 2019 to 2024 (extracted from international databases like Humdata or Portwatch), disaggregated by vessel type (tankers, bulk carriers, container ships, etc.) and by strait. This dataset captures traffic volumes before, during, and after each major disruption event, enabling a longitudinal analysis of rerouting patterns.

To estimate the associated GHG emissions, we employ a «bottom-up estimation approach» consistent with the methodology used in the IMO Fourth GHG Study (Faber et al., 2020). Specifically, for each identified rerouting event. Moreover, this estimation follows a before-after analysis logic where only changes are assessed (Gonzalez-Feliu, 2018). In this logic, the GHG emissions in excess at chokepoint *s* due to disruption *d* can be estimated as follows:

$$Excess\ GHG_s^d = \Delta {N_v}_s^d . D_{additional} . EF_v . \overline{Capacity_v}$$

Where $\Delta {N_v}_s^d$ represents the estimated number of rerouted vessels of type v;

$D_{additional}$ is the additional sailing distance of the alternative route;

EF_v is the emission factor per vessel type expressed in grams of CO_2 per tonne-nautical mile;

$\overline{Capacity_v}$ is the mean deadweight tonnage per vessel category.

Data will be analyzed using Interrupted Time Series Analysis (ITSA, McDowall et al., 2019), which allows to estimate the immediate emission impact at the onset of the disruption, the change in emission trajectory during the disruption period, and the post-disruption recovery pattern, including the time to return to baseline emission levels and whether a "new normal" emerges with persistently altered emission levels. Moreover, a cross-strait correlation analysis using Granger causality tests (Shojaie and Fox, 2022) will be carried out to examine whether traffic reductions in a disrupted chokepoint are statistically associated with traffic increases in alternative chokepoints, and to measure the temporal lag of such cascading effects.

EXPECTED RESULTS AND CONTRIBUTIONS

Data collection and initial descriptive analyses of traffic patterns across chokepoints have been carried out, identifying 59 main disruptions where 54 are of natural origin (storms, cyclones, earthquakes, etc.) and 5 of anthropic nature. The emission estimation model is currently being calibrated using IMO emission factors. Preliminary results for the Suez Canal disruptions (2021 and 2023–2024) suggest that «the carbon penalty of rerouting is substantial» and varies significantly by vessel type. Full ITSA modelling and

Although this research is at an early stage, we anticipate several contributions relevant to the decarbonisation agenda of maritime transport. First, this study provides a first systematic, multi-event quantification of the excess carbon footprint attributable to chokepoint disruptions. This fills a significant gap, as current IMO emission scenarios and decarbonisation roadmaps do not explicitly account for disruption-induced rerouting as a source of emission variability.

Second, by analysing carbon recovery patterns» across different disruption types (geopolitical, climatic, accidental, sanitary), this study contributes to the emerging literature on supply chain resilience by adding an environmental dimension that has been largely absent from resilience frameworks.

Third, the analysis of whether successive disruptions lead to «more carbon-efficient responses» speaks to the question of organisational learning» in maritime networks, a question with direct implications for policy design. From a policy perspective, findings will help assessing the hidden environmental cost of geopolitical and climatic instability on maritime decarbonisation efforts. This has direct implications for the IMO's GHG strategy, for the EU Emissions Trading System's inclusion of maritime transport, and for port and infrastructure investment decisions aimed at reducing chokepoint dependency.

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Operational load-based evaluation of EPL in a container vessel

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Extended Abstract

INTRODUCTION

The decarbonisation of maritime transport has become a central objective under the International Maritime Organization (IMO) strategy, targeting significant reductions in greenhouse gas (GHG) emissions by 2030 and net-zero emissions by 2050 (IMO, 2023). Within this regulatory framework, short-term technical measures such as the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII) have been introduced to enforce compliance (IMO, 2021a; IMO, 2021b). Among these, Engine Power Limitation (EPL) has emerged as a widely applied measure due to its relatively low implementation cost and immediate applicability to existing vessels (IACS, 2022).

Container ships, which account for a substantial portion of global maritime emissions, are particularly affected by these regulations due to their operational profiles and high installed propulsion power (European Commission, 2023). In practice, many container vessels operating in European trade routes are required to comply with strict sulfur limits (0.10% m/m in Emission Control Areas) and increasingly stringent carbon intensity requirements (IMO, 2022). These regulatory pressures often lead to the implementation of EPL as a primary compliance strategy.

However, the effectiveness of EPL is typically evaluated under idealised operating conditions, assuming steady-state engine performance near optimal load ranges. In reality, container ships frequently operate under variable load conditions due to port operations, maneuvering, traffic constraints, and slow steaming practices (Völker, 2015). Therefore, there is a critical need to assess EPL performance based on real operational data rather than theoretical assumptions.

METHODOLOGY

This study presents a real-data-driven evaluation of EPL using operational data collected from the container vessel. The vessel is a 2,478 TEU container ship equipped with a MAN 7L70ME-C two-stroke main engine with a Maximum Continuous Rating (MCR) of 21,770 kW.

High-resolution engine load data were recorded at 5-minute intervals, resulting in a detailed dataset representing actual ship operations. While previous studies have utilised extended datasets, this study focuses on a representative 10-day operational period to capture short-term variability in engine loading conditions.

To evaluate EPL performance, a load distribution-based approach is adopted. Engine operating points are analysed in relation to their corresponding specific fuel consumption (SFC) characteristics, with particular emphasis on deviations from the optimal load region. In addition, fuel consumption values are standardised using equivalent fuel energy conversion methods to ensure consistency across different operational scenarios.

RESULTS AND DISCUSSION

The analysis demonstrates that the main engine operates predominantly under partial load conditions, with a significant proportion of operating time occurring below 50% MCR. This observation is consistent with previous findings indicating that container ships engaged in short-sea and regional European operations experience highly variable load profiles (Völker, 2015; Viran and Mentes, 2021).

From a thermodynamic perspective, marine diesel engines achieve minimum specific fuel consumption within the range of approximately 70–80% MCR (Barsali et al., 2004). Operation outside this range leads to increased fuel consumption per unit power output, thereby reducing overall energy efficiency.

The implementation of EPL, which effectively restricts the maximum available engine power (typically to 75–83% of MCR for EEXI compliance), is intended to reduce fuel consumption and associated emissions (IMO, 2021a; IACS, 2022). However, the present analysis indicates that, under real operating conditions, EPL does not necessarily lead to improved efficiency. Instead, since the engine already operates below optimal load levels for a considerable portion of time, further restricting available power does not significantly alter the load distribution.

Moreover, EPL may introduce additional operational constraints, particularly in scenarios requiring higher power availability, such as adverse weather conditions, schedule recovery, or safety-critical maneuvers. This limitation reduces operational flexibility, which is a critical parameter in container shipping due to strict schedule requirements.

In contrast, previous studies on hybrid propulsion systems and alternative fuel applications have demonstrated that energy efficiency improvements can be achieved through system-level optimisation and operational flexibility. For example, diesel-electric and hybrid configurations enable generators to operate closer to optimal load conditions, resulting in fuel savings and emission reductions (Zahedi and Norum, 2013). Similarly, alternative fuel retrofit solutions, such as methanol engine conversion, have shown promising results in achieving EEXI and CII compliance while reducing lifecycle emissions (Bayraktar et al., 2023).

The comparison highlights that EPL, as a standalone regulatory measure, lacks the capability to address inefficiencies arising from real operational conditions. Instead, it functions primarily as a compliance tool rather than an optimisation strategy.

CONCLUSIONS

The findings of this study have important implications for regulatory frameworks such as EEXI and CII. While EPL provides a practical short-term solution for meeting EEXI requirements, its contribution to actual emission reduction may be limited when evaluated under realistic operational profiles.

For container vessels operating in European waters, compliance with both sulfur regulations and carbon intensity targets necessitates a more integrated approach. This study provides a real operational assessment of Engine Power Limitation (EPL) using high-resolution engine load data from a container vessel. The results demonstrate that:

- The main engine operates predominantly outside the optimal efficiency range
- EPL does not significantly improve energy efficiency under real operating conditions
- Operational flexibility may be negatively affected by power limitations
- Data-driven evaluation is essential for accurate assessment of regulatory measures

The findings emphasise that decarbonisation strategies in maritime transport should not rely solely on power limitation approaches but should instead incorporate operational optimisation and advanced propulsion technologies. This study highlights the importance of integrating real-world operational data in evaluating energy efficiency measures in container shipping.

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Working Group 2 on Hydrodynamic hull and propulsor design for energy-efficient performance

Interaction of textured and hydrophobic coatings with microbiological fouling and their impact on hydrodynamic drag

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Extended Abstract

Maritime transport, which accounts for approximately 80% of global international trade, is one of the largest energy consumers worldwide, making its environmental impact increasingly significant (Fan et al., 2022). Intensively operated vessels emit substantial amounts of greenhouse gas pollutants into the atmosphere, including CO_2, SO_x, NO_x, and particulate matter (Fan et al., 2022; Ghaemi et al., 2025). Fuel consumption depends on numerous parameters, such as vessel speed, navigation conditions, and the hydrodynamic environment, including wind and wave intensity (Zhou et al., 2022). It has been observed that in rough sea conditions, increased resistance leads to reduced propulsion efficiency, resulting in higher fuel consumption compared to calm conditions (Ghaemi & Zeraatgar, 2022). One potential solution to improve the energy efficiency of ships is the application of surfaces with extremely low water–surface interaction. Superhydrophobic surfaces allow water droplets to retain an almost spherical shape and slide off rapidly due to the formation of air pockets between surface structures, which significantly reduces water adhesion (Hwang et al., 2017). Another important factor contributing to increased ship resistance is biological fouling, where microorganisms, algae, and other aquatic organisms accumulate on submerged surfaces. This process not only reduces vessel speed and increases fuel consumption but also contributes to the spread of invasive species (Qiu et al., 2024).

To mitigate this issue, antifouling coatings are commonly used; however, most of them contain biocides that are harmful to aquatic ecosystems and can accumulate in seabed sediments (De-la-Torre et al., 2023). In response to increasingly stringent environmental regulations, intensive research is being conducted to identify alternatives to conventional coatings. One promising approach involves nanostructured polymer coatings, which can provide superhydrophobic, antibacterial, and high-durability properties. Considering these challenges, the present study evaluates the effects of a ZnO- and PMHS-based coating on the resistance of textured and non-textured surfaces to microbiological fouling, as well as their hydrodynamic drag characteristics. Experimental results demonstrate that appropriately selected hydrophobic coatings combined with surface texturing can reduce hydrodynamic resistance while exhibiting antimicrobial properties. The findings of this study may contribute to reduced fuel consumption and associated emissions in the maritime sector, while from a scientific perspective, the project offers a novel insight into the combined interaction of active and passive drag-reduction methods.

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Leidenfrost phenomena in marine engineering: A new method creation for drag reduction

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Extended Abstract:

In recent years' research and engineers have been searching for new methods and approaches how to reduce ship drag, while ship building companies continue developing innovative technologies for drag reduction. The most common ways that currently are used for ship drag reduction are the use of optimized ship hulls (Armanfar et al., 2024), energy saving devices (Song et al., 2023), antifouling (Fu et al., 2024) and super-hydrophobic (Lyu et al., 2013) coatings, micro-grooved surfaces (Zhang et al., 2024) or air lubrication systems (Kringel et al., 2025). The latter technology, that could be used for drag coefficient reduction, gets a lot scientific attention and is based by gas/air layer formation (Kumagai et al., 2024) near the moving object and microbubble spraying allows to reduce it even by 26% (Zhu et al., 2023). Currently, in maritime sector nearly two hundred ships have already installed air lubrication systems. However, this technology deals with the problem of non-uniform bubble distribution that can cause instabilities for ship when inject large bubbles near the ship hull. It has an impact for extra turbulence viscosity, and therefore the ship can become unstable (Zhao et al., 2022). Boundary layer theory states that drag reduction can be achieved by forming a boundary layer around overflown objects, while results show 25% drag reduction and up to 10% energy savings (Mohamad et al., 2025). Our implemented research and experiments are related with an alternative approach to create a new method of how to reduce hydrodynamic drag by forming a stable vapour layer around the heated solid surface, which is in contact with water. Research investigates Leidenfrost effect (LE) and its application for drag reduction in maritime sector.

LE maintenance requires high energy loads; therefore, its application for large-scale is challenging. While new methods is only in the stage of creation the first goal and attempt is to maintain a stable vapor layer around the heated specimen. Our experimental investigations have showed a good LE formation when lowering the Leidenfrost temperature occurrence in salt environment, when heated surface temperature was only 120 ºC in salt water.

However, LE formation is highly dependent from thermal fluid properties, surface roughness and flow-related parameters. Investigation involves surface microstructure changes to create super-hydrobical surface (SHS) (Du et al., 2023). For drag reduction and effective energy savings are super-hydrophobic surfaces (SHS) or thin films creation becomes one of the main issues to observe LE. In this work SHS was created by applying two stage surface treatment when in first stage chemical etching is applied, while in the second stage surface is covered with PMHS polymer or octadecyltrichlorosilane (OTS). Polymers addatives increase hydrophobic film water contact angle and help to maintain coating durability and self-cleaning properties. Advanced polymer selection, for example polydimethysiloxane (PMDS) is a good choice to create antifouling coatings oriented to the maritime sector because such coatings have low surface energy, biological impact, and corrosion to seawater.

The newly created two stage hydrophobic surface helps to cause Leidenfrost effect faster by pushing away water layer from the surface. Experiments are implemented in vertical water tower where heated samples are free falling in water. Super-hydrophobic surface has impact for the LE generation because it helps to push away water in boundary layer. The changes of drag reduction when LE forms around sample are monitored. The formed small air gap between liquid and surface allow body to slide with a lower drag force. For the specimens used in the experimental set up, surface characterization was performed by using scanning electron microscopy (SEM), X-ray diffraction (XRD) and water contact angle (WCA) measurements. Performed surface analysis provides a detailed insight into surface morphology, structure and wettability impact for Leidenfrost effect generation. Research provides unique experiments conducted with different materials to observe Leidenfrost generation and its maintenance on the surface. This study is interdisciplinary and is relative for thermo hydrodynamic and material sciences

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CLEAR: A coefficient-domain Bayesian state-space framework for hull fouling estimation from operational ship data

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1 GENERAL INTRODUCTION

1.1 *Background and proposed method*

Biofouling on ship hulls is a persistent challenge that reduces fuel efficiency, raises costs, and impacts sustainability. The buildup of marine organisms increases drag, requiring more power to maintain speed—boosting fuel use by 10–40% for moderate fouling and over 50% in severe cases (Schultz et al., 2011). As shipping significantly contributes to global CO_2 emissions, accurately monitoring fouling is essential for both cost control and regulatory compliance (IMO, MEPC, 2012). Traditional fouling assessment relies on periodic inspections or dry-docking, offering only limited snapshots of hull condition. The industry is shifting to continuous performance monitoring using operational data, but isolating fouling effects is difficult due to environmental factors, loading changes, and data noise. While the ISO 19030 standard guides speed-power analysis, practical use is challenged by data quality and operational variability.

Recent advances in machine learning enable improved fouling estimation using models like regression, neural networks, and Gaussian processes (Coraddu et al., 2017). However, these approaches often 1) treat fouling as static or slowly-varying rather than explicitly modeling its dynamic evolution, and 2) rely on power-domain assumptions about velocity dependence that may not always hold. Schultz presented foundational work that models the coefficient of fouling as additive roughness penalty (Schultz 2007). Coefficient-based modeling provides alternatives to power-domain assumptions by directly supporting additive fouling term and using coefficient-based decomposition (Uzun et al., 2019).

Recent research reveals that the accumulation and growth of marine organisms on submerged hull surfaces are governed by a complex interplay of environmental conditions, vessel operational profiles, and ecological processes (Valchev et al., 2022). Key influencing factors include water temperature, which affects metabolic and reproduction rates of fouling organisms; salinity and nutrient availability, which influence species composition; and the duration of exposure to favorable growth conditions. The existing fouling community structure also plays a critical role, as early-stage biofilm formation can facilitate the subsequent colonization of more complex macrofouling species, leading to nonlinear growth behavior. Taken together, these factors suggest that fouling evolution is inherently dynamic, path-dependent, and stochastic, thereby motivating the use of state-space or probabilistic modeling approaches to accurately capture its progression and impact on vessel performance.

In this paper, we propose a framework that formulates the fouling estimation problem in the resistance coefficient domain. For a vessel moving at speed V through water of density ρ, with wetted surface area S, the shaft power can be expressed as

$$P = C_T \cdot \frac{1}{2}\rho S V^3 / \eta_P$$

where η_P represents the propulsive efficiency. Instead of modeling power directly under the Bayesian framework, we adopted and modeled the resistance coefficients to capture the hydrodynamic characteristics of the hull.

We decompose the total resistance coefficient into three physically meaningful components added to observation noise: the calm-water resistance characteristics of the clean hull, the environmental increment comprises of the added resistance from environmental resistance and drag coefficients, and the fouling increment that represents the time-varying contribution of biofouling to hull resistance. By modeling fouling as an additive increment coefficient, we aim to align more closely with the underlying physical mechanisms associated with surface roughness and its impact on hydrodynamic resistance. In particular, it captures how small-scale irregularities on the hull surface translate into measurable increases in frictional drag independent from other factors such as wave, currency and air drag, thereby providing a more physically interpretable framework than purely empirical correction factors.

This approach also establishes a natural and consistent connection to well-established resistance prediction methodologies in naval architecture, enabling integration with existing performance models and simulation tools. Furthermore, it offers a flexible structure for incorporating uncertainty and variability, as the fouling contribution can be treated as a time-dependent augmentation to baseline resistance.

Specifically, we adopt this formulation also to facilitate the representation of the fouling coefficient as a latent state variable, whose evolution is not directly observed but can be inferred from operational data, and which evolves according to biologically and environmentally motivated dynamics over time. The proposed model can hence be time-series data-driven that is capable of better handling the often-heavy observation noise compared with single-sample-based methods.

Inference is performed using Hamiltonian Monte Carlo, enabling full posterior quantification of model parameters and fouling trajectories.

1.2 *Experiments*

We validate the approach using 18 months of operational data from a bulk carrier, demonstrating successful tracking of fouling accumulation, detection of a documented hull cleaning event, and meaningful separation of fouling and environmental power penalties across 19 distinct voyages. The raw dataset comprises 810,845 records sampled at approximately 1-minute intervals, containing measurements of shaft power, speed through water, displacement, environmental conditions (wave height, wind speed, current velocity), water properties (temperature, density, salinity), and vessel position. For all experiments reported in this paper, we run MCMC chains with 500 warmup iterations followed by 500 sampling iterations.

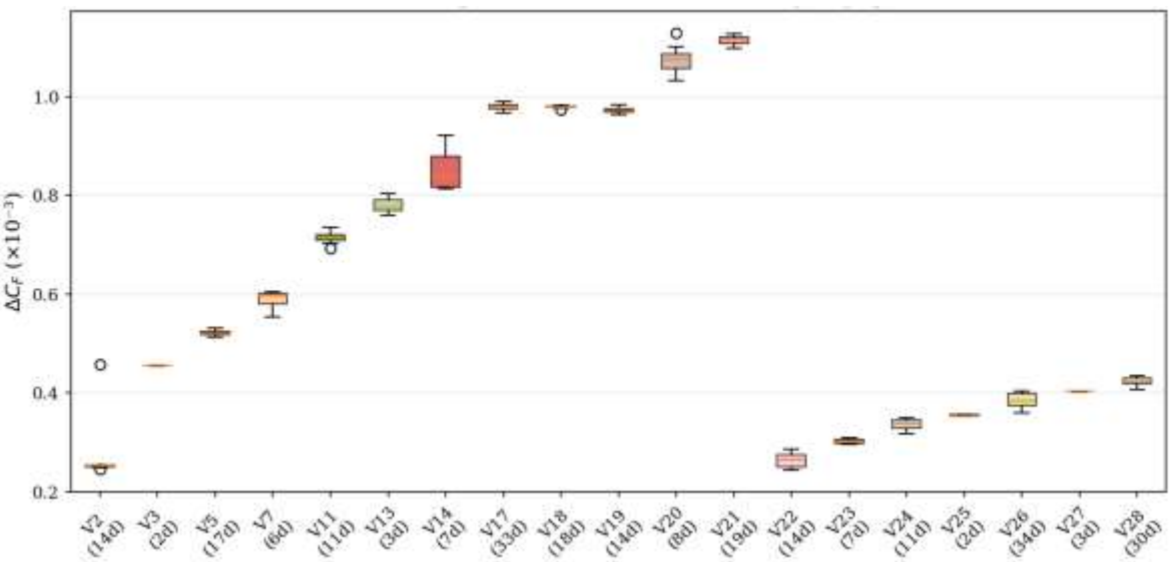

Figure 1. Fouling accumulation tracking results by voyage

The experimental results show that the estimated fouling is lowest during the initial voyage (v2), which is consistent with the vessel being newly commissioned and thus having minimal surface degradation. As operations progress, fouling gradually increases until a pronounced drop in (ΔC_F) is observed between voyages 21 and 22, clearly indicating a hull cleaning event—an event that is also independently detected by our model.

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Structured thin-film coatings for ship drag reduction

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Extended Abstract:

1 SCIENTIFIC BACKGROUND AND EXPERIMENTAL INVESTIGATION OF DRAG REDUCTION

1.1 *Introduction*

Energy efficiency, reduced environmental impact, and sustainable development are the most important goals in Europe and worldwide. Reducing CO^2 emissions is one of the global goals that need to be addressed to achieve a cleaner environment and combat climate change [Balcombe, P. 2019]. Road transport is one of the largest emitters, accounting for more than 70% of annual greenhouse gas emissions [Xu, L. 2020.]. The remainder is accounted for mainly by shipping and aviation. Shipping accounts for 80-90% of global trade, with more than 10 billion tonnes [Ampah, J.D. 2021] of cargo moving across the world's oceans every year. At the end of 2019, global trade was up 18% compared to 2016, and this trend could lead to a 50% increase in shipping fuel consumption between 2012 and 2040. Because of these reasons, Europe and the whole world must decarbonize the transport sector to reach the CO^2 reduction targets by 2050 [European Environment Agency 2019].

The maritime sector remains highly dependent on fossil fuels [Balcombe, P. 2019], with limited viable alternatives compared to other transport domains. As hydrodynamic resistance significantly influences vessel performance, fuel consumption, and energy losses, reducing friction drag is a critical challenge for achieving sustainable shipping [Kumar, S. 2020]. In hydrodynamics, moving bodies in water create hydrodynamic resistance. Friction can be reduced through innovative solutions that conserve energy. They are constantly sought in material sciences. Friction reduction measures such as polymer-covered films [Asidin, M.A. 2019]; micro bubbles [Zhao, X. 2025], or airbag after a bottom; frame vibration [Ebrahimi, E. 2021]; hydrophobic coatings [Tian, H. 2015]; elastic coatings [Tian, L. 2017], supercavitation (SC) [Kandula, J. 2021] are already used in practice. It is confirmed that, when using these solutions, hydrodynamic resistance can be reduced by up to 12-30% [Rad, S.V. 2021]. Measures such as changing the body geometry [Mohandas, S. 2019] have also been tested to reduce drag around the floating object by an amount similar to that achieved with coatings. SC is also an effective means of reducing body resistance. When bodies move at high speed [Shao, S. 2017], the liquid is compressed at a specific surface, and the pressure behind it drops suddenly. Thus, in liquids, an airbag forms due to the pressure difference near the body surface. In this case, the body loses direct contact with the water, allowing the drag to be reduced by forming an air layer between the moving body and the liquid. In this study, it is proposed to create an analogue of SC by using the concept of two-phase flow generation by the complex application of innovative materials. To achieve the new-with-no-analogues concept, the possibility of applying a second-degree boiling crisis (Leidenfrost effect (LE)) to reduce hydrodynamic drag is considered. The well-known conditions for the rise of two-phase flow can be influenced by the right choice of innovative materials. This study introduces structured thin-film coatings, particularly plasma-activated coatings and superhydrophobic coatings such as ZnO tetrapod coatings [Vorotinskienė, L. 2026], which can act as active surfaces that facilitate the formation of a vapour layer. These coatings are designed to influence the LE and promote the formation of a stable vapour on heated surfaces in water of 20 °C. Such a mechanism enables the formation of a persistent vapour interface, potentially reducing friction drag beyond the capabilities of conventional technologies.

1.2 *Investigation of thermochemical processes and Leidenfrost temperature*

The experimental setup was designed to investigate thermochemical processes and the formation of two-phase flow on heated samples. The system consisted of a heating furnace, a water tank, a data acquisition unit, and a high-speed imaging device. Spherical samples were heated to 260 °C in air, then immersed in water at 20 °C. The sample temperature was measured with an E-type thermocouple, approximately 1.5 mm from the surface, connected to a TC-08 data logger. To ensure accurate heat transfer, the thermocouple junction was fixed using a thermally conductive compound. During the experiments, forced convection was minimised by stopping water circulation before immersion. After heating, the sample was rapidly transferred from the furnace into the water tank, and the cooling process was recorded using a video camera. Temperature evolution was monitored until thermal equilibrium with the surrounding water was reached. The LE was determined from temperature–time data and visual observation of vapour layer formation.

1.3 *Cooling dynamics of spherical specimens*

The cooling curves and heat transfer coefficient trends revealed distinct dynamic behaviour for identical samples with different surface coatings. The dependence of the Leidenfrost temperature (LT) was summarized and results indicate that LT is governed by key factors, including surface temperature, surface structure and properties, and physicochemical processes. The Leidenfrost effect strongly depended on surface modification. Polished samples did not form a stable vapor film at low temperatures (160–200 °C), while superhydrophobic coatings (ZnO tetrapods, smooth samples and textured ($FeCl_3$ etched)) enabled vapour film formation even at 160 °C. Coated samples produced significantly thicker and longer-lasting vapour films (up to >10 s), compared to uncoated or only textured copper (≤1–2 s). The combined textured and coated surface showed the best performance, forming the most stable vapour layer across all temperatures. At higher temperatures (260 °C), vapour films formed on all samples but remained thinner and less stable for unmodified surfaces. Overall, surface texturing and superhydrophobic coatings significantly enhance LE initiation, stability, and duration.

1.4 *Drag Reduction Concept for Ship*

A novel approach is currently being developed, based on a fundamentally different perspective compared to conventional drag reduction methods. The research aims to propose an analogue to cavitation, where a body moving in water becomes enveloped by a vapor/gas layer. Under such conditions, friction can be reduced by up to two times, which could result in approximately 20–25% lower fuel consumption and, consequently, significant reductions in CO_2 emissions.

In terms of applicability to ship flows, this concept could be implemented through the integration of dynamically operating plates installed on the ship hull. These plates would function in an alternating regime, activating primarily under conditions of peak hydrodynamic resistance, where drag reduction would be most effective. However, the approach is still under development, and its operational feasibility, control strategies, and performance under real maritime conditions require further investigations.

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A dynamical model for the prediction of propulsion performance under wave-induced motions and loads

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1 ABSTRACT

Propeller performance prediction is a challenging, yet crucial objective in view of the stricter, current-in-force legislative framework regarding environmental protection and shipping decarbonization. Reliable simulation models of the propulsion system response under the effect of the encountered weather can be useful for the development of a physics-based digital twin of the vessel and supply the master with a decision support tool. Moderate and heavy weather conditions lead to added wind and wave resistance, caused by the diffraction of the waves on the hull and the dynamic motion response of the vessel, leading to significant energy losses of the system and excessive fuel consumption. The focus of the present study is the development of a propulsion system simulation model, especially accounting for the effects of the encountered seaway on the propeller's thrust and efficiency. This variation of the operational profile of the propeller is caused firstly by the modification of the wake field reaching the propeller and secondly by the vertical motion of the propeller, following the vessel's oscillation. The present model accounts for these effects, serving the purpose of accurately predicting the loading and performance of the drivetrain.

For the unsteady propeller loading and response prediction, the Vortex Element Method is employed; see Belibassakis & Politis (1999), Belibassakis (2004). The method relies on the framework of potential, lifting flow methodologies, modelling the vorticity generated by the propeller blade operation inside the wake, as trailing vortex sheets. The representation of the propeller disturbance velocity field is obtained by distribution of source-sinks and vorticity elements on the blades and the trailing vortex surfaces. The unsteady blade thrust and torque for the key blade is obtained by pressure integration over the propeller blade, which is performed at each time step, assuming a different position of the blade inside the propeller disk, assuming the wake to be undisturbed by the propeller's rotation itself. Subsequently, the propeller thrust and torque coefficients can be calculated as the summation of the contributions of all blades, accounting also for the phase difference of the corresponding load histories. The method has mainly two advantages; the first one is the versatility to account for additional axial wake components (beyond the ship's viscous effects expressed via the wake fraction), such as the wave velocities on the propeller disk and the vertical motion of the propeller due to the ship's heave and pitch motion, while the second advantage is its computational efficiency, compared to viscous CFD methods. Through this method, both the open water characteristics of the propeller and the loading of the propeller operating inside the wake of the ship can be calculated, while also regular and irregular wave velocities contributions can be taken into account.

For the calculation of the vertical propeller motion, but more importantly for the estimation of the added wave resistance, the radiated energy method, in conjunction with strip-theory assumptions, is employed. The method is developed for regular waves of small amplitude (compared to the wavelength), but they are extended to account for irregular waves, characterized by spectra, by using standard spectral analysis in irregular seaways. The process allows the derivation of the mean added resistance for different sea states, vessel speed and primary wave directions, with reference to the ship's forward speed of advance, providing useful information for the entire range of anticipated operational and weather conditions.

The next step of the analysis is the development of a dynamical model for ship propulsion performance in waves. The method relies on the surge equation of motion for the vessel, under the effect of the total load in the longitudinal direction:

$$(1-t)N_pT_p - (R + R_{AW}) + T_{WASP} + F_1 = (m + a_{11})\ddot{\xi}_1 + b_{11}\dot{\xi}_1 \quad (1)$$

where, $\ddot{\xi}_1$, $\dot{\xi}_1$ are the surge acceleration and velocity, respectively, m is the ship's displacement, a_{11} and b_{11} are the added mass and hydrodynamic damping in surge, correspondingly, t is the thrust deduction factor, N_p is the number of propellers, T_p is the thrust per propeller, R is the calm water resistance, R_{AW} is the added wave resistance, T_{WASP} is the total thrust from any installed Wind Assisted Systems of Propulsion (WASP) and F_1 is the wave excitation surge force.

By neglecting the fast-time scale of the surge wave excitation force F_1, which is negligible compared to the calm water resistance and the added mass a_{11} which is also very small, the surge equilibrium can be expressed by means of the following time-varying coefficient:

$$C(t) = \frac{K_T}{J^2} = \frac{(R + R_{AW} - T_{WASP})/N_P}{\rho(1-t)(1-w)^2(U + \alpha u_w)^2 D^2} \tag{2}$$

where, K_T is the propeller thrust coefficient, J is the propeller advance ratio, ρ is the density of water, $1-w$ implies the mean volumetric wake fraction on the propeller disk, U is the mean axial propeller inflow velocity, u_w is the wave velocity on the propeller disk, D is the propeller diameter and finally α is a tunable parameter that enables and controls the intensity of the effects of waves and stern vertical motion in the analysis. The effect of the latter tunable parameter is the main scope of the current work.

Therefore, at each time step a quasi-steady equilibrium point can be achieved, by using open water propeller characteristics and the time-varying coefficient presented in Eq.(2). The process concludes with the derivation of the advance coefficient J at each time step, by intersecting the coefficient with the open water characteristic of the thrust coefficient (see Fig. 1) and finally, the instantaneous shaft horsepower demand can be determined.

To apply the methodology discussed and investigate the effects of the α-parameter in the performance prediction, a Kamsarmax bulk carrier is used as a demonstrator. A parametric analysis of the effect of α is performed, assuming different operational scenarios and prevailing weather conditions. An example of the results regarding the SHP is given in Fig. 2. The figure shows the time average SHP value for different wave directions and α value, while the black bar indicates the standard deviation of the engine output response. The results clearly show that the variation of the α-parameter keeps the average SHP almost constant, but significantly affects the standard deviation, implying that higher peak values are predicted, pushing the engine to the limits. The analysis also extends to the examination of different operational conditions, including draft and speed of advance, but also sea states.

In this work the applicability of this cost-effective methodology for the analysis and prediction of the performance of the propulsion system is shown, while at the same time the model proves to be effective in capturing qualitative differences between different operational conditions, adequately taking into consideration the effects of the wave orbital velocities and the stern's motion response in the analysis. Due to its effectiveness, the model can be utilized for systematic investigation of different cases in realistic ship operational conditions to support the development of digital twins and decision support systems.

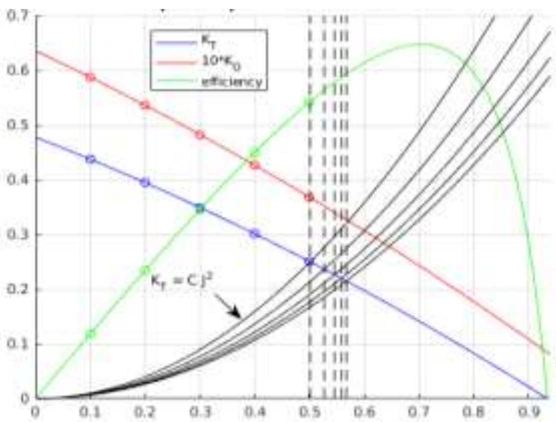

Fig. 1: Propeller quasi-steady analysis based on open water propeller characteristics

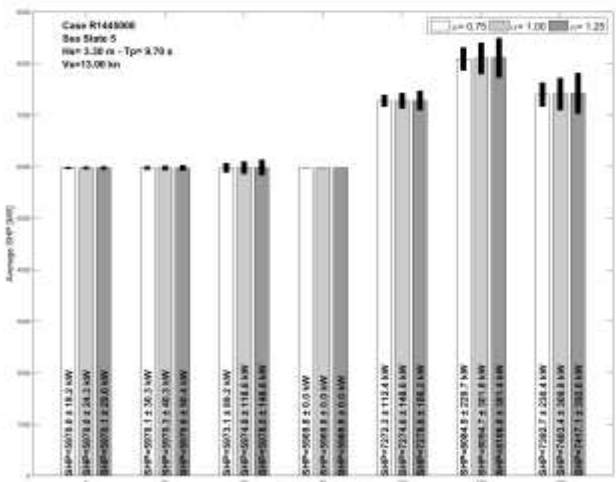

Fig. 2: SHP variation for a given loading condition, speed and sea state and different wave directions and α values

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Estimation of ship resistance in head waves from pitch motion

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ABSTRACT

Accurate estimation of ship resistance in waves is important for propulsion control, fuel savings, and emission reduction. Direct resistance measurement is feasible in model tests, but difficult in real operation. This study examines whether pitch motion can be used as an indirect indicator of resistance variation in waves. The analysis is based on towing-tank experiments for a KVLCC2 tanker model in regular head waves, with surge force, pitch, heave, and wave parameters analysed in time and frequency domains. The results show a consistent relation between pitch motion and added resistance. Both responses vary strongly with wavelength, and the strongest relation is observed when the wavelength is close to ship length. Time-domain analysis shows similar amplitude development and comparable signal behaviour, while frequency-domain analysis shows corresponding dominant components and interpretable relative phase behaviour. These results indicate that pitch carries useful information on the hydrodynamic loading state of the ship and may be used for indirect resistance estimation.

1 INTRODUCTION

Waves increase ship resistance. This increases fuel consumption and emissions, and affects propulsion performance (Liu & Papanikolaou 2016). In real operation, resistance is difficult to measure directly. A practical indicator is therefore needed. In regular head waves, the ship responds through added resistance, heave, and pitch (Salvesen, Tuck & Faltinsen 1970). Pitch is of special interest because it is a key longitudinal response and is easier to measure than resistance. Experimental observations for the KVLCC2 model show that both added resistance and pitch vary systematically with wavelength relative to ship length (Fournarakis, Papanikolaou & Liu 2017; Moctar, Sigmund & Schellin 2017). This creates the basis for using pitch as an indirect source of resistance information. The objective of this study is to assess whether pitch motion can be used as an indirect estimator of ship resistance in regular head waves. Added resistance denotes the mean increase in resistance in waves relative to calm-water resistance, whereas resistance-increase denotes the time-varying instantaneous resistance signal analysed in time and frequency domains.

2 METHODOLOGY

The study is based on towing-tank experiments for a KVLCC2 tanker model, conducted in accordance with ITTC (2002). The model scale factor was 110. It was tested in a towed configuration, without rudder and propeller, and was free in heave and pitch. The measured quantities were surge force, pitch, heave, wave height, and speed. The tests were performed in regular head waves for a range of wavelength ratios λ/L_{pp}. Added resistance was evaluated from the difference between mean resistance in waves and mean resistance in calm water. Motion amplitudes were obtained from the analysed time series, and Fourier analysis was used for the spectral evaluation. In the time domain, resistance and pitch histories were compared in terms of amplitude development and relative timing. In the frequency domain, dominant frequency components and relative phase behaviour were compared.

3 RESULTS AND DISCUSSION

The results show that both resistance-increase and pitch motion depend strongly on wave conditions. In the present tests, the largest increase in resistance occurs when the wavelength is comparable to the ship's length. This is consistent with earlier studies on added resistance in waves (Liu & Papanikolaou 2016; Fournarakis, Papanikolaou & Liu 2017; Moctar, Sigmund & Schellin 2017). Pitch response also changes strongly in the same range. This is consistent with the known distinction between short-wave and long-wave mechanisms of added resistance (Liu & Papanikolaou 2016). Figure 1 shows the wavelength dependence of the mean added-resistance increment and mean pitch response obtained from the model tests.

The main result is the consistency between pitch and resistance. This is first visible in the amplitude trend. When the wave condition approaches the critical range, resistance increases markedly and pitch response becomes more pronounced. A more direct confirmation is obtained from the time-domain analysis of instantaneous resistance-increase and pitch motion (see Figure 2). The two signals show comparable oscillatory development under the same excitation. This observation is consistent with the correlation between instantaneous resistance increase in waves and ship motion reported by Ghaemi, Zeraatgar & Bozorgmehr (2025).

The similarity is visible in signal amplitude evolution and relative timing. This is important for practical estimation. The frequency-domain analysis further confirms this relation. Pitch and resistance are responses to the same regular wave excitation. Their spectra contain corresponding dominant components. The dominant first-harmonic frequencies of pitch motion and instantaneous resistance increase vary systematically with wavelength and follow the same decreasing trend as the encounter frequency. This is consistent with the general relation between encounter frequency and wave-induced ship response (Salvesen, Tuck & Faltinsen 1970).

For the analysed cases, the deviation between encounter frequency and dominant response frequency remains below 5%, which further supports the dynamic consistency between the two signals. Pitch should not be treated as a perfect one-to-one substitute for resistance in all conditions. It is a measurable proxy variable that contains useful resistance-related information and can support indirect resistance estimation in a physically meaningful way. This is relevant for ship operation, because a better estimate of resistance may improve the matching between propulsion response and actual sea load.

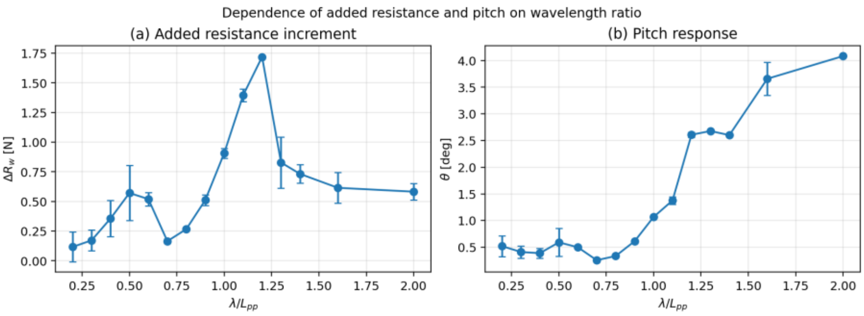

Figure 1. Dependence of added-resistance (mean increment) and pitch response on wavelength ratio for the KVLCC2 model in regular head waves.

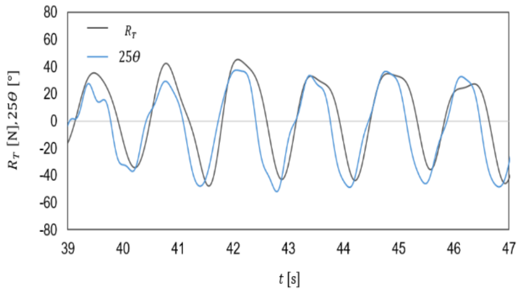

Figure 2. Example of time-domain consistency of resistance-increase and pitch for a selected regular head-wave condition.

4 CONCLUSIONS

The study shows that pitch motion and resistance-increase in regular head waves respond consistently to changing wave conditions. This consistency is visible in amplitude change, time-domain signal behaviour, and frequency-domain response. These results indicate that pitch motion contains useful information on ship resistance state and may be used as a practical signal for indirect resistance estimation.

Future work should quantify this relation more precisely and integrate the method into control or onboard decision-support systems.

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Comparative study on prediction of added resistance for energy-efficient ship operation

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Extended Abstract

Added resistance significantly influences the prediction of propulsion power and the overall energy efficiency of ships. Recent discussions at the International Maritime Organization (IMO) have led to the introduction of the Energy Efficiency Design Index (EEDI) as a metric to quantify greenhouse gas emissions from ships and to regulate their reduction. Consequently, ship designers are required to develop optimized hull forms that minimize resistance in ocean waves, making the prediction of added resistance a critical aspect of ship design. This study systematically investigates the added resistance problem using both classical analytical approaches and modern numerical methods. Maruo (Marau, 1963)introduced a far-field approach based on momentum conservation in the early 1960s. In the 1970s, Salvesen (Salvesen) introduced strip theory, which enabled accurate prediction of ship motions in waves and, consequently, added resistance. Zakaria et al. (Zakaria, 2008) applied three-dimensional numerical methods to estimate added resistance for a Series 60 hull and a full-form bulk carrier, achieving reasonable accuracy for slender hulls but notable discrepancies for fuller forms at low Froude numbers, particularly in short waves. Orsic et al. (Orsic, 2012) predicted the speed loss due to added resistance and associated CO2 emissions in a seaway for a container ship using both Faltinsen and Salvensen's methods. More recently, Wang et al. (Wang, 2021) validated the SHOPERA-NTUA-NTU-MARIC (SNNM) method, which was developed using regression analysis of 1,477 experimentally added resistance datasets obtained from eight institutions. The present study compares analytical methods, namely Maruo's and Salvensen's, with modern Computational Fluid Dynamics in OpenFOAM for two different hull forms KCS and KVLCC2, the particulars of which are mentioned in Table 1.

Table 1: Principal Particulars of the vessels

Specification	Symbol	Full Scale (KCS)	Model Scale (KCS)	Full Scale (KVLCC2)	Model Scale (KVLCC2)	Unit
Length between perpendiculars	L_{PP}	230.00	6.0702	320	5.517	[m]
Maximum beam of waterline	B_{Max}	32.20	0.8498	58.0	1.000	[m]
Depth	D	19.00	0.5067	30.0	0.517	[m]
Draft	T	10.80	0.2850	20.8	0.359	[m]
Block Co-efficient	C_B	0.6505	0.651	0.810	0.810	--
Wetted surface area	S_W	9424.0	6.6177	27194	8.084	[m^2]
Scale	λ	1:1	1:37.89	1:1	1:58	--

When the ship moves through the waves, it causes involuntary speed loss. To maintain such service speed, the ship needs to increase its power. The expression of added resistance and the added resistance coefficient are given by the following equations (1) and (2).

$$R_{AW} = \bar{R}_{wave} - R_{calm} \tag{1}$$

$$C_{AW} = \frac{R_{AW}}{\rho g \zeta^2 B^2 / L} \tag{2}$$

The obtained results are compared with experimental data in Figure 2 and Figure 3 for KCS and KVLCC2 hulls, respectively, to evaluate the accuracy, consistency, and applicability of different methods for practical ship performance assessment, and to examine their potential impact on power prediction.

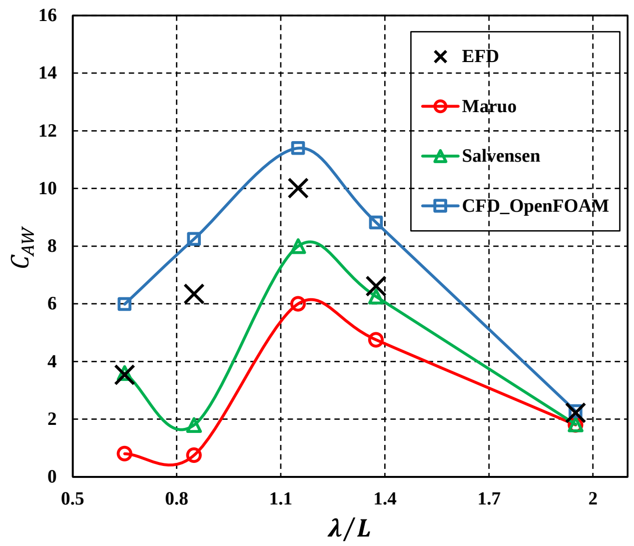


Figure 1: Comparison of added resistance coefficient among different methods (KCS).

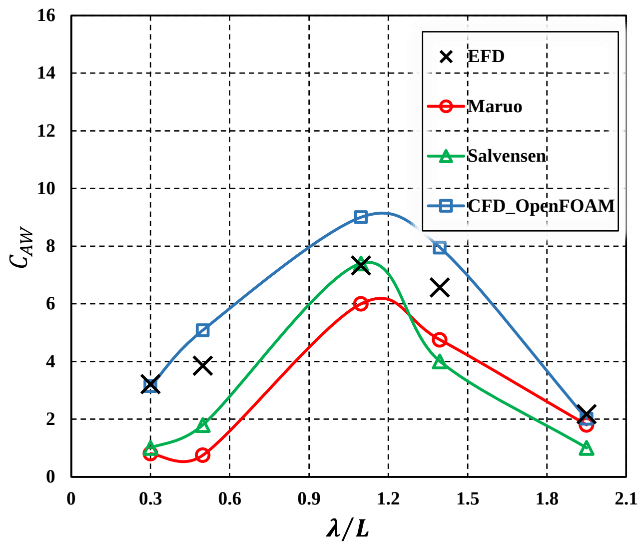
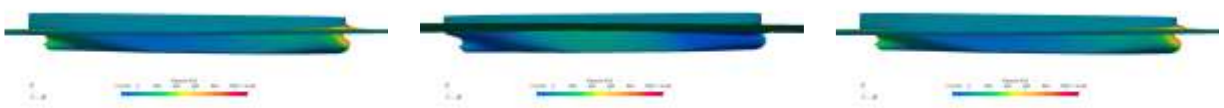


Figure 2: Comparison of added resistance coefficient among different methods (KVLCC2).

Accurate prediction of added resistance is not only important for powering performance but also for seakeeping analysis. The bow slamming event for KVLCC2 hull is shown in Figure 3.



t/Te = 0 t/Te = 0.50 t/Te = 1.00

Figure 3: Bow slamming event captured by CFD simulations around an encountering interval.

Computational fluid dynamics is gaining its popularity for dealing with non-linear complex problems like multiphase flows and ship wave interaction. However, the accuracy is limited to the solution algorithm order, the free surface treatment technique and grid resolution. The study reveals that analytical methods are limited in their ability to predict added resistance, particularly at short wavelengths, especially for a blunt hull form like KVLCC2; for a finer hull form like KCS, the overall results are satisfactory. On the other hand, the CFD results exhibit reasonable accuracy across both short and long wavelengths and are consistent across hull forms, though the results are over-predicted due to limited computational power. The results of the study support a better understanding of the suitability of different methods during the early stage of ship design, which may provide useful insights for energy-efficient ship operation and performance optimization.

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A combined PyGeM–OpenFOAM framework for ship hull dataset generation

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1 INTRODUCTION

The 2023 revision of the International Maritime Organization's greenhouse gas strategy has introduced stricter standards, underscoring the need to improve energy savings in the shipping sector. Hull optimization therefore represents a promising strategy for improving efficiency. In recent years, Machine Learning (ML) and AI methods have been explored to accelerate design through rapid performance prediction and exploration of new design spaces. Applications include performance prediction in (Ao et al., 2023), where datasets are generated using Free-Form Deformation (FFD) combined with panel method. Generative design approaches have also been proposed, such as in (Khan et al., 2023) and (Bagazinsk & Ahmed, 2023), where hull geometries are generated through parametric modifications and evaluated using potential flow solvers. However, these approaches strongly depend on reliable datasets.
In this work a geometric approach based on FFD is coupled with RANS simulations to obtain a complete dataset including both geometric and hydrodynamic data. The framework can be applied to different hull types and provide a basis for hull form generation and optimization using Generative AI models.

2 METHODS

2.1 *Geometry Deformation*

The dataset of hull geometries is generated using the open-source Python library PyGeM (Tezzele & all, 2021). FFD works by placing a cage around an object and defining several control points. By moving selected control points, the geometry inside the cage is smoothly deformed. The details of this process can be found in (Giovannini & Dashtimanesh, 2026). The selection of active control points and deformation parameters is a key step. For this reason, we are working to automate that with machine learning algorithms.

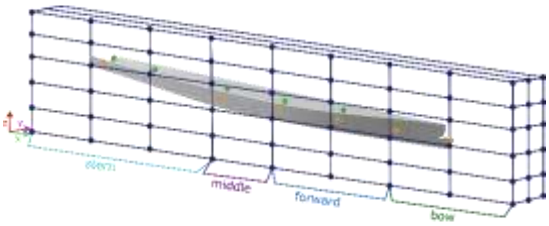

Figure 1. Cage around the hull.

2.2 *CFD Simulation*

Hydrodynamic simulations are performed using the open-source CFD software OpenFOAM v2412. The solver interFoam is used, employing a two-phase Volume of Fluid (VOF) approach to capture free-surface effects. The flow is modeled using RANS SST k–ω. The ship is simulated in a fixed position (0DOF) to reduce computational cost for large-scale dataset generation. A local time-stepping approach is applied, with a maximum Courant number equal to 1. The domain includes a velocity inlet, outlet boundary, and no-slip hull walls conditions. A pressure boundary condition is imposed at the top boundary to represent the free surface. The mesh is unstructured, with local refinement near the hull.

3 CASE STUDY AND RESULTS

The proposed methodology is applied to the KRISO Container Ship (KCS), whose main characteristics are reported in Table 1.

An example of a deformed hull is shown in Figure 4. The Euclidean distance between the original and modified geometry is represented using a color scale, where blue indicates minimal deformation and red indicates the maximum displacement. The modifications remain relatively small to preserve the global hull shape.

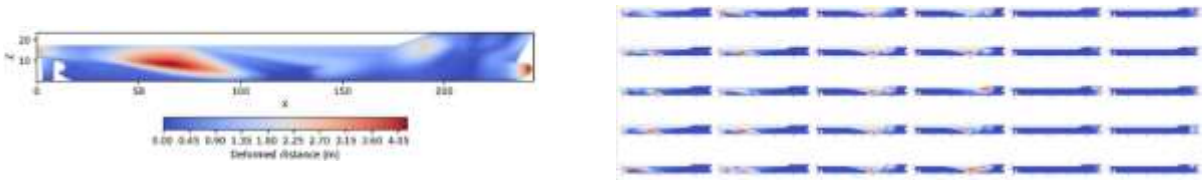

Figure 2 a) & b): Euclidean distance between original points and deformed hull.

For CFD validation, the KCS hull is scaled with factor 31.599. The experimental resistance coefficients from Kim et al. (2001) are used for evaluation. The comparison between experimental and numerical results of the total resistance coefficient C_T and the residual resistance coefficient C_R in Table 2 shows reasonable agreement. This confirms the suitability of the CFD setup for dataset generation, with a relative error of 2.63%.

Table 1. KCS parameters.

Items	
Type	Container ship
Length	230.0 m
Breadth	32.2 m
Depth	19.0 m
Block coefficient	0.651

Table 2. Comparison between Experimental results and simulation.

Items	EFD	CFD simulation
C_T (x10^3)	3.56	3.65
C_R (x10^3)	0.73	0.68

However, some improvements are still required. In particular, the computed y+values are approximately 310, which is slightly higher than the recommended range for wall-function approaches (typically 30–300). This may affect the accuracy of the boundary layer resolution and, consequently, the resistance prediction.

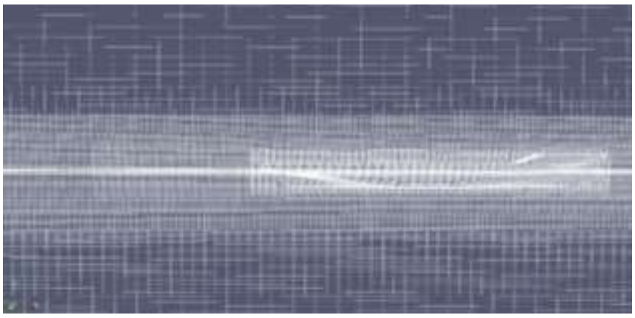

Figure 1. Mesh resolution of the hull.

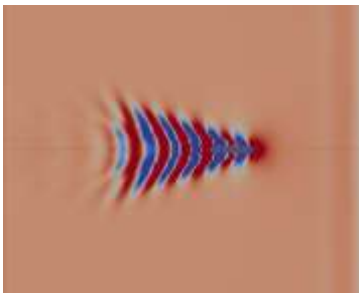

Figure 2. Visualization of wave field.

4 CONCLUSION

This study shows a method for generating a large set of different hull forms with reasonable computational cost. The generation of approximately 700 different hulls, considering different combinations, requires about ten minutes, making it an efficient approach for large-scale dataset creation.
Once the CFD setup is validated for the reference hull, the same configuration can be applied to all the deformed geometries. This enables the generation of datasets containing both geometric and hydrodynamic data, which can be used to train machine-learning models for hull generation and resistance prediction.

Future work will focus on identifying the deformation parameters that most influence ship resistance and on developing a generative AI tool for hull generation and optimization.

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Spectral characteristics of propeller torque in CFD simulations using polyhedral grids

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1 MOTIVATION

The hydrodynamic characteristics of a ship propeller in a seaway differ in many respects from those in calm water. As the ship heaves and pitches in waves, the propeller advance coefficient varies continuously, and the non-uniform wake inflow imposed by the hull produces periodic blade loading, that can be seen at the shaft frequency and its harmonics. Resolving this frequency content in CFD requires a propulsion model capable of explicitly representing propeller rotation which is in contrast with often employed body force (actuator disk) methods. At the same time, the choice of mesh topology in the vicinity of the propeller is known to influence both the accuracy of the mean force prediction and the fidelity of the captured flow structures. Polyhedral cells, with their inherent non-uniform discretization method are unjustly considered as a sub-ideal choice for rotating geometries in CFD. Therefore, the aim of this work is to examine the spectral characteristics of the propeller torque signal as predicted by a high-fidelity CFD model employing polyhedral discretizaton.

2 NUMERICAL FRAMEWORK

All simulations are performed within the open-source CFD toolbox OpenFOAM (Weller et al (1998.)). The governing equations are the incompressible Navier–Stokes equations, closed with the k-ω SST turbulence model. The air-water interface is resolved using the Volume of Fluid (VOF) method with the isoAdvector interface advection scheme (Roenby et al (2016.)). Six-degree-of-freedom (6-DOF) rigid body motion is coupled to the fluid solver with constraints on sway, yaw, and roll, allowing the ship to heave and pitch freely in waves. Propeller rotation is modelled using the Coupled Sliding Mesh (CSM) approach, a method developed and implemented in OpenFOAM that couples the prescribed rotating motion of the propeller with the 6-DOF hull response. The CSM model uses the Arbitrary Mesh Interface (AMI) for face-based field interpolation between the rotating propeller region and the deforming outer mesh, combined with a morphing mesh approach to accommodate hull motion. This avoids the volumetric interpolation errors associated with overset (chimera) methods, which are known to introduce mass imbalances that can corrupt unsteady force signals (Lemaire et al (2023.)). The propeller geometry is fully discretized using polyhedral cells, with the time step constrained to resolve a propeller rotation increment of 1°–5° per iteration.

3 TEST CASE AND EXPERIMENTAL REFERENCE

The Duisburg Test Case (DTC) Post-Panamax container ship hull is used as the benchmark (Rabliås et al (2022.), Rabliås (2022.), Shigunov et al (2012.)). Model tests were carried out at SINTEF Ocean, Trondheim, at a scale of 1:63.65. The model operates in free-running mode with an autopilot, fitted with a five-bladed fixed-pitch propeller and a twisted rudder with a Costa bulb. Propeller thrust and torque are recorded via a dynamometer, and rigid body motions are tracked with an Oqus optical positioning system. The calm-water self-propulsion point is established at a propeller rate of 11.5 rpm and a model speed of 1.03 m/s. Wave experiments are conducted at constant propeller revolution rate across three regular head-wave conditions, covering wave steepness ratios H/L_{pp} of 0.011, 0.016, and 0.020, and encounter wavelength-to-ship-length ratios λ_e/L_{pp} of 0.187, 0.303, and 0.460.

4 RESULTS

The numerical results presented here were previously reported in (Sulovsky et al (2026.)). Calm-water self-propulsion results on two polyhedral grid densities confirm the baseline accuracy of the CSM model. Thrust predictions of 14.965 N (coarse) and 14.321 N (fine) compare against the experimental value of 14.126 N, while torque predictions are 0.327 Nm and 0.311 Nm against 0.323 Nm. In both cases, total resistance and propeller thrust agree to within 1%, confirming that the self-propulsion point is correctly captured. The polyhedral discretization resolves the swirling propeller slipstream in detail, providing a physically consistent inflow field for the unsteady wave simulations. In the wave simulations, the torque signal is analysed in the frequency domain to identify the dominant spectral components. The torque spectrum reflects contributions from multiple physical sources: the encounter frequency of the waves, the shaft rotation frequency and its blade-rate harmonics, and cross-coupling between wave-induced motion and propeller loading.

5 CONCLUSIONS

The CSM model on polyhedral grids provides a robust framework for extracting spectral characteristics of propeller torque in regular head waves. The combination of face-based AMI interpolation, morphing mesh hull motion, and polyhedral cell topology in the propeller region demonstrates good accuracy for mean force prediction and captures the multi-frequency nature of the torque signal in a seaway. The results highlight the capability of the polyhedral grid type for resolving high-frequency blade-rate content and underscore the importance of using a geometry-resolving propulsion model when unsteady loading is the quantity of interest. Future work will extend the analysis to irregular waves and examine the influence of propeller geometry fidelity on the predicted spectral content.

ACKNOWLEDGMENTS

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Real-time simulation for feasibility assessment of a charging station at the North Sea

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Extended Abstract

The EU MAGPIE project aims to take action to accelerate the introduction of green energies and logistic optimisation through automation and autonomous operations in ports. A living lab approach is applied in which 12 technologies are developed or demonstrated and non-technological innovations are developed. The combined results feed into the masterplan for the European green port of the future, aiming at full decarbonisation by 2050.

Under the work package 5 (WP5) of the project, Bluewater (a consortium partner) has designed an offshore e-charging solution involving a fixed tower in the North Sea. The proposed operation involves an electrically propelled Service Operations Vessel (e-SOV) arriving to an e-Tower (similar to a tower loading unit), located nearby a wind farm in the North Sea. Upon arrival, deck personnel onboard the vessel will have to pick-up the messenger lines and connect the hawser and charging cable. Considering the manned operation, the environment and motions at the bow of the vessel will largely determine the safe operability limits. Considering the prolonged charging period, crew comfort at the bridge is also of interest.

The validate this innovative concept, MARIN, together with Bluewater and Van Oord (other consortium partners), performed a 3-day simulation campaign at its Seven Oceans Simulation centre to assess feasibility of the operation and investigate safe operability limits.

Figure 1: Visual representation of the operation from the simulator.

For a sound numerical model in the simulator, the vessel model was generated using a combination of frequency and time domain calculations. The vessel was modelled with linear hydrostatics, with the Froude Krylov and 1st and 2nd order wave excitation forces coming from a frequency domain solution. The resistance and manoeuvring model for the vessel was generated using data generated from a scaled model experiment performed at one of MARIN's model basins. Wind coefficients for the vessel were taken from wind tunnel test results for a similar vessel. In the simulations, the waves were modelled as sea and swell components, generated using JONSWAP spectrum. The wind was modelled using Davenport spectrum. The current was modelled as a constant vector field. The area was modelled with a constant depth of 35m.

During the simulations, the e-SOV bridge was set up at the Large Motion Simulator (LMS) of MARIN, with an active motion base. For simulating deck operations, a VR setup was deployed in the mixed reality Lab, placing the deckhand virtually on the bow of the e-SOV. In some simulations, the vessel was also operated from a multi-purpose bridge simulator without a motion base, while deck operations were simulated on the LMS with motion base active.

During the simulations, the captain focused on manoeuvring the vessel into position, while the deckhand provided guidance from the deck (bow/mooring deck) to ensure accurate alignment for messenger line reception. The deckhand was visible to the captain as an avatar on the fore deck. Once near the e-Tower, continuous communication was maintained between bridge and the deck. The deckhand walked through all operational steps, including confirming hawser and electrical line connections. These actions were animated in the simulation, showing the steady lowering and winching of lines, following the expected duration. While physical tasks like grabbing the messenger lines were not performed, all procedural steps were followed to ensure compliance.

During the 3-day simulation campaign, 19 simulations were performed with varying weather conditions. Among them, 13 were arrival runs, 4 departure runs, and 3 emergency runs with departure scenarios. Evaluations were performed both in terms of vessel manoeuvring capabilities, and human safety and comfort for involved bridge and deck operation.

The results suggest that for the simulated conditions, the studied e-SOV proved to have sufficient power to perform arrival, residence (charging), and departure manoeuvres safely. Considering only the manoeuvring aspect, almost all runs were commented as safe by the simulator instructor and the captain. Considering the NORDFORSK criteria, vessel motions and accelerations also remained below limit in all studied conditions. From the human factor side, the captains did not mention discomfort at the bridge due to large motions. However, the deck personnel expressed some discomfort with increasing severity of weather.

The chosen simulation set-up was instrumental in finding the safe limits for the operation and allowed for good cooperation between bridge and deck-team. With a focus on human operations, the simulation campaign helped in identifying key operational aspects for human cantered design. Along with validating the concept, the simulator study also helped in building experience with the process, which should prove helpful after the system has been built.

Comparative assessment of container and bulk carrier performance and CO_2 emissions in actual seaways

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Extended Abstract

Shipping accounts for approximately 3% of global CO_2 emissions, while transporting more than 90% of global trade (EU Emission Report, 2020), and the total number of ships in operation continues to increase. Increasing regulatory and societal pressure to reduce greenhouse gas (GHG) emissions from maritime transport has intensified the need for improved hull designs, enhanced energy efficiency, and optimized operational strategies. In this context, the reliable prediction of ship performance in actual sea conditions is essential for both economic efficiency and environmental sustainability. In this study, a numerical modelling framework developed by Prpić-Oršić & Faltinsen (2012) and Prpić-Oršić et al (2016) is applied to two merchant ship types, a container ship and a bulk carrier, to enable a comparative assessment of attainable speed, involuntary and voluntary speed losses, fuel consumption, and carbon dioxide (CO_2) emissions under identical environmental and operational conditions.

A ship's performance under operational conditions is significantly affected by real weather environments. Key influencing factors include wind speed and direction, significant wave height, wave period, wave heading, initial ship speed, and vessel-specific characteristics such as principal dimensions, hull geometry, windage area, and loading condition. While ship speed/resistance, propulsion performance, and propeller characteristics are typically estimated under calm water conditions, actual operations expose vessels to a wide range of sea states where environmental effects substantially alter performance. In particular, added resistance in waves arises primarily from wave generation and ship-wave interactions, and is strongly influenced by ship motions. Consequently, accurate prediction of ship motions is essential for reliable estimation of added resistance. The ability of a vessel to maintain speed in a seaway therefore represents a key consideration in ship design and performance assessment.

As sea conditions become more severe, deviations from calm water performance increase. In mild sea states, speed loss is mainly associated with additional resistance due to wind and waves. However, in rough weather, ship safety becomes a dominant concern, and a wider range of dynamic effects must be considered. These include increased propulsion loading, reduced propeller and engine efficiency, and phenomena such as propeller ventilation, which may occur due to large-amplitude motions, shallow propeller submergence, or unfavorable loading and trim conditions. Furthermore, ships may experience excessive accelerations, slamming, green water on deck, propeller racing, and large roll motions, all of which can compromise operational safety. In such situations, the ship master may voluntarily reduce speed or alter course to mitigate these effects. Although modelling such decisions is explicitly challenging, they can be incorporated into a numerical framework through limiting criteria that define safe operating conditions. Within this context, the instantaneous ship speed is determined by accounting for propeller and engine performance in waves, as well as ship inertia, under constant propeller torque conditions.

The numerical framework employed in this study integrates nine interconnected modules to simulate ship performance, fuel consumption, and CO_2 emissions in realistic sea conditions. These modules address key components including calm-water resistance, propeller characteristics, environmental modelling (wind and waves), ship motions and loads, relative motions, added resistance, and propeller ventilation effects. Accurate prediction

of ship performance in a seaway therefore relies on the consistent and reliable integration of all these contributing factors.

The framework accounts for both involuntary speed losses, due to increased resistance from wind and waves, and voluntary reductions imposed to avoid critical dynamic effects such as excessive motions, slamming, deck wetness, and propeller racing. Irregular sea states are represented as a sequence of regular waves with varying amplitudes and frequencies. A selected wave spectrum is first used to generate a time-domain wave trace for a given sea state, which is then decomposed into individual regular waves using a zero up-crossing method. Ship motions and loads in these regular waves are computed using strip theory. Total resistance is evaluated as the sum of calm water resistance, added resistance in waves, and wind resistance. The latter is estimated using Blendermann's approach, with wind represented as a combination of steady and gust components, while added resistance is calculated using either direct pressure integration or asymptotic formulations (Faltinsen et al., 1980).

Propulsion is modelled by coupling engine and propeller characteristics. The main engine is represented as a zero-dimensional model based on interconnected control volumes, enabling estimation of time-dependent fuel consumption and CO_2 emissions. Propeller performance is derived from B-series characteristics, accounting for wake effects and thrust deduction, while ventilation-induced thrust losses are incorporated using empirical models based on experimental data (Smogeli, 2006). The instantaneous ship speed in each wave is obtained from the equilibrium between thrust and total resistance, accounting for inertia and thrust losses. Time domain simulations over each wave period are performed using a fourth order Runge-Kutta method Prpić-Oršić & Faltinsen (2012).

The framework is applied to two merchant ship types: a container ship (length 175 m, breadth 25.40 m, draft 9.5 m) and a bulk carrier (length 160.4 m, breadth 27.20 m, draft 9.82 m). Although similar in principal dimensions, these vessels differ in hull geometry and operational characteristics, enabling a direct assessment of the influence of ship type on performance and emissions. Environmental conditions are defined using the ITTC two-parameter wave spectrum, with long-crested waves and aligned wind and wave directions. Wave headings range from following seas (0°) to head seas (180°). Simulations are conducted for both vessels in full-load condition across sea states with significant wave heights between 1 and 12 m, over a duration of 3 hours. To ensure consistency, both ships are evaluated under identical initial operating speeds, despite differences in their design service speeds. Time series of attainable ship speed are obtained for each sea state, accounting for both voluntary and involuntary speed losses. Mean values of speed reduction are then determined over the simulation period. Based on these results, fuel consumption per unit distance and corresponding CO_2 emissions are estimated under constant engine torque conditions. Emission factors are taken from EMEP/CORINAIR guidelines (EMEP/CORINAIR, 1999).

The presented comparative analysis demonstrates the capability of the numerical framework to consistently evaluate ship performance, fuel consumption, and emissions across different merchant ship types under realistic environmental conditions. By applying the model to vessels with similar principal dimensions but distinct hull characteristics, the study highlights the influence of ship type on operational efficiency in a seaway. The results confirm the robustness and versatility of the framework, supporting its application for performance assessment, design evaluation, and emission studies beyond a single reference vessel.

ACKNOWLEDGEMENTS

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Working Group 3 on Operation of ship propulsion systems with alternative fuels

Assessing global atmospheric emissions from shipping: A meta-review and best practices for future work

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Extended Abstract

1 INTRODUCTION

Shipping-related air pollution, which accounts for approximately 2–3% of global greenhouse gas (GHG) emissions depending on the scope and methodology applied, has increasingly become the subject of focused attention by the international shipping community and regulators. Global emission inventories are needed to quantify, compare, and track emissions from shipping worldwide, support climate and air quality modelling, inform international policy, and assess the health and environmental impacts of maritime activities.

This paper presents a meta-review of the existing literature reviews on ship emissions, with a primary emphasis on global emission inventories, as these are relevant to the discussion on Climate Change.

The rest of the paper is organized as follows. Section 2 directs the reader to the main systematic literature reviews on ship emission inventories and discusses, in separate subsections, the emission estimates reported by the International Maritime Organization (IMO) and the Intergovernmental Panel on Climate Change (IPCC). Section 3 concludes by outlining potential extensions and additional applications of ship emission inventories.

2 GLOBAL EMISSION INVENTORIES AND PROJECTIONS

A substantial body of literature has examined methods for estimating shipping emissions. In this section, we highlight key review studies that synthesize this literature, with a particular emphasis on global emission inventories. While individual studies are not discussed in detail here, it is worth noting that global ship emission inventories were reported as early as 1997. Corbett and Fischbeck (1997) presented global estimates of NOx and SOx emissions (excluding CO_2), reflecting their relevance to air quality and the fact that these pollutants were already central to discussions at the IMO. Most early studies (e.g., Corbett and Fischbeck, 1997) primarily employed top-down approaches, relying largely on international marine fuel consumption statistics published by the U.S. Energy Information Administration (EIA). The relevant studies have examined in various review studies; the interested reader is referred to the below for more details. Miola and Ciuffo (2011) provided a comprehensive meta-analysis of both top-down and bottom-up modelling approaches and the data sources used in early shipping emission studies. Their analysis highlighted the uncertainties associated with different methodologies and attributed these uncertainties to variations in input data quality and availability. Most recently, Yan et al. (2025) presented an extensive review of 78 academic studies published between 2009 and 2024, with a particular focus on inventories using AIS data as the primary data source.

3 GLIMPSE INTO THE FUTURE OF GLOBAL EMISSION INVENTORIES

The review studies discussed in Section 2.1 highlight several persistent challenges in ship emission modeling. Many of these challenges are expected to be progressively addressed through improvements in modeling techniques, and, critically, the systematic validation and calibration of emission models using real-world datasets such as those provided by the EU MRV and the IMO Data Collection System (DCS).

The Terms of Reference for upcoming IMO studies (see Section 2.3) further identify key priorities for future work. A central requirement is the comprehensive calculation of all relevant greenhouse gas (GHG) emissions from shipping, but also other pollutants. In this context, the increasing uptake of alternative fuels such as ammonia, methanol, and hydrogen necessitates explicit consideration of associated non-CO_2 emissions and fuel-specific slips, including methane (CH_4) and nitrous oxide (N_2O). In addition, hydrogen fuel use may be associated with hydrogen slip; while hydrogen itself is not a greenhouse gas, it exerts an indirect warming effect through atmospheric chemical interactions.At the same time, ship emission inventories have long quantified emissions of sulphur oxides (SO_x) and nitrogen oxides (NO_x), which, although not greenhouse gases, have well-established impacts on the climate system. This climate interaction has been widely discussed in the literature (e.g. Sofiev et al., 2018; Kontovas, 2020). Against this background, we recommend that future ship emission inventories aim to quantify as broad a range of relevant emissions as possible, including both greenhouse and non-greenhouse species. This should include the calculation of well-to-wake emissions, as increasingly emphasized in policy discussions, as well as an assessment of the total climate impacts of different emission species.

3.1 Future Elements: Beyond emissions

One might argue that, as increasingly accurate operational data become available, the need for emission inventories will diminish. For example, the IMO DCS provides reported fuel consumption data (note here: reported and not real) that, in principle, could be used directly to estimate emissions without relying on modeling. While such datasets represent a major improvement over earlier assumptions-based approaches, this view overlooks several fundamental reasons why ship emission inventories (and ship activity models more broadly) remain essential.

First, emission inventories are indispensable for future-oriented analysis. Reported data describe historical or current conditions, whereas inventories embedded within activity-based models allow emissions to be projected under alternative future scenarios. These models are built on transparent assumptions that can be systematically adjusted to assess the effects of changing market conditions, fleet evolution, fuel/energy pathways, operational measures (such as speed optimization and WASP), and policy interventions. Examples include the evaluation of regional measures such as the EU Emissions Trading System (EU ETS), fuel carbon intensity standards (FuelEU or IMO GHG Fuel Intensity), and other market-based measures (i.e. regional or global “taxes”). Without emission inventories, it would not be possible to consistently explore counterfactual scenarios or assess the long-term impacts of prospective regulations.

Second, emission inventories enable detailed spatiotemporal characterization of shipping emissions, which cannot be derived directly from aggregated reporting systems such as the IMO DCS. Ship activity models are required to allocate emissions geographically and temporally—at the level of coastal zones, ports, or sensitive regions such as the Arctic. They also allow emissions to be differentiated by voyage type such as international versus domestic shipping. This spatial and temporal resolution is, more importantly, essential for air quality modeling, as dispersion and chemical transport models require geographically resolved emission inputs to simulate pollutant concentrations accurately.

Furthermore, equity and distributional analysis and integrated assessment modeling also rely critically on ship emission inventories. Spatially resolved inventories make it possible to assess how the environmental and health impacts of shipping emissions are distributed across countries, regions, and population groups, including coastal and port communities, developing countries or Small Island Developing States (SIDS), that may experience disproportionate consequences despite limited economic benefits from maritime transport. In addition, ship emission inventories provide essential inputs to integrated assessment models (IAMs), where they are used to represent the maritime sector within economy–energy–climate systems. In this context, inventories support the evaluation of long-term decarbonization pathways, interactions between shipping and other sectors, and the economy-wide implications of alternative climate and air pollution policies.

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Evaluating e-fuel pathways in fishing vessels from a well-to-wake life cycle perspective

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Extended Abstract

The maritime sector supports a broad range of economic and social functions yet remains predominantly dependent on conventional fossil fuels. The combustion of Marine Diesel Oil and Heavy Fuel Oil leads to significant greenhouse gas (GHG) and air pollutant emissions, contributing to climate change and environmental pollution, particularly in coastal regions (Kanchiralla et al., 2022). In response, international and regional regulatory frameworks, including International Maritime Organization (IMO) Revised GHG Strategy (2023), increasingly promote the transition toward zero and near-zero GHG fuels and well-to-wake (WTW) GHG accounting approaches (International Maritime Organization, 2023). Among the available options, electrofuels (e-fuels) are increasingly considered a promising solution for reducing GHG emissions. These fuels are produced using electricity as the primary energy input, through hydrogen production via electrolysis followed by fuel synthesis. Their environmental performance depends primarily on upstream production processes, including carbon intensity of electricity, carbon dioxide (CO_2) sourcing, conversion efficiency and synthesis-related energy demand (Roux et al., 2024). Therefore, a WTW life cycle assessment (LCA) approach, encompassing both well-to-tank (WTT) and TTW phases, is required to ensure methodological consistency and enable transparent comparison of fuel pathways.

Although not all regulatory instruments directly apply to fishing vessels, long-term decarbonisation targets increasingly influence the wider maritime sector (Perčić et al., 2023). Existing studies focus on large deep-sea vessels, leaving the fishing sector comparatively underrepresented (Sjerić et al., 2026). There is a lack of studies applying WTW LCA approaches to fishing vessels that explicitly account for vessel-specific operational characteristics. The Croatian fishing fleet represents a relevant case, with diverse vessel categories and operational practices. Purse seiners and bottom trawlers represent two dominant vessel categories, characterised by different operational profiles (Koričan et al., 2023). These differences highlight the need for an assessment framework tailored to fishing vessel operations. This study addresses this gap by developing a WTW LCA framework tailored to fishing vessel operations. As shown in Figure 1, the proposed framework evaluates conventional Marine Gas Oil (MGO) as a baseline alongside two e-fuel-based pathways, e-Fischer-Tropsch diesel (e-FT diesel) and e-methanol. Different upstream production scenarios are considered, reflecting variability in electricity supply (renewable and grid electricity mix) as well as CO_2 sourcing through carbon capture and utilisation (CCU) from an ethanol production plant and direct air capture (DAC), to assess their influence on overall WTW carbon intensity. The system boundaries include WTT processes covering electricity supply for hydrogen production via electrolysis, CO_2 capture and processing, fuel synthesis and upgrading, as well as transport and bunkering, and TTW combustion in the marine propulsion system, applied consistently to both e-methanol and e-FT diesel pathways. The analysis adopts consistent assumptions across fuel pathways, including identical engine efficiency, electrolysis efficiency and representative operational profiles, while electricity carbon intensity and CO_2 sourcing scenarios are treated as key drivers of WTW emissions. The analysis is based on literature-derived data and established LCA datasets (e.g. GREET) for modelling fuel production pathways and vessel operations. The assessment is applied to two representative fishing vessel categories, a purse seiner and a bottom trawler. The functional unit is defined as one fishing cycle, reflecting real operational conditions of fishing vessels. The primary impact category considered is climate change, expressed as CO_2-equivalent emissions. Indicative results show that WTW emissions are significantly reduced under renewable electricity and DAC-based e-methanol pathways, reaching approximately -48 kg CO_2-eq per fishing cycle for bottom trawlers and -59 kg CO_2-eq for purse seiners, corresponding to net-negative emissions relative to the MGO baseline. In contrast, scenarios based on grid electricity mix reduce these benefits, while differences between DAC and CCU pathways depend on the carbon source and system configuration, highlighting the dominant influence of electricity carbon intensity and carbon sourcing on overall WTW performance.

The framework is consistent with FuelEU Maritime and IMO WTW accounting principles, ensuring comparability with regulatory GHG intensity metrics. The results provide insights into practical implementation of e-fuels in fishing vessels, highlighting their compatibility with existing engine technologies, retrofitting potential and operational applicability. The objective is to provide a transparent methodological basis for assessing the climate mitigation potential of e-fuels within representative fishing vessel categories.

This research is conducted within the GREEN-FISH project, which aims to support the sustainable transition of the Croatian fishing fleet through integrated assessment approaches.

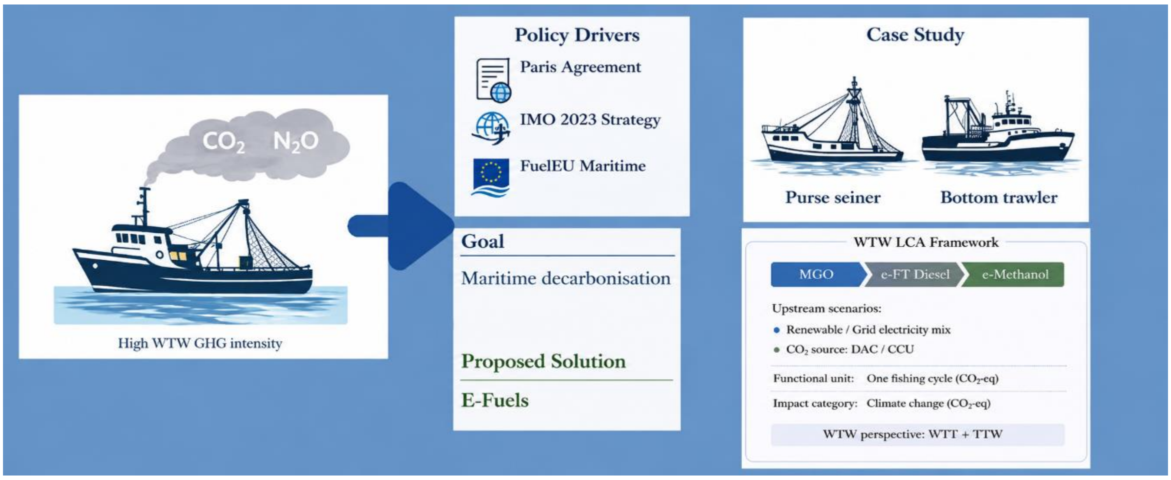

Figure 1. Conceptual framework for evaluating e-fuel pathways in fishing vessels under a WTW framework

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Nuclear propulsion for decarbonizing maritime transport: A SWOT analysis

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Extended Abstract

Maritime transport is the most efficient mode of transport in terms of cargo carried per unit distance traveled. However, the fuels commonly used in maritime transport, such as heavy fuel oil (HFO) and marine diesel oil (MDO), are low-quality fuels, which lead to the release of pollutant emissions and greenhouse gases. Currently, in addition to HFO and MDO, liquefied natural gas (LNG), liquefied petroleum gas (LPG), methanol, and biodiesel are used on ships. These fuels are alternatives to conventional fuels. Although these fuels have the potential to reduce emissions, they also have several drawbacks, including low energy density, limited bunkering infrastructure, and limited potential for emissions reduction. Maritime transport is transforming with the increasing use of alternative fuels on ships. Fuel production facilities, supply chain infrastructure, bunkering facilities, and alternative fuel technologies for ships have emerged over the course of this transformation. During the transformation of the maritime industry, nuclear power may be a viable option for decarbonizing maritime transport. This study focuses on the feasibility of nuclear power for civilian shipping by doing a SWOT (Strengths, Weaknesses, Opportunities, Threats) confrontation matrix analysis.

Nuclear power for civilian shipping is obtained from fissile materials, uranium isotope 235 (U-235), uranium isotope 233 (U-233), and plutonium isotope 239 (Pu-239) (DNV, 2025). U-235 is the only fissile isotope found in nature. U-233 is derived from thorium-232 (T-232), and Pu-239 is derived from U-238, which are fertile isotopes, in the nuclear reactor. The civilian shipping nuclear enrichment level is below 20%, and this is the only option for safe and secure maritime transport. However, mostly 3-5% enrichment, which is called low-enrichment, is enough for civilian shipping. For the new advanced reactor designs, the energy source will be High-Assay Low-Enriched Uranium (HALEU) with enrichment between 5% and 20% (LR, 2024). The new advanced reactors are named the Generation IV reactors. These reactors provide efficient operation, besides their compactness and reliable power for civilian shipping. The Generation IV consists of six technologies, which are the pressurized water reactor (PWR), gas-cooled fast reactor (GFR), lead-cooled fast reactor (LFR), molten salt reactor (MSR), sodium-cooled fast reactor (SFR), and very high-temperature reactor (VHTR) (EMSA, 2024). The most promising ones for merchant ships are PWRs, VHTR-based small modular reactors (SMRs), and MSR-based SMRs. PWRs have high maturity and proven reliability; on the other hand, VHTR- and MSR-based SMRs have extended refueling cycles, passive safety systems, waste-management advantages, and compact reactor designs. The propulsion system in a nuclear-powered ship can be either a mechanically driven steam turbine system, which is fed by steam from a boiler that receives heat from the reactor, or an electric propulsion system, in which a steam turbine-alternator couple generates electricity. Although there have been technological developments regarding the use of nuclear energy in maritime transport, several barriers may hinder its widespread adoption. These include high initial investment cost, insufficient technology readiness level for civilian maritime applications, high operational complexity, the lack of port infrastructure for nuclear energy, and the cautious public perception toward nuclear power. In Figure 1, the SWOT confrontation matrix sums up the strengths, weaknesses, opportunities, and threats of nuclear power in maritime transport. Equations (1) to (5) are used to calculate the feasibility index (FI) of nuclear power for the maritime industry. During the FI calculation, the confrontation points of -2 (very negative), -1 (negative), 0 (neutral), 1 (positive), and 2 (very positive) are given to each matrix combination.

$$S_{TOT} = S_O + S_T \quad (1)$$

$$W_{TOT} = W_O + W_T \quad (2)$$

$$O_{TOT} = O_S + O_W \quad (3)$$

$$T_{TOT} = T_S + T_W \quad (4)$$

$$FI = (S_{TOT} + O_{TOT})/(W_{TOT} + T_{TOT}) \quad (5)$$

Where S_O, S_T, and S_{TOT} are points of strengths perspective of nuclear power at opportunities, threats, and total points, respectively. W_O, W_T, and W_{TOT} are points of weaknesses perspective of nuclear power at opportunities, threats, and total points, respectively. O_S, O_W, and O_{TOT} are points at strengths, weaknesses, and total point of opportunities perspective, and T_S, T_W, and T_{TOT} are points at strengths, weaknesses, and total point of threats perspective.

		Opportunities						Threats						
		Decarbonization pressure and regulation	Competition constraints of alternative fuels	Advancement in reactor technologies	Standardization and modularization	Digitalization and automation	New business models	Regulatory uncertainty	Public perception and social acceptance	Safety and security risks	Geopolitical and fuel supply risks	Port access restrictions	Competing decarbonization technologies	Long development and deployment timeline
Strengths	New-zero emissions and decarbonization potential	2	2	2	2	2	2	-1	-2	-2	-1	-1	-1	-2
	High energy density	2	2	2	2	1	0	0	0	0	-1	0	-1	0
	Operational advantages	2	2	2	2	2	1	-1	-2	-2	-1	-1	-1	-1
	Long fueling intervals	1	2	2	2	0	0	0	0	-1	-2	-1	-1	0
	Compatibility with future energy systems	2	2	2	2	2	0	-2	-1	-2	-1	-1	-1	-2
	Potential long-term cost competitiveness	2	2	2	2	2	1	0	0	-1	-1	-1	-1	-1
					TOTAL		60					TOTAL		-41
Weaknesses	High capital expenditure	2	2	2	2	1	1	-1	-1	-2	-1	-1	-2	-2
	Technological immaturity for civilian shipping	1	1	2	2	2	0	-2	-2	-2	0	0	-2	-2
	Complex fuel cycle and waste management	1	1	2	2	1	1	-2	-2	-2	-1	-2	-2	-2
	High operational complexity	1	1	2	2	2	0	-1	0	-2	0	-1	-2	-1
	Limited port infrastructure	2	1	0	1	1	2	-2	-2	-2	-2	-2	-2	-2
	Insurance and liability challenges	0	0	1	2	2	2	-2	-1	-2	0	-1	0	0
					TOTAL		48					TOTAL		-60

Figure 1. SWOT confrontation matrix of nuclear power in maritime transport.

The strengths perspective of the SWOT confrontation matrix gets +19 points, while the weaknesses perspective receives -12 points. The opportunities and threats perspectives achieve +108 and -101 points, respectively. The FI is calculated as 1.124. Above 1 means nuclear power has a positive feasibility for the maritime industry. To increase the advancement and adoption of nuclear power in civilian maritime transport, the weaknesses would be improved, and threats to nuclear power, especially regulatory uncertainty, public perception and social acceptance, and safety and security risks, would be eliminated by the support and collaboration of maritime industry stakeholders. A radical transformation of the maritime industry is necessary for nuclear-powered ships.

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A holistic review of LNG-fuelled vessels from environmental, economic, technological, and regulatory dimensions for advancing net-zero maritime objectives

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Extended Abstract

Maritime transport accounts for approximately 2.9% of global emissions (European Commission, 2026), and numerous studies are being conducted to mitigate these emissions. switching the utilized fuel of ships' main engines at the forefront of such efforts. In the maritime industry, liquefied natural gas (LNG) currently represents the most extensively utilized fuel, within the transitional phase from conventional fossil fuels to alternative fuel solutions. The utilization of LNG for ship main propulsion systems has expanded exponentially over the last 15 years, and the number of 921 marine vessels and a wide range of ship types encompassing container ships, car carriers, crude oil tankers and more, have been powered by LNG (DNV, 2026). However, conventionally-fuelled vessels with 98.9% rates continue to dominate maritime transport despite the exponential increase in the number of LNG-fuelled vessels which rates will be 8.08% with the order ships in maritime shipping (DNV, 2026). This is because various obstacles and uncertainties still surround the use of alternative fuels in the ship propulsion system.

This study offers an in-depth examination of research conducted over the past two decades on the application of LNG as a fuel in ships, highlighting, identifying, and synthesizing the key issues from a holistic perspective, including environmental, economic, technological, and regulatory challenges. From an environmental perspective, methane slips and the life-cycle emissions of LNG constitute critical considerations, and measures need to be taken regarding greenhouse gas emissions (Pavlenko, Comer, Zhou, Clark, & Rutherford, 2020). Because, according to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, the Global Warming Potential (GWP) values of methane are 29.8 times higher than those of carbon dioxide (CO_2) (Muñoz, Schmidt, & Weidema, 2024). Furthermore, if green and environmentally friendly methods are not followed during the LNG production phase, life-cycle emissions will reach levels higher than those from conventional fuels (Al-Douri et al., 2022). From an economic perspective, the cost of LNG is relatively higher than compared to conventional fuels. At the beginning of 2026, the unit price of LNG for Rotterdam port is 626.0 $/mt, while the prices for Intermediate Fuel Oil (IFO)-380, Marine Gas Oil (MGO), and Very Low Sulphur Fuel Oil (VLSFO) are 364.5 $/mt, 623.5 $/mt, and 415 $/mt, respectively (ShipandBunker, 2026). Nevertheless, the abundance of natural gas reserves, coupled with the potential for cost reductions through technological advances in production, transportation, and bunkering, is expected to drive prices further downward.

Notwithstanding the high level of technological maturity achieved, a number of ship operators and owners continue to exhibit reluctance toward its adoption as a marine fuel. The main reasons for this reluctance are that onboard storage is less flexible than with traditional fuels, requiring additional safety measures; a shortage of personnel qualified to work with low-flashpoint fuels on board, where The IGF Code (International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels) requirements apply, and the lack of readily available LNG bunkering infrastructure in many locations (Klopott, Popek, & Urbanyi-Popiołek, 2023).

From a regulatory perspective, LNG is highly effective in reducing Sulphur Oxides (SO_X) and Nitrogen Oxides (NO_X) emissions as mandated by International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI Prevention of Air Pollution from Ships (Livaniou & Papadopoulos, 2022), and it is also well-suited to meet energy efficiency indexes including Energy Efficiency Design Index (EEDI), Carbon Intensity Indicator (CII) and other ones. However, when life-cycle emissions are considered in the regulations, such as the Greenhouse Gas Fuel Intensity (GFI) Index, the focus on production methods of LNG will increase even further (Zhou et al., 2026).

In summary, although LNG serves as a critical transitional fuel for achieving the IMO short and medium term decarbonization targets, its contribution to long-term net-zero emissions goals remains conditional upon integration with complementary emission reduction technologies such as carbon capture and storage. The findings clearly demonstrate that meeting the 2050 net-zero emissions goal requires a multifaceted strategy. No

single fuel can serve as a standalone solution; instead, the maritime sector must simultaneously integrate diverse alternative fuels with a range of complementary emission abatement technologies.

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Occupational and social health safety assessment of ammonia-fuelled ships

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Extended Abstract

1 INTRODUCTION

Ammonia is increasingly recognised as a promising zero-carbon fuel for the maritime sector, supporting the International Maritime Organization's (IMO) target of achieving net-zero greenhouse gas emissions by 2050 (IMO, 2015). As a carbon-free fuel at the point of use, ammonia offers significant potential to eliminate CO_2 emissions from shipping. However, its combustion characteristics present challenges, including lower flame speed, higher ignition energy requirements, and the formation of nitrogen-based emissions such as NO_x, N_2O, and ammonia slip. These factors influence engine efficiency and raise environmental concerns that must be addressed alongside decarbonisation objectives.

In addition to emissions-related challenges, ammonia is highly toxic, posing substantial occupational, operational, and social health and safety risks to crew members, passengers, and port-side personnel (OSHA, 2022). Accidental releases can lead to severe consequences due to toxic exposure, particularly in confined or poorly ventilated environments. Therefore, ensuring the safe storage, handling, and utilisation of ammonia is critical for its successful adoption as a marine fuel.

This study aims to assess the safety implications of ammonia-fuelled ships through a combination of regulatory review and risk-based analysis. The work focuses on identifying key hazards, evaluating associated risks, and providing risk-informed guidance to support the safe and sustainable implementation of ammonia in the maritime sector.

2 METHODOLOGY

A comprehensive review of international rules, standards, and classification society guidelines relevant to ammonia-fuelled ships is conducted. These include the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code), classification society requirements (e.g., ABS, 2025), and safety studies from regulatory bodies such as the European Maritime Safety Agency (EMSA, 2023). Particular emphasis is placed on Occupational and Social Health and Safety (OSHS) considerations, including exposure limits, hazard classification, and safety management practices (OSHA, 2022).

Building on this regulatory framework, the study integrates findings from the EU Horizon-funded NH3CRAFT project (NH3CRAFT, 2025), focusing on both demonstrator and conceptual vessel designs. The analysis primarily targets fuel storage, fuel supply, and handling systems, where the majority of safety challenges are concentrated (Jang et al., 2023).

Qualitative risk assessment methods are employed to systematically identify potential hazards and failure scenarios. These include Hazard Identification (HAZID), Hazard and Operability Studies (HAZOP), and Failure Modes and Effects Analysis (FMEA). These techniques enable the identification of credible accident scenarios associated with ammonia leakage, system failure, and operational deviations.

In parallel, a Quantitative Risk Assessment (QRA) framework is applied to evaluate the likelihood and impact of identified hazards. The QRA incorporates toxic dispersion modelling, fire and explosion analysis, and the application of risk acceptance criteria aligned with international practices (EMSA, 2023). The analysis considers both normal operation and abnormal conditions, including bunkering, fuel transfer, and emergency situations.

3 RESULTS AND DISCUSSION

The results indicate that toxic release scenarios are the dominant contributors to overall system risk in ammonia-fuelled ships. These risks are particularly significant during fuel handling, bunkering operations, and maintenance activities, where the likelihood of accidental release is higher. Toxic dispersion analysis shows that even small releases can result in hazardous exposure levels, especially in enclosed or semi-enclosed spaces.

Fire and explosion risks, although present, are generally less dominant compared to toxicity-related hazards due to ammonia's relatively narrow flammability range. However, these risks become more significant under certain conditions, such as high-pressure releases or confined environments, and must be carefully managed through appropriate design and safety measures.

The study demonstrates that the implementation of mitigation measures can significantly reduce overall risk levels. Key measures include the use of double-walled piping, effective ventilation systems, continuous gas detection, emergency shutdown systems, and the segregation of hazardous zones. These measures are particularly important in reducing crew exposure and enhancing emergency response capabilities.

From an emissions perspective, the safe handling and controlled combustion of ammonia are essential to minimise unintended releases, such as ammonia slip, and to ensure compliance with environmental regulations. Identified risk scenarios, particularly during fuel handling and bunkering operations, are also significant, as accidental releases may contribute to atmospheric pollution.

The safe integration of ammonia systems is therefore critical to its viability as a low-emission fuel. Operational safety directly influences the acceptance and deployment of ammonia technologies, highlighting the need for a holistic approach that addresses both emissions and safety in the design and operation of ammonia-fuelled vessels.

4 CONCLUSIONS

This study provides a comprehensive assessment of the safety challenges associated with ammonia-fuelled ships, combining regulatory review with qualitative and quantitative risk analysis. The results highlight the dominance of toxicity-related hazards and the importance of targeted mitigation measures to ensure safe operation.

The findings contribute to the development of practical, risk-informed safety guidelines for ammonia-fuelled vessels, supporting designers, classification societies, and regulatory authorities. By addressing key safety concerns, this work facilitates the safe adoption of ammonia as a marine fuel and supports its role in achieving maritime decarbonisation goals.

The study highlights that safety and emissions performance are closely interlinked and must be addressed simultaneously to enable the sustainable adoption of ammonia as a marine fuel. Future work should focus on integrating safety and emissions optimisation strategies, as well as developing harmonised international guidelines to support the large-scale deployment of ammonia in shipping.

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Assessment of biodiesel use with respect to FuelEU maritime, EU ETS, CII, and financial implications: A real-time ship-based analysis

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Extended Abstract

Commercial fuel consumption in merchant vessels has significant economic and environmental implications, particularly within the framework of maritime decarbonization. Given the substantial share of fuel costs in total operating expenditures, ship operators increasingly prioritize energy efficiency measures and the adoption of alternative fuels. At the same time, global pressure to reduce greenhouse gas (GHG) emissions continues dramatically. The maritime transport sector holds approximately 3% of total global carbon emissions (IMO, 2023; UNCTAD, 2023). In this context, optimizing fuel consumption has become a critical factor not only for cost efficiency but also for achieving environmental sustainability objectives.

In recent years, more stringent and comprehensive environmental regulations have been introduced for vessels operating within the European Union. These regulations primarily focus on the monitoring, reporting, and reduction of GHG emissions, aiming to steer the maritime sector toward low-carbon operations. Accordingly, ship operators have to identify their fuel consumption strategies to ensure regulatory compliance while maintaining their competitive position.

This study investigates the environmental and economic impacts of real-time biodiesel use on a commercial bulk carrier operating on a European route, with particular emphasis on compliance with the European Union Emissions Trading System (EU ETS) and the Carbon Intensity Indicator (CII) requirements. CII and GHG intensity calculation methodologies were employed to determine emission values and performance classifications. The key regulatory frameworks developed by the European Union and the International Maritime Organization (IMO) concerning biodiesel use and emission reduction are outlined as follows.

FuelEU Maritime is a regulation implemented by the European Union as of 1 January 2025, aimed at decarbonizing the maritime sector by imposing progressively stricter limits on the GHG intensity of fuels used onboard ships. Applicable to vessels above 5000 gross tonnages, the regulation promotes the adoption of low-carbon fuels such as green methanol and ammonia, as well as the use of clean energy in ports, thereby contributing to the reduction of maritime GHG emissions (BIMCO, 2026). This initiative is aligned with the EU's climate targets for 2030 and 2050 (Von Malmborg, 2023; DNV, 2026).

The European Union Emissions Trading System (EU ETS), established in 2005, is the world's first and largest carbon market designed to reduce GHG emissions. Operating under a "cap-and-trade" mechanism, the system sets an upper limit on emissions from sectors such as energy, heavy industry, and aviation. Companies are required to purchase emission allowances (EUAs) corresponding to their emissions. Covering approximately 40% of total EU emissions, the system was extended to include maritime transport as of 2024. The EU aims to reduce GHG emissions by 62% by 2030 compared to 2005 levels and to achieve net-zero emissions by 2050 (Climate EU, 2026; Pietzcker et al., 2021).

The Carbon Intensity Indicator (CII) is an operational energy efficiency rating system mandated by the IMO for ships of 5000 gross tonnage and above. It measures the amount of CO_2 emitted per transport work (i.e., per deadweight ton and nautical mile). Vessels are rated annually from A to E (with A representing the highest efficiency), with a requirement to progressively improve performance by 2026. The system aims to reduce the carbon footprint of the maritime sector and contribute to the target of a 40% reduction in emissions by 2030 compared to 2008 levels. Cargo, Ro-Pax, and passenger vessels engaged in international voyages fall within the scope of this regulation (IMO, 2026).

The dataset used in this study was obtained from a Liberia-flagged handysize bulk carrier built in 2003 and engaged in real-time maritime operations. The vessel is approximately 180 meters in length and 28 meters in beam, operating in dry bulk transportation. It is equipped with a MAN B&W 7S35MC main engine, manufactured by MAN Energy Solutions, with a power output of 5180 kW. The engine is a low-speed, two-stroke, camshaft-driven mechanical marine diesel engine with seven cylinders and a bore of 350 mm.

The analysis is based on operational data collected during a biodiesel usage phase between 11-19 October 2025, lasting approximately 8,3 days. During this period, the vessel operated under comparable weather and route conditions at an average speed of approximately 10,5 knots. Fuel consumption was observed to be approximately 10,5 tons/day when using Marine Gas Oil (MGO) and around 12,0 tons/day when using biodiesel.

The results are shown below.

- FuelEU Maritime: Without biodiesel use, a deficit of 39,72 tons of CO_2 would have occurred. With biodiesel, no penalty was incurred, and a net surplus of 234,45 tons of CO_2 was generated. The economic value of this surplus is approximately €51579 (234,45 × 220 €/tons).
- EU ETS: Biodiesel is considered biogenic; therefore, EUA requirements are effectively zero. The use of B100 biodiesel resulted in approximately USD 18000 in ETS savings. In contrast, exclusive use of MGO would have resulted in an ETS liability of approximately €119026 for the current year.
- CII: The attained CII value was 3,20 gCO_2 / (DWT/nmi), corresponding to an IMO rating of "Superior (A)".

Overall, biodiesel use resulted in an approximate 84% reduction in GHG emissions. These findings highlight the effectiveness of biodiesel in reducing emissions and mitigating additional regulatory costs (Sagin et al., 2024; Selvam et al., 2026). However, the use of biodiesel may lead to certain technical challenges, such as increased wear or replacement requirements for components including fuel pumps, barrel-plunger assemblies, injector systems, sealing elements, piston rings, and filter units.

Considering these potential additional costs, the Net Present Value (NPV) method was applied to assess the economic feasibility of biodiesel use in comparison with conventional marine fuels. Although the NPV results indicate that biodiesel represents a financially viable investment, the analysis also reveals that biodiesel use leads to higher operational costs compared to Marine Gas Oil (MGO)

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Low carbon shipping: several ideas from MAGPIE to reduce barriers for implementation of alternative Fuels

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Extended Abstract

To decarbonize ships, a large number of stakeholders is required to facilitate this. Not only the ship needs to be adjusted e.g. to low carbon fuel energy systems or Onshore Power Supply (OSP), but also ports need to be able to handle the new fuels and OSP, sometimes requiring the extension or development of supply chains. Based on the work of Hekkert (2020) on Mission oriented innovation systems, seven general barriers exist for such innovations (table 1). As the energy transition clearly falls within the scope of mission oriented innovations, these seven barriers formed the key basis for our analysis of challenges and the identification of solutions for key challenges.

Table 1: Seven Barriers for Mission Oriented Innovation Systems

#	Type	Barrier example
1	Economic	Lack business case
2	Knowledge	Lack of adequate models describing the multimodal dependencies
3	Standards & Regulation	Lack of non-fossil fuel standards
4	Interaction	Lack of trust between stakeholders
5	Directionality	Lack of clear emission reduction goals
6	Technology	Immature technology
7	Infrastructure	Absence of sustainable energy infrastructure

MAGPIE has studied a plethora of options to deal with these barriers and this presentation will discuss some of the lessons learned. Two were selected here for a short discussion: In light of the economic barrier, Port Fee rebates were investigated for effectiveness, while a specific approach to shore power installation was used to understand the importance of interaction.

The port fee price differentiation considered the price differentiation scheme used by Port of Rotterdam (lighthouse port for MAGPIE) and the NavigaTE model from Maersk to investigate the impact on the vessel TCO for various vessel types. Although not effective currently (with the current fuel prices and no ETS), several scenarios were identified where in the future the port fee differentiation could make te difference that closes the price gap between fossil and cleaner fuels. As such the measure is not without value towards the economic barrier, but it is not decisive in the transition, from the vessel owner perspective. From the port side however, it could act as a clear signal to send green ships to their port and through that lower their overall impact significantly (locally), but not overall (globally).

The shore power case was selected to address stakeholder trust as both ship owners and ports are waiting for enough and stable demand to install the required systems. These are both more effective if a large market exists, so there is a clear early mover disadvantage. On top of that (especially in the Port of Rotterdam), on the land side many parties are involved as well, all with different priorities and incentives. Figure 1 gives an overview of these stakeholders and how their alignments change through the introduction of a joint venture.

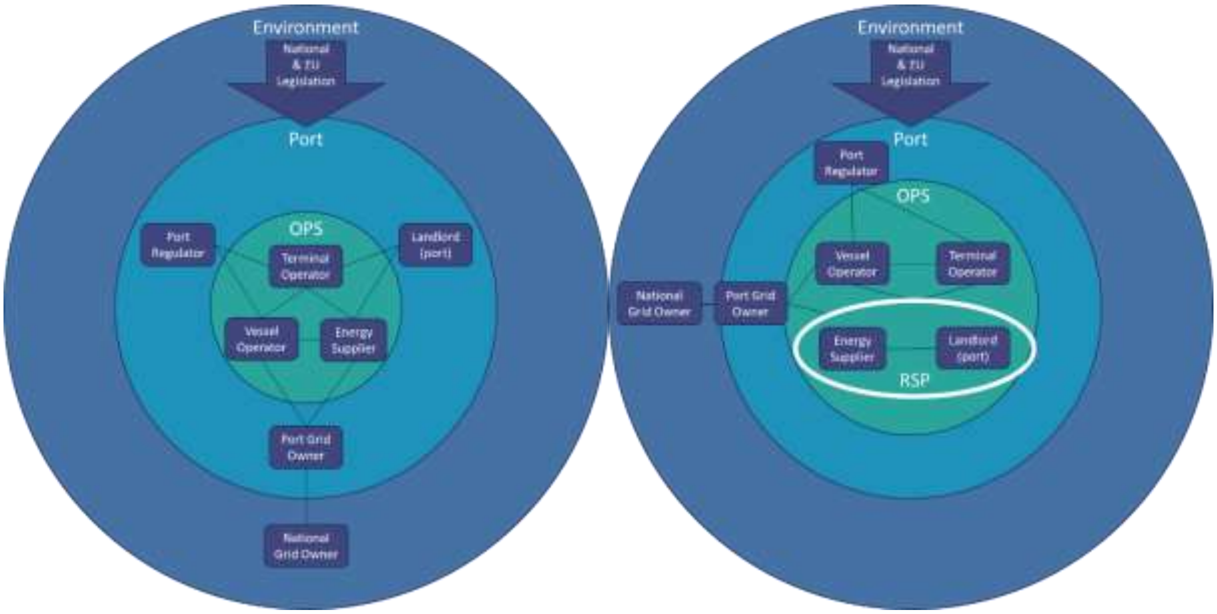

Figure 1: Shore Power stakeholder overview without and with the RSP joint venture.

Rotterdam Shore Power is a joint venture between PoR and a energy company to reduce the number of stakeholders involved on the land side, using a lease concept towards terminals to ensure income (that can in the future be covered by income from electricity sales), in return terminals do not have to invest themselves and can start offering shore power before the 2030 requirement is in place. So far they have successfully installed shore power in several cases, but all concern situations where the owner of the vessel is the owner of the terminal, further reducing stakeholders and thus risks. Besides removing stakeholders, RSP also has access to the energy bulk market reducing the cost of energy, which many researchers have shown to be not economic currently.

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From EU-funded innovation to routine operation: technology transfer pathways for alternative-fuel propulsion systems in Europe’s inland vessel build and retrofit ecosystem

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Extended Abstract

BACKGROUND

Alternative-fuel propulsion systems are a core route to reducing greenhouse gas emissions from waterborne transport. In practice, many EU-funded propulsion innovations do not progress from demonstration to routine industry use. This matters also in inland vessel build and retrofit, where Europe retains strong expertise, but value chains often span multiple countries, for example construction in one location, outfitting in another, and operation elsewhere. These cross-border supply chains can support diffusion, but they can also create dependencies and slow uptake.

AIM AND RESEARCH QUESTION

This contribution examines why alternative-fuel propulsion innovations often stall between demonstration and routine adoption, and what transfer pathways enable repeatable deployment across fleets. It is grounded in a PhD project that treats “sovereignty” as practical control over the capability to industrialise, integrate, certify, service, and repeatedly deploy key technologies across the OEM–shipyard–shipowner ecosystem, rather than as domestic production of every component.

CONCEPTUAL APPROACH

The paper applies an ecosystem transfer lens developed for regulated inland waterway transport systems. Successful transfer is treated as a capability-building process that includes productisation (often OEM-led), shipyard integration routines, certification and compliance evidence, after-sales and service ecosystems, and shipowner uptake supported by credible performance verification.
To analyse where progress breaks down, the study uses a project-to-deployment pipeline model and the concept of pipeline leakage, meaning predictable points where promising results lose momentum. For alternative-fuel propulsion, adoption depends not only on onboard performance but also on ports, standards, safety cases, and compliance regimes.

METHODOLOGY AND EMPIRICAL BASIS

The study uses qualitative process tracing and cross-case comparison. Evidence is drawn from (1) structured review of public EU project outputs relevant to propulsion decarbonisation in inland shipping, and literature concerning technology transfer/uptake pathways and (2) semi-structured interviews across the ecosystem, including technology providers, shipyards and integrators, and vessel operators. The analysis codes barriers and enabling conditions across pipeline stages and identifies recurring leakage mechanisms that shape whether technologies reach routine operation.

EXPECTED RESULTS AND CONTRIBUTION

The expected output is a practical set of tools that can support both research and implementation, including a pipeline leakage map for alternative-fuel propulsion transfer, pathway patterns (for example OEM-led vs shipyard-led vs integrator-led scaling), and readiness criteria that indicate which prerequisites need strengthening for sustainable scale-up.

Best practice for risk analysis of battery-driven passenger ferries: A safety-case-oriented framework

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Extended Abstract

1 INTRODUCTION

Battery-driven passenger ferries are emerging as an important decarbonization solution for short-sea shipping. Their operational profiles—frequent port calls, high passenger density, and repetitive charge–discharge cycles, introduce safety challenges distinct from conventional vessels. The main risks arise from lithium-ion battery energy storage systems (BESS), where thermal runaway, off-gas generation, and flammable gas accumulation may escalate into fires or explosions in confined spaces. These hazards are strongly influenced by system arrangement, ventilation, detection and shutdown logic, and crew response (EMSA, 2023; DNV GL, 2016). High-power DC systems and automated energy management further increase the need for robust fault handling, particularly during charging. Despite evolving regulations, battery installations remain diverse, and safety increasingly relies on risk-based justification. Existing approaches are often overly qualitative or overly quantitative and are rarely structured for lifecycle safety-case development.

This study proposes a safety-case-oriented, lifecycle-integrated framework tailored to battery-driven passenger ferries. The novelty lies in integrating hazard identification, bow-tie modeling, selective FTA/ETA analysis, and fire-and-gas validation into a unified, approval-oriented workflow aligned with classification and flag requirements. Unlike fragmented approaches, it provides a coherent system-level methodology supporting both engineering decisions and safety-case justification. The framework includes four pillars:

1. Lifecycle hazard identification with passenger-centric and arrangement-aware focus.
2. Bow-tie barrier modeling with defined performance and dependencies.
3. Targeted FTA/ETA for high-consequence scenarios.
4. Fire-and-Gas validation of gas dispersion, explosion risk, and evacuation conditions.

2 PROBLEM DEFINITION AND SCOPE

The framework targets ferries where BESS is safety-critical for propulsion or essential services. The scope includes charging interfaces, high-power DC distribution, thermal management, BMS/PMS logic, ventilation/extraction, fire protection strategies, and emergency operating modes. Battery safety is treated as a ship-level socio-technical problem. The same battery system may present different risks depending on compartment arrangement, ventilation design, sensor independence, crew procedures, and evacuation constraints (EMSA, 2023; DNV GL, 2016). This perspective extends beyond component reliability to system interactions and operational conditions.

3 BEST-PRACTICE WORKFLOW

The proposed workflow begins with system definition and safety goals, clarifying operational envelopes, critical functions that must be maintained, credible single-failure expectations, and passenger safety objectives (EMSA, 2023). It then proceeds in a staged manner:

Stage A — Multi-stakeholder HAZID (concept to early design): HAZID develops a comprehensive hazard register and prioritizes key top events. It involves stakeholders including operators, shipyards, integrators, battery OEMs, class/flag representatives, and fire safety experts to capture both technical and operational risks.

Outputs include a ranked risk register and a shortlist of top events such as thermal runaway propagation, flammable gas accumulation/explosion, toxic release affecting evacuation, charging incidents, flooding impacts, and collision-induced failures (Wang et al., 2020; EMSA, 2023).

Stage B — HAZOP + FMEA/FMECA (design detail and control logic): HAZOP identifies functional deviations in systems such as ventilation, suppression, shutdown logic, and interlocks, focusing on deviations like insufficient airflow, delayed response, or incorrect operation. FMEA/FMECA evaluates component-level failures in BMS/PMS, sensors, actuators, and supporting systems, highlighting common-cause failures and dependency issues, which are critical in maritime battery applications (DNV GL, 2016; Bugryniec et al., 2025).

Stage C — Bow-tie barrier models (safety case backbone): Bow-tie models structure risk by linking causes, top events, and consequences, while defining preventive and mitigative barriers with performance and dependency characteristics. Key bow-ties include thermal runaway, gas explosion, toxic exposure, and charging incidents. This approach improves transparency by explicitly representing system dependencies such as ventilation performance and detection reliability (DNV GL, 2016).

Stage D — Quantitative Analysis (FTA/ETA): FTA models the likelihood of initiating events, while ETA evaluates escalation pathways based on barrier success or failure. Quantification is applied selectively to support comparison of risk control options and ALARP justification (Wang et al., 2020).

Stage E — Fire-and-Gas engineering (validation of key barriers): Because battery hazards are tightly linked to gas dispersion and compartment aerodynamics, best practice includes F&G engineering evidence that validates the barrier assumptions used in bow-ties and ETAs. This includes ventilation and dispersion analysis to identify stagnation/recirculation, evaluation of flammable cloud formation and safe exhaust outlet placement, explosion overpressure/relief and vent-path checks, and smoke/toxic dispersion assessment linked to escape-route tenability in passenger spaces (DNV GL, 2016; EMSA, 2023). For ferries, this step is crucial because passenger survivability depends not only on "putting out the fire," but on ensuring evacuation routes remain usable and that explosion risk is controlled.

4 EXPECTED CONTRIBUTIONS AND DELIVERABLES

The study provides a practical, ferry-specific risk analysis framework for engineering and regulatory application. It delivers structured outputs including hazard registers, bow-tie models, quantitative analyses, and safety-case documentation. The full paper will expand the framework with example bow-tie models, ETA parameterization guidance, and practitioner-ready templates (risk register, barrier requirements, ALARP justification, and verification matrices). It also links analysis results to commissioning, crew training, charging procedures, and continuous improvement. For example, key top events include thermal runaway propagation and flammable gas accumulation leading to explosion, with strong sensitivity to ventilation effectiveness and detection response time. Compared to existing approaches, which are often fragmented or not aligned with approval processes, the proposed framework provides a coherent, lifecycle-oriented methodology integrating qualitative and quantitative analysis with engineering validation, improving both technical rigor and practical applicability.

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Parametric and optimization study of a low-temperature ORC for maritime WHR

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Extended Abstract

The decarbonisation of waterborne transportation requires practical solutions for improving shipboard energy efficiency and reducing fuel consumption without major disruption to existing propulsion arrangements. A significant fraction of the energy supplied to marine engines is rejected as low- and medium-grade heat through jacket-water circuits, exhaust-gas streams, charge-air cooling, lubricating-oil systems, and seawater cooling loops. Organic Rankine Cycles (ORCs) offer a technically attractive route for converting part of this waste heat into useful electrical power, particularly when heat-source temperatures are in the range of approximately 70–150 °C. However, the practical design of maritime ORC systems remains challenging because shipboard heat sources are highly variable, cooling conditions depend strongly on seawater temperature, and compactness, safety, working-fluid selection, and integration constraints are more restrictive than in stationary applications.

The specific gap addressed in this work is the lack of a consistent comparative design framework for assessing low-temperature ORC performance across different maritime waste-heat-recovery configurations under realistic ship-operating constraints. Most available studies focus either on a single heat source, a limited operating point, or idealised thermodynamic assumptions. This paper therefore presents a parametric and multi-objective optimization study of three representative maritime ORC configurations: a jacket-water ORC, an exhaust-gas economiser ORC, and a hybrid ORC combining jacket-water and exhaust-gas heat sources.

The analysis is performed using the open-source ORC modelling environment ORCmKit, with component-level models for the evaporator, expander, condenser, pump, and auxiliary subsystems. The modelling approach combines thermodynamic cycle calculations with semi-empirical component descriptions, while accounting for pressure losses, heat-exchanger effectiveness, expander and pump efficiencies, parasitic power demand, and practical pressure and temperature constraints. Model credibility is supported through comparison with published low-temperature ORC performance data and consistency checks against established thermodynamic trends for subcritical ORC operation.

The reference case considers a representative marine diesel-engine installation operating over a variable-load profile (2 MW output at full load), with jacket-water temperatures in the range of 85-90 °C, exhaust-gas heat-source temperatures in the range of 360-370 °C, and condenser seawater temperatures between 20-30 °C. The working fluids considered include R245fa alternatives such as R1234ze(E), selected according to current environmental constraints on ozone depletion potential, global warming potential, safety, and technical suitability. The optimization decision variables include evaporation pressure, condensation pressure or temperature, working-fluid mass-flow rate, heat-source utilisation, and heat-exchanger sizing indicators, subject to constraints on pinch-point temperature difference, maximum pressure, expander operating limits, seawater cooling capacity, and auxiliary power demand. The parametric analysis shows that ORC performance is strongly governed by the interaction between heat-source temperature levels and condensation conditions. For the jacket-water configuration, the available heat is more stable, but the low temperature level limits cycle efficiency and makes condenser performance critical. The exhaust-gas economiser configuration provides higher specific power potential but is more sensitive to engine load variation and heat-exchanger pinch-point limitations. The hybrid configuration improves heat-source utilisation and broadens the feasible operating envelope but introduces additional complexity in heat-exchanger integration and control.

The preliminary results indicate that, for the examined operating envelope, the jacket-water ORC achieves a net electrical output of approximately 20-25 kW with a thermal efficiency of 7%. The hybrid configuration provides the highest overall recovery potential. The optimization results further show that maximum net power output and maximum thermal efficiency do not occur at the same design point, confirming the need for multi-objective rather than single-objective ORC design in maritime applications.

The study identifies robust design regions in which net power output, thermal efficiency, compactness, and auxiliary consumption can be balanced. In particular, the optimized hybrid ORC configuration provides the

most favourable trade-off when sufficient exhaust-gas heat is available, whereas the jacket-water configuration remains attractive for simpler installations with lower integration complexity and more stable heat input. Sensitivity analysis confirms that seawater temperature has a significant impact on net performance, with warmer cooling conditions reducing net power output.

In addition to thermodynamic performance, the study includes environmental and economic assessment. The environmental analysis estimates the achievable primary energy savings and associated reductions in fuel consumption and greenhouse gas emissions resulting from recovered electrical power. For the representative operating profile, the ORC configuration yield annual CO_2 emission reduction of 82 tonnes/year (5000 hrs operation). The economic evaluation estimates capital and auxiliary system costs, compares the three configurations, and calculates indicative payback periods or return-on-investment ranges. The results suggest that maritime ORC feasibility depends not only on thermal performance but also on operating profiles, annual engine running hours, fuel price, integration cost, and available space.

Overall, the paper provides a comparative and optimization-based design framework for low-temperature maritime ORC systems. By combining parametric performance mapping, multi-objective optimization, environmental assessment, and economic screening, the work offers practical guidance for selecting and integrating ORC-based waste-heat-recovery systems on ships. The findings support the role of ORC technology as a complementary energy-efficiency measure contributing to reduced auxiliary fuel consumption and lower emissions in waterborne transportation.

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Onboard waste treatment for maritime systems: Reducing volume and emissions via pyrolysis and gasification

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Extended Abstract

Cruise ships are floating towns with several thousand inhabitants. About 370 ocean going vessels of varying sizes are currently in operation with a combined capacity of over 700.000 passengers (Cruise Market Watch, 2026). This means a lot of produced waste, that needs to be disposed of. Waste streams contain sewage sludge, food waste, contaminated plastics, household waste, paper, and other waste streams. The handling of these waste streams has become an increasingly time-consuming and space consuming task. Since more and more cruise lines abandoned the practice of floating waste on high seas (not only solid parts as cardboard and plastics but also food waste and sewage sludge), due to stricter regulations other solutions besides storage have to be found, since cold storage occupies valuable cargo space and consumes a lot of energy.

The most robust and usual solution for waste disposal is the gasification or combustion of the waste streams. Current commercially available combustion solutions, e.g. the MAGS™, distributed by Terragon Environmental Technologies Inc. 2026 or the "Incinerator" distributed by Environmental Systems GmbH, 2026 have severe limitations in regard to operability in ports or in handling. Solutions as described by Toneatti et al. 2022 might offer better flue gas quality and process stability, but have yet to be tested in operation.

The project MAAT intends to develop a robust waste disposal system, based on pyrolysis, gasification and combustion. By combining three process steps, better process control can be achieved and a wide range of operation from partial load to full load can be achieved. The project aims to test a full- scale demonstrator with a realistic waste mixture, prepared as pellets or briquettes. In cooperation with the company Carnival Corporation & PLC together with its cruise line AIDA a typical waste stream composition was determined, containing

Table 1: Representative IMO-Mix of waste on cruise ships

Dried sewage sludge	25.0 wt.%
Food waste	25.0 wt.%
Paper	16.0 wt.%
Cardboard	22.5 wt.%
Plastics	8.0 wt.%
Wood	3.0 wt.%
Rags	0.5 wt.%.

For preparing the tests the waste was mixed from fresh materials, dried and sanitized sewage sludge and according to the described mix with the difference that no real food waste was used here. Instead in total 50 wt.% of sewage sludge was used. The material was both pelletized and briquetted to show the mechanical and thermal differences in application as fuel.

For the experiments a large-scale pyrolysis screw reactor was adapted and put into operation. The system is double-walled and is heated with a natural gas burner. Under normal operation a maximum pyrolysis temperature of 800 °C is reached and up to 25 kg/h of waste can be pyrolyzed. Off-gas was burned with an exhaust gas burner, gas analysis was done with ABB multi component exhaust gas measurement systems for CO, H_2, CH_4, CO_2 and O_2. Results of the measurements show a volumetric pyrolysis gas composition of CO: 19.0 %, H2: 13.3 % CH_4: 13.2 %, CO_2: 41.0 %. The exhaust gas has a high calorific value, which easily can be used for combustion to generate thermal energy on ships. The resulting char contains between 40 and 50 wt.% carbon and is an ideal feedstock for gasification. These tests show the efficiency of the pyrolysis processes depending on temperature and dwell time of mixed waste and the overall suitability of a screw reactor for mixed waste in form of pellets or briquettes.

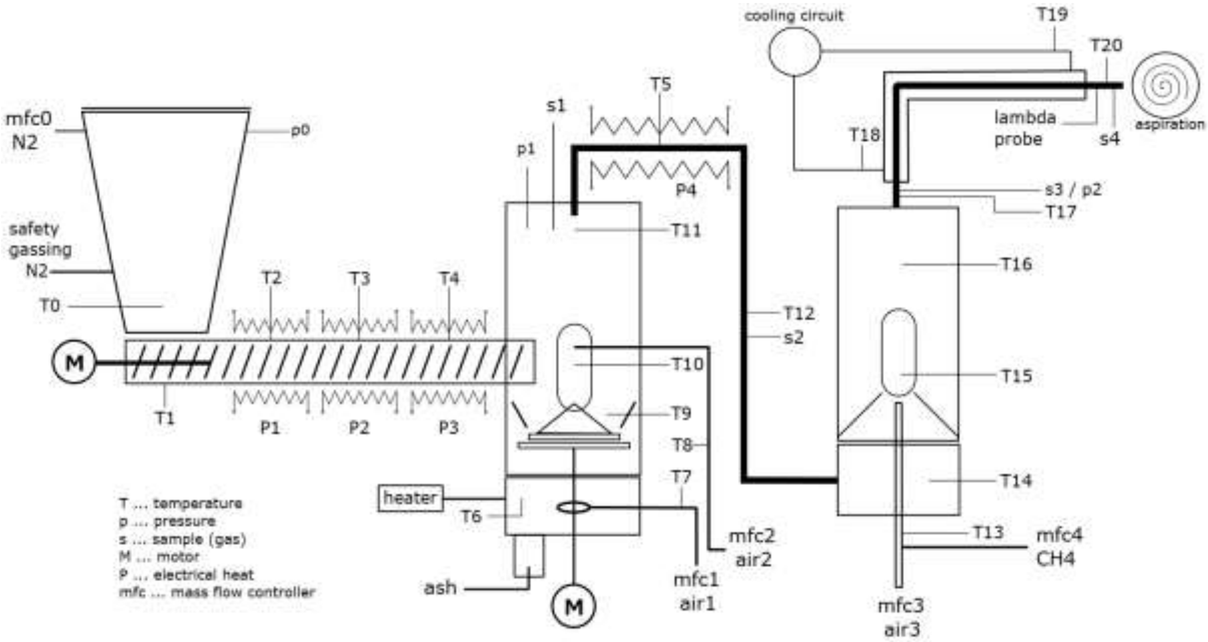

Figure 1: P&ID-Scheme of the small-scale test plant

Furthermore, a combined small-scale pyrolysis-gasification-combustion system was developed to approach and connect the whole process: pyrolysis – gasification – combustion. An overview is given in Figure 1. It consists of an electrically heated pyrolysis screw with 3 heating zones, capable of reaching 750 °C outlet temperature with a maximum throughput of 3 kg per hour. The gasification step reaches up to 900 °C. The combustion chamber is designed to reach 1100 °C and can be cofired with natural gas for the start-up process. The results of process temperatures and gas-measurements as well as char-/ash analyses give an interesting overview of the process, which can be stabilized over several hours in test operation due to the semi-automatic deashing system.

In summary, the system shows great promise in reducing waste volume and mass and can help to make waste treatment on ships cleaner and more sustainable through heat recovery for drying material of the preceding processes. The contribution will also give a short overview of the later demonstration system, which is designed for a throughput of 75 kg/h of mixed waste.

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Beyond the conventional internal combustion engine: The free piston linear generator technology

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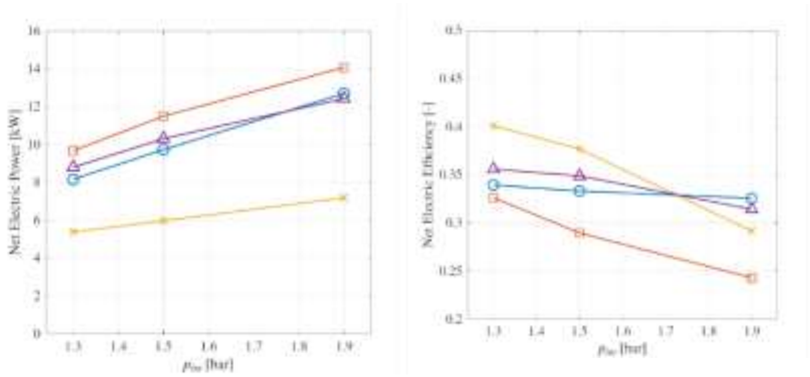
Extended Abstract

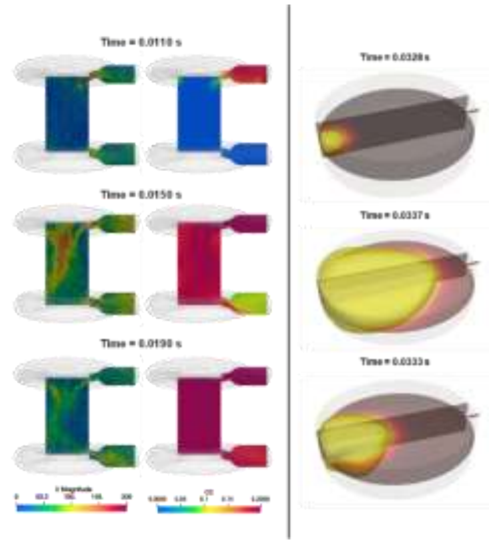
This work, a core component of the national research program "Flex-Gen" (funded by the Ministry of Research), describes advances in design methodology for the free piston linear generator technology. It presents an integrated numerical framework combining 1D and CFD simulations, applied to two FPLG use cases: electrified mobility and power generation.
Parallel research was conducted to integrate FEMM models of electromagnetic linear generators into a MATLAB/Simulink environment. This co-simulation approach enables an accurate representation of both the generator geometry and the associated electrical circuitry, providing a reliable basis for the virtual prototyping and experimental validation of axial motor-generator systems in hybrid and electric powertrain applications.
The system configuration was chosen after a preliminary assessment of the state of the art supported by a numerical comparison between Boxer and Opposed configurations. The opposed configuration was selected as the most promising option, primarily due to lower heat exchange losses resulting from the absence of a cylinder head. The results of the numerical analysis showed that the opposed configuration provides higher in-cylinder pressures and higher work per cycle due to faster combustion event and improved scavenging characteristics. The motor size was selected based on an experimental database published by the American research group Sandia, which has developed an opposed free piston linear generator prototype having the following parameters.

Trapped Volume	Combustion Bore	Stroke per piston (nominal)	Overall Length	Operating Frequency	Electrical Power Output
Liters (in^3)	mm (in)	mm (in)	mm (in)	Hz	kW
1.97 (120.2)	81.15 (3.195)	220 (8.66)	2286 (90)	30-35	15-19

The modeling framework consisted of two activities carried out in parallel: the first one [Morandi et al. 2025] focused on the development of a one-dimensional fully integrated FPLG model within the GASDYN software; A simplified approach was adopted for the linear generator model, assuming that the electromagnetic force was proportional to the piston velocity. Subsequently, a co-simulation framework using Simulink was introduced, incorporating a more detailed generator model into the computational process. In addition, CFD simulations were carried out with user-defined displacement profiles to perform a preliminary assessment of the FPLG geometry, and a reference results to calibrate the 1D simulation model. In the following charts quantitative results are presented as obtained from simulations.



It can be observed that the indicated efficiency depends on both the intake pressure and the generating load coefficient. In particular, at a fixed engine load, an increase in intake pressure leads to a decrease in indicated efficiency. For each plot, different fuels and combustion strategies were explored. The indicated efficiency reached values above 0.45 for hydrogen fueling and lambda=2, showing the potential to go around 0.50 by further increasing the relative air-to-fuel ratio. The net electric power reached values of around 12 kW for intake pressure of 1.9 bar, in the case of stoichiometric mixtures of natural gas or ethanol were applied.
In the following charts are presented the quantitative results obtained from the CFD simulations.



Simulations were performed using biomethane as fuel, which is delivered via a low-pressure, single-hole injector located in the cylinder liner. The sparkplug was placed on the opposite side. The proposed combustion chamber configuration generates a strong tumble vortex at the end of the gas exchange process, and this favors the mixing of the direct injected fuel with air, also generating turbulence towards the end of compression stroke which ensures a fast and stable combustion process.
To overcome certain limitations of the simplified 0D linear generator model a tubular permanent-magnet linear electric generator was developed in FEMM (Finite Element Method Magnetics) environment [Capuano et al., 2025]. It was reproduced the same SANDIA prototype geometry. The generated mesh allowed for a detailed examination of the magnetic induction field within the linear generator.
Once the static distribution of the magnetic field along the entire stroke of the mover is known, we use the derivative of the flux with respect to position and the velocity of the mover (derived from literature data) to calculate the induced voltages in the single coils. Once the circuit was reconstructed in the Simulink environment, we were able to simulate the phase current waveforms for all coils. A good agreement between the experimental data and the numerical results was found.

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Assessing thermoelectric generators in marine waste heat recovery systems

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Extended Abstract

Enhancing the range autonomy of maritime vessels to enable operation with expensive sustainable fuels or battery electrification requires the use of efficiency-improving technologies onboard, including more effective utilization of wasted thermal energy. Waste heat recovery (WHR) technologies enable the conversion of low- to medium-grade heat into electrical power, with differemt technologies suitable for specific thermal ranges (Singh and Pedersen 2016). Among these, thermoelectric generators (TEG) represent a promising solution for marine applications due to their ability to harness waste heat across a wide range of thermal qualities while offering direct energy conversion, maintenance-free operation, and an extended service lifespan (Saha et al. 2023).

This study presents a technical feasibility assessment for integrating a TEG unit in the exhaust stream of the main engine, upstream of both high-pressure and low-pressure economizers, as illustrated in Figure 1. The primary objective is to evaluate the tradeoff between direct electrical power generation and the subsequent reduction in downstream steam production. By quantifying this energy paradigm, the study seeks to identify an optimal TEG capacity that maximizes electrical output while maintaining the ship's required steam demand.

The analysis utilizes a previously validated TEG model (Felgner et al. 2014) and the Modelica library TIL (*TIL Suite* 2023) applied to a dataset from a large passenger vessel. Four representative operating points are chosen for this analysis. The simulation evaluates the waste heat recovery through three stages:

1. Thermoelectric Generator: Direct conversion of thermal energy to DC power via the Seebeck effect.
2. High-Pressure Economizer: Primary steam generation stage.
3. Low-Pressure Economizer: Secondary heat recovery stage.

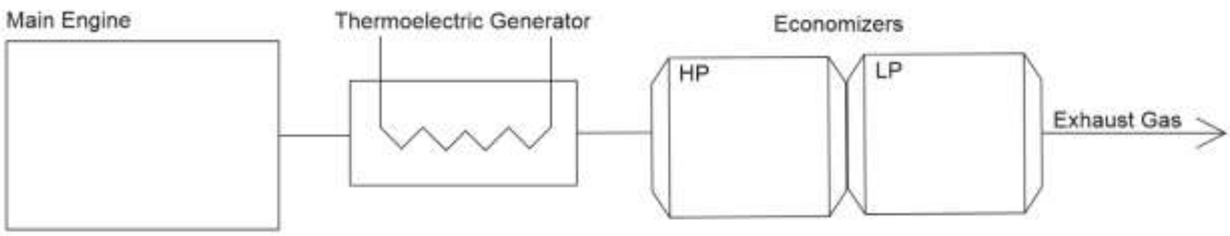

Figure 1. Waste heat recovery scheme

The vessel power plant consists of four medium-speed generator engines belonging to two engine classes (Type A and Type B). Selected representative operating windows were extracted from real onboard measurements and used to define boundary conditions for the thermal system analysis. Table 1 shows the interested operational points for the feasibility assessment analysis.

Table 1. Operational Points

Case	Engines	Load [%]	Exh. gas temp [°C]	Exh. gas m flow [kg/h]	Status
OP1	2 × Type B	40	352.4 ± 5.2	1213.5 ± 10.6	Underway
OP2	3 × Type B	60	339.9 ± 14.6	1252.1 ± 21.2	Underway
OP3	1 × Type B	15	361.9 ± 1.7	961.6 ± 11.9	Berth
OP4	1 × Type B	15	372.9 ± 1.4	939.5 ± 15.3	Anchored

Error! Reference source not found. summarizes the baseline steam generation from waste heat recovery, the corresponding steam demand for each operating condition, and the available steam margin. The steam margin is defined as the surplus steam production relative to demand and therefore indicates the maximum thermal energy that could potentially be utilized for TEG integration without compromising steam supply to onboard consumers. The thermoelectric generator capacity is varied as the independent variable to simulate different installation scales. Performance metrics include total electrical output and the resulting margin of steam surplus, defined as the differential between hourly production and onboard demand.

Table 2. Baseline steam production and steam demand onboard vessel according operational case

Case	Baseline steam production [kW]	Steam demand [kW]	Steam margin [%]
OP1	6822 ± 47	5717 ± 475	16.2
OP2	9438 ± 76	7770 ± 493	17.7
OP3	3042 ± 31	2781 ± 476	8.6
OP4	3182 ± 34	2699 ± 382	15.2

The results show that upstream TEG integration is viable, but constrained by the vessel's thermal margin. As shown in Figure 2, net steam surplus is plotted against TEG electrical power for each operating point (OP). The electrical power values are obtained by parametrically varying the TEG heat transfer conductance (UA) over a range of 0–2500 W/K. For each OP, a maximum heat transfer conductance exists beyond which the net steam surplus becomes negative, defining the upper limit for heat recovery without compromising steam availability. The corresponding maximum electrical outputs are approximately 50 kWe, 77 kWe, 12 kWe, and 22 kWe for OP1–OP4. These values represent the feasible upper limits for TEG integration under steady-state conditions without requiring auxiliary steam generation.

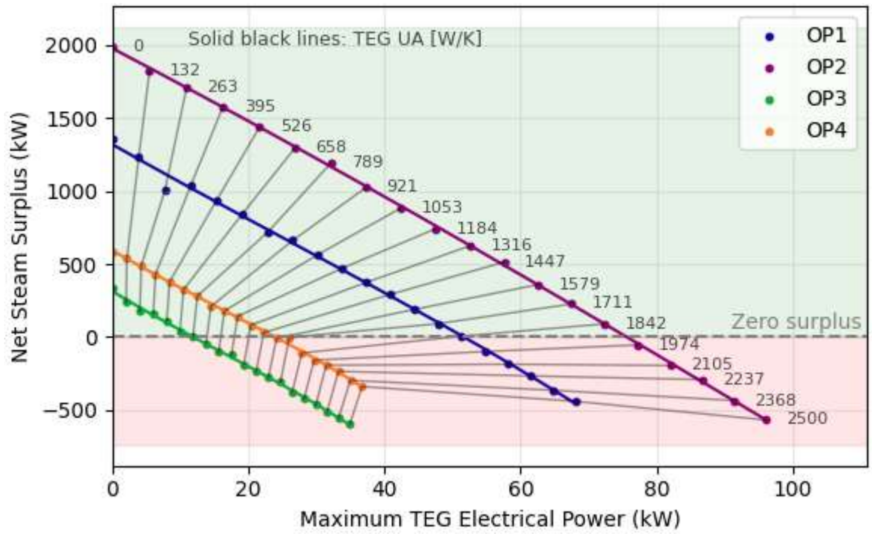

Figure 2. Steam Surplus vs Maximum TEG Electrical Power for Each Operating Condition

This study will investigate the optimal integration of upstream TEG systems under varying operating conditions, recognizing that the feasible heat extraction is constrained by the available steam surplus at each operating point. As demonstrated, the maximum allowable TEG heat transfer conductance differs significantly across operating conditions, requiring a compromise between electrical power generation and steam availability. The objective is therefore to identify a TEG design that maximizes overall energy efficiency gains, quantified, for instance, through Energy Efficiency Existing Ship Index (EEXI) improvement, while ensuring that steam generation remains sufficient across the full operational range. This approach aims to define a TEG integration strategy that delivers consistent performance benefits without compromising the thermal integrity of the vessel's WHR system.

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A modular scenario-driven simulator for hybrid-electric ship power systems

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1 MOTIVATION AND CONTRIBUTION

Decarbonising waterborne transportation requires reliable, transparent tools to evaluate how energy sources, power-conversion chains, and operational profiles impact energy use at the ship power-system level (Bø et al. 2015). This work presents *mcpowersimpy*, a Python-based system-level simulator designed for repeatable decarbonisation studies of hybrid-electric ship power systems. *mcpowersimpy* is developed within the EU STEESMAT project as a platform for verification and testing of energy and emission management algorithms and concepts, supporting consistent benchmarking under controlled scenarios (Sakhrieh et al. 2026). The work contributes:

(1) A reference architecture for modular, plug-compatible unit models (sources, converters, buses, and loads), enabling rapid assembly of test cases.
(2) A rigorous "scenario-as-data" configuration concept, where experiment definition is stored and validated against a schema for reproducibility.
(3) A validation strategy with standardized outputs and quantitative acceptance targets supporting credible comparisons across scenarios.

The intent is to provide an auditable simulation model for studies such as energy/emission benchmarking, architecture comparison, and subsequent integration with supervisory strategies and onboard decision-support algorithms (Najjaran & Skjetne 2025). *mcpowersimpy* targets system-level questions: power routing, conversion losses, energy/fuel use, emissions bookkeeping, operational sequencing, and constraint compliance under realistic load profiles. Power-electronic stages are represented using continuous-time averaged models at the control time scale, enabling loss and emissions evaluation aligned with established assessment approaches (Ghimire et al. 2021). To facilitate reuse and discoverability, *mcpowersimpy* is distributed through Awesome MCLab, a collection of control software and simulation packages developed for research on autonomous and cyber-physical ships (NTNU-MCS 2025).

2 SIMULATOR ARCHITECTURE

The simulator is organized as a layered package with a deterministic runtime, a library of averaged unit models, adapter interfaces for external load sources, and a logging pipeline. The unit-model layer is structured so that converters, sources, storage, and loads are plug-compatible via uniform I/O contracts.
A typical reference configuration captures hybrid-electric ship power-system building blocks:

- Multi-domain buses (MVAC/MVDC/LVDC/LVAC).
- Conversion stages (AC/DC, DC/DC, DC/AC).
- Energy storage interfaces (battery and fuel-cell).

Each experiment is defined by a single scenario file that is validated against a schema. The scenario is the source of truth for unit selection, parameter sets, operating timelines, efficiency maps, constraints, and an RNG seed to enable deterministic runs.

3 EXECUTION MODEL

mcpowersimpy follows a load-driven power-flow philosophy. At each time step:

(1) Propulsion and hotel/aux load demands are generated from a mission profile or from propulsion loads generated by an external ship simulation model directly. An example is the sister Python package *mcsimpy*, which is a 6DOF hydrodynamic model of fully-actuated low-speed vessels (Gezer et al. 2025).
(2) Per-bus net demand is aggregated with loss accounting.
(3) Upstream dispatch setpoints are computed subject to constraints.
(4) Energy, fuel, and emissions accounting are integrated and reported.

When active constraints make the demanded load infeasible, the simulator introduces explicit variables (unserved load or prioritized load shedding). This keeps the simulation numerically well-posed and produces diagnostics that are directly relevant to energy-management design. Figure 1 summarizes the scenario-driven workflow and the deterministic runtime loop used in *mcpowersimpy*.

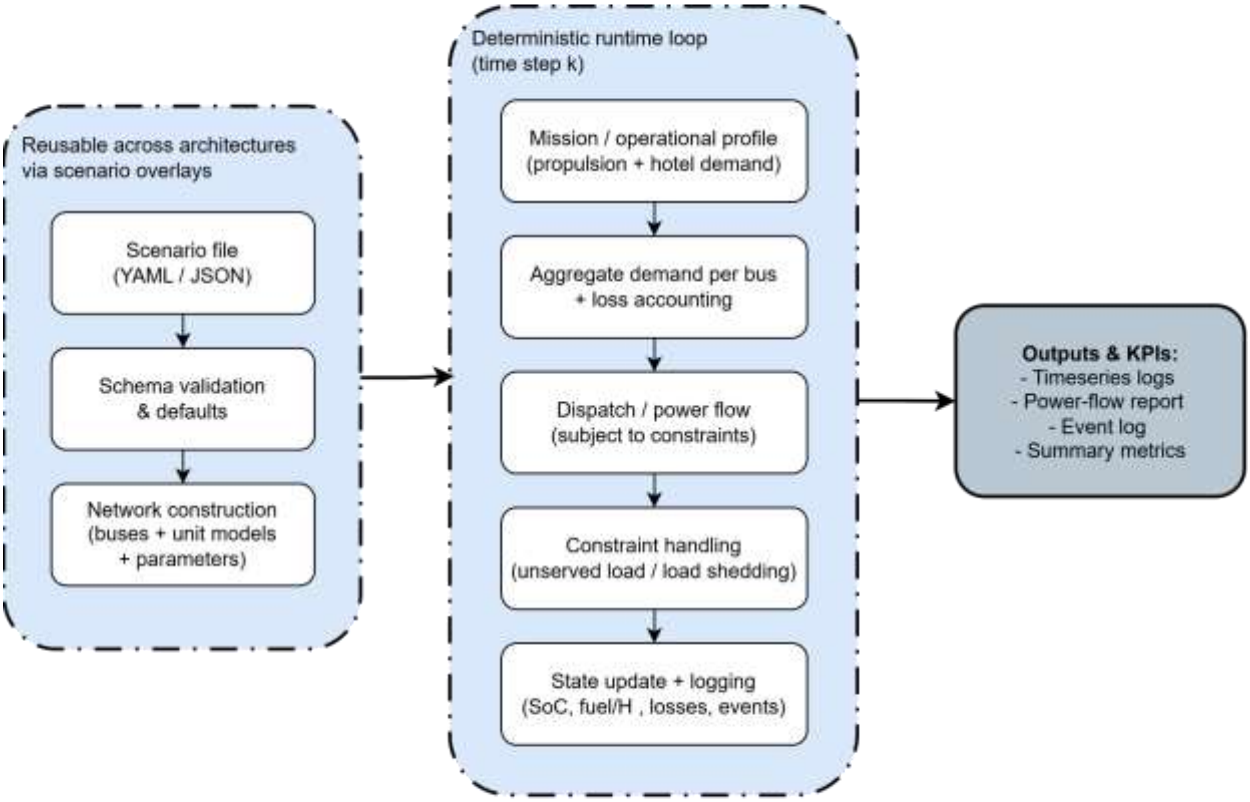

Figure 1. *mcpowersimpy* workflow and reference simulation loop.

4 OUTPUTS AND VALIDATION METHODOLOGY

Each run emits a compact, reviewable record that includes time-series logs (bus voltages/powers, losses, storage states), standard plots, a power-flow report (stage-by-stage cumulative losses), and an event log. Verification proceeds from unit checks to integration checks to system validation, ensuring results are physically consistent and traceable. These checks are complemented by KPI reporting for conversion losses, energy use, emissions factors, and constraint violations to support consistent benchmarking across scenarios. Such standardized logs are intended to support systematic verification and comparison against testbed-derived profiles and to support co-simulation integration testing using the Open Simulation Platform (Smogeli et al. 2020).

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Sizing optimisation of hybrid energy conversion for sustainable inland navigation

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1 INTRODUCTION

Vessel design makes a compromise between operational range and cargo capacity, as there is a limit to the weight a ship can carry. In conventional fossil-based energy and power systems, this compromise is relatively minor given the higher energy densities of fossil-based fuels and powertrains. However, the same cannot be said for greener alternative energy carriers, as their lower energy densities and larger storage requirements reduce payload capacity and add weight.

A key challenge related to the choice of alternative power and energy systems for inland vessels is related to onboard storage and integration. As mentioned earlier, compared with conventional diesel fuel, the low energy densities of these alternatives necessitate an additional volume or weight to accommodate the equivalent capacity of diesel fuel. This issue is further exacerbated by specific storage containment methods and non-negotiable safety considerations.

Particularly for inland navigation, this requires optimal energy system sizing and energy management strategies for different powertrain configurations within the constraints of the possible availability of infrastructure. However, methods for sizing energy systems and energy management are mainly for maritime applications. (Hein et al. 2022) proposed a probabilistic risk-averse method for energy storage sizing for a fully electric ship. With a Monte Carlo simulation, the authors generated varying operational profiles to account for uncertainties in voyage planning based on mission and payload constraints. (Li et al. 2023) utilises an adaptive multi-objective approach for energy management and system sizing, aiming to achieve minimum investment cost and minimum battery degradation in a hybrid propulsion powertrain. Similarly, (Wang et al. 2025) proposed a multi-objective optimisation method to balance ship endurance, cargo capacity utilisation, and emission reduction for bio-methanol hybridisation for container ships.

2 METHOD

This study evaluates hybrid propulsion configurations (Internal Combustion Engine (ICE)–battery and Fuel Cell (FC)–battery) using a time-dependent sizing and energy management optimization model.

Objective Function

The objective is to minimize the total primary energy consumption over the operating profile:

$$\min \sum_{t \in T} \left(\frac{P_t^\chi}{\eta^\chi} - P_t^{\mathrm{bat}} \right) \Delta t, \quad \chi \in \{\mathrm{ICE,FC}\}$$

where P_t^χ is the converter power, η^χ its efficiency, and P_t^{bat} the battery power.

System Constraints

At each time step, propulsion demand must be satisfied, and the converter output is limited by its installed capacity:

$$P_t^\chi + P_t^{\mathrm{bat}} = P_t^{\mathrm{dem}}, \quad \forall t \in T$$
$$P_t^\chi \leq S^\chi, \quad \forall t \in T$$

where S^χ is the design variable representing converter size.

The battery state of charge (SoC) evolves dynamically as and subject to operational limits:

$$SoC_t = SoC_{t-1} - \eta_{\mathrm{bat}} P_t^{\mathrm{bat}} \Delta t$$
$$0.2\, C^{\mathrm{bat}} \leq SoC_t \leq 0.8\, C^{\mathrm{bat}}, \quad \forall t \in T$$

where C^{bat} is the battery capacity. Battery degradation is not considered.

Power Management

Two energy management strategies have been implemented. For the fuel cell configuration, the converter operates as a steady base-load unit following a smoothed demand profile:

$$P_t^{\mathrm{FC}} = P^{\mathrm{sm}} = f(P^{dem}, u) \mid_{u \in \mathcal{U}}$$

where $\mathcal{U}$ is the set of smoothing parameters. The battery compensates for transient and peak loads. However, for the internal combustion engine configuration, a threshold-based control strategy is applied to maximise efficiency:

$$P_t^{\mathrm{ICE}} = \min\left\{P^{\mathrm{high}},\ \max\left\{P^{\mathrm{low}},\ P_t^{\mathrm{dem}}\right\}\right\}$$

Battery power balances the remaining demand:

$$P_t^{\mathrm{bat}} = P_t^{\mathrm{dem}} - P_t^{\mathrm{ICE}}$$

In both configurations, the converter supplies base-load power while the battery absorbs load fluctuations, discharging during peak demand and charging during low-load operation.

3 RESULTS

Using the proposed methodology, a propulsion power profile was generated for a round trip on the Rhine River between Rotterdam and Köln (see fig 1 a). The simulation accounts for loading conditions, river current, and waterway geometry (depth and width) in both sailing directions, and as can be seen in the distribution, more propulsion power is required in the upstream voyage relative to the downstream voyage.

A conventional direct internal combustion engine (ICE) configuration was used as a reference benchmark to evaluate the two hybrid concepts (ICE–battery and FC–battery). The resulting propulsion power balances and instantaneous efficiencies are shown in fig 1 b.

For the FC–battery configuration, the fuel cell operates at a smooth and stable power level, maintaining high efficiency, while the battery compensates for transient loads through charge and discharge cycles.

In the ICE–battery configuration, the engine is controlled to operate near its optimal efficiency region fig 1 c. Compared to the fuel cell system, the ICE accommodates a larger share of short-term fluctuations. However, during the upstream leg, sustained high propulsion demand leads to continuous battery discharge, with recharging mainly occurring downstream.

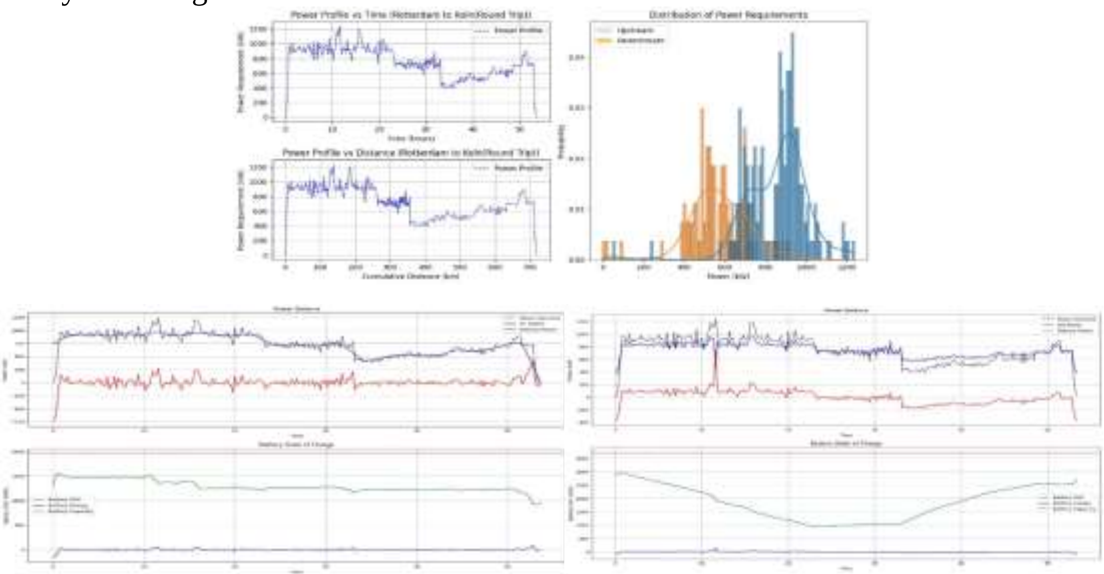

Figure 1: a) Power Profile b) Fuel cell -Battery Configuration c) ICE - Battery Configuration

4 CONCLUSIONS

The ICE–battery system handles peak loads flexibly, while the FC–battery system operates more steadily and efficiently. Energy demand varies strongly with upstream and downstream conditions, and river geometry further amplifies these effects.

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Techno-economic assessment of hydrogen retrofits for feeder containerships

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Extended Abstract

1 INTRODUCTION

The maritime sector faces increasing pressure to reduce greenhouse gas (GHG) emissions. Shipping is widely regarded as a hard-to-abate industry due to long vessel lifetimes and high propulsion energy demand. In response, the International Maritime Organization (IMO) revised its 2023 GHG strategy, targeting net-zero emissions by 2050 (Brouzas et al., 2025; Li et al., 2025). Achieving this target will require large-scale retrofit or replacement of existing vessels (Kondratenko et al., 2025).

Hydrogen fuel cells are considered a zero-carbon propulsion option because they eliminate operational emissions at the point of use (Jang et al., 2022). Pilot projects such as MF Hydra and the H_2 Barge program have demonstrated the technical feasibility of hydrogen based marine propulsion (Aida Čučuk, 2024; Ajsa Habibic, 2023). However, applying hydrogen to feeder containerships remains challenging because of its low volumetric energy density, which requires larger onboard storage systems and may reduce cargo capacity. In addition, hydrogen retrofit systems involve high capital expenditure and uncertain fuel price trajectories.

This study addresses that gap by developing a fleet-informed techno-economic framework to evaluate hydrogen retrofit options under different fuel price and carbon-pricing scenarios.

2 METHODOLOGY

The technical basis of the assessment was established using a statistical dataset of 3,873 feeder containerships. Linear regression was applied to key principal dimensions, and both LOA-Beam and LOA-Draft showed strong linearity ($R^2 > 0.8$), sup-porting the selection of a representative 1,800 TEU feeder containership (16,488 GT, 14,280 kW) as the case vessel. Operational characteristics were modelled using a non-linear relationship between speed and fuel consumption ($R^2 = 0.78$). The analysis also accounts for storage-related cargo capacity loss.

The economic evaluation was conducted over 25 years using Total Cost of Ownership (TCO) and Net Present Value (NPV). A discount rate of 7.18% was applied. The retrofit capital cost is estimated at USD 75 million. TCO indicates cumulative cost parity, while NPV reflects discounted investment recovery.

3 RESULTS AND DISCUSSION

Figure 1 presents the Total Cost of Ownership (TCO) trajectories of the evaluated fuel pathways over the 25-year project horizon. In addition to the baseline HFO and LH_2 cases, three compressed hydrogen (CH_2) price scenarios are included: a high-price case (USD 4.3/kg), a moderate case (USD 2.5/kg), and a low-price case (USD 1.0/kg). These scenarios are used to show how hydrogen price uncertainty affects the long-term cost competitiveness of the retrofit option.

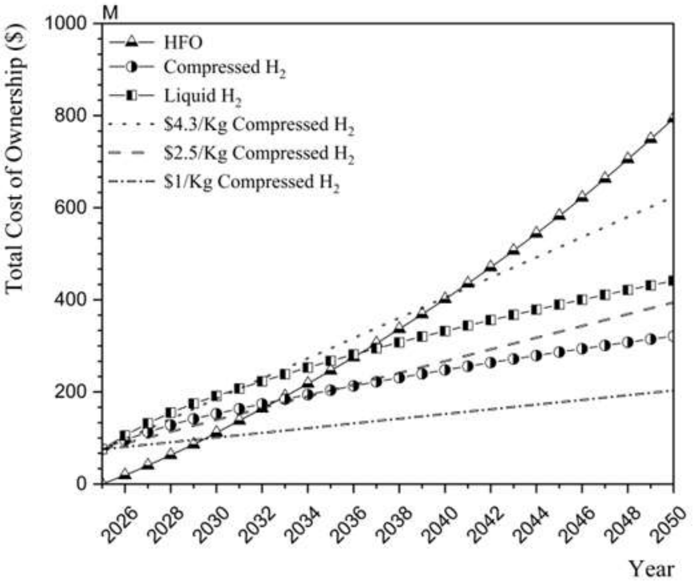

Figure 1. Total cost of ownership evolution of different fuel over a 25-year operational period under the modelled scenarios.

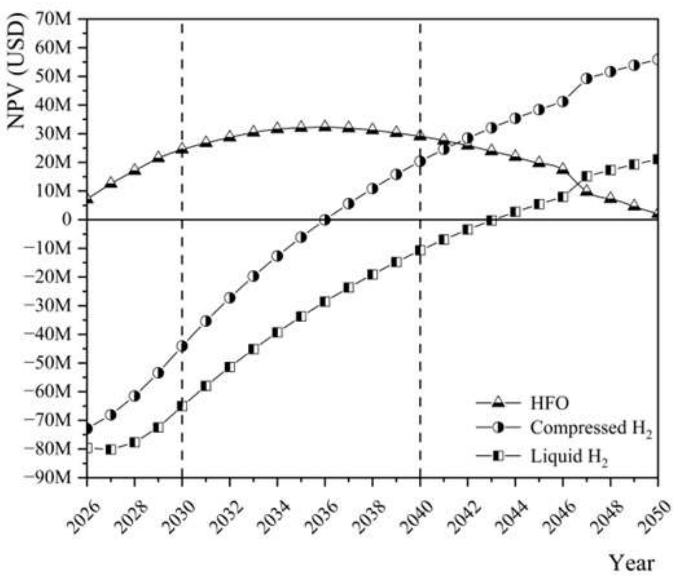

Figure 2. Net Present Value Evolution of Different Fuel Options Over A 25-Year Operational Lifecycle (2026-2050) for the Vessel.

As shown in Figure 1, the CH_2 pathway consistently outperforms LH_2 across all scenarios. Although LH_2 offers higher energy density and requires less storage volume, liquefaction introduces additional energy and cost burdens, increasing lifecycle cost. Under baseline conditions, CH_2 reaches TCO parity with HFO after approximately 8 years, while LH_2 reaches parity later due to these additional costs. Lower CH_2 prices accelerate parity, whereas higher prices delay it but remain more competitive than LH_2. TCO therefore indicates the point at which hydrogen retrofits become operationally cost-competitive.

The NPV results provide a complementary perspective by accounting for the time value of money, as shown in Figure 2. CH_2 reaches NPV breakeven after approximately 11 years, showing that investment recovery occurs later than cost parity. This three-year gap reflects the impact of high upfront capital costs. LH_2 requires a significantly longer recovery period and does not achieve comparable financial performance within the project horizon.

Overall, CH_2 provides a better balance between technical feasibility and economic performance, while LH_2 remains constrained by the additional cost and energy burden of liquefaction.

4 CONCLUSIONS

This study assesses the techno-economic feasibility of hydrogen retrofits for feeder containerships using a fleet-based approach and lifecycle analysis. The results show clear differences between CH_2 and LH2. LH_2 does not achieve positive NPV within the vessel lifetime, whereas CH_2 reaches TCO parity with HFO after approximately 8 years and NPV breakeven after about 11 years.

These results indicate that retrofit feasibility is pathway-dependent and governed by the balance between storage constraints, cargo-capacity loss, and lifecycle economic recovery, rather than fuel substitution alone.

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Minimizing Port Emissions for a Strait of Messina Ferry through Methanol Fuel Cells and LTO Battery Hybridization.

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Extended Abstract

To meet stringent IMO emission regulations, the shipping industry is adopting alternative fuels and hybrid-electric systems, with ferries acting as ideal early candidates. This paper presents a hybridization strategy for a passenger ferry operating in the Strait of Messina, with the specific objective of achieving zero-emission operations during port stays (ZEP). This specific case study was previously investigated in (Baia et al., 2023), which analyzed full-electric and ZEP architecture relying exclusively on battery-based configurations and in-port shore charging. Specifically, concerning this marine area, the initial focus was on analyzing the pollution levels within the Port of Messina. According to Transport & Environment (2023), 48 cruise ships dock in the port annually, keeping their engines running to power onboard services for a total exceeding 1,500 hours. The estimated emissions are as follows: SO_x = 4,369 kg; PM5 = 4,857 kg; NO_x = 195,626 kg; CO_2 = 12,595,624 kg. These emissions are equivalent to a threefold increase in annual urban traffic; furthermore, PM5 and SO_x levels have risen by more than 38% over the last four years. To mitigate emissions during port stays, solutions such as cold ironing could be considered. However, for ferry, the brief docking duration poses a significant challenge. In this scenario, factoring in the plug-in and unplug-in times required to connect to a potential onshore charging infrastructure, the effective port stay time would be further reduced, thereby resulting in an extremely high-power demand from the ferry. Consequently, this solution proves unfeasible to implement in both ports, due to the logistical constraints of integrating new infrastructure within already developed areas, leading to a lack of available space, as well as the necessity of transmitting substantial electrical power on board. In the existing configuration, two diesel engines are typically dedicated to propulsion, while the third provides redundancy and emergency support. The hybrid system is designed to allow complete shutdown of the remaining diesel engines during port stays, thereby eliminating localized greenhouse gas and pollutant emissions in proximity to urban centers. The proposed architecture achieves almost negligible direct emissions in port proximities, specifically during maneuvering, hoteling, and acceleration phases, by deactivating the main engines. Power is instead supplied by a hybrid system comprising a Fuel Cell (HT-PEMFC) unit operating at a constant power output, integrated with an Energy Storage System (ESS). The ESS functions as an energy buffer, effectively mitigating the fuel cell's inherent limitations in tracking highly variable electrical loads. Ferry operations can be classified into two main categories: cruising, representing steady-state navigation at service speed, and transient operations, which include maneuvering at sea, hotelling and maneuvering in port, including acceleration during departure. The data were obtained using MATLAB/Simulink software. Based on the ferry's power data recorded during a specific route, the power demand of the engines was determined. Subsequently, the average power was calculated and integrated over time to obtain the overall energy demand of the vessel. Fuel consumption was similarly derived from data provided by the operating company, which also supplied the emission factor required to calculate the CO_2 emissions based on the Marine Diesel Oil (MDO) consumed. This enabled the calculation of the average power required for the ZEP solution, which was evaluated at approximately 750 kW to support the port approach, hotelling, and acceleration phases. Consequently, the deployment of two HT-PEMFC modules per engine was proposed; given that the vessel's peak power demand is 400 kW per engine during transient operation, a nominal maximum capacity of 500 kW ensures an adequate safety margin (considering that the average efficiency of a converter is typically above 90%). Finally, the net difference between the energy demanded and the energy supplied by the fuel cells was utilized to simulate the behavior of the battery pack within the Simulink environment. Figure 1 presents the power profile analysis of the ferry during a standard crossing and the power supplied by the fuel cell, whereas Table I summarizes the corresponding operational times, distances and energy requested.

The system utilizes HT-PEMFC fed by methanol, featuring an integrated reformer within the module that converts methanol into the hydrogen required to power the cells, a choice that simplifies onboard fuel storage and mitigates the volumetric and safety constraints associated with compressed or liquefied hydrogen. Complementing the fuel cell system, a Lithium Titanate Oxide (LTO) Battery Energy Storage System is installed as a high-power dynamic buffer. The selection of LTO chemistry is motivated by its capability to withstand extreme charge and discharge rates without accelerated degradation. For the proposed solution, a total of two ESS,

one for each engine, were considered and subsequently simulated. Each ESS features a capacity of 400.2 kWh and a nominal voltage of 1000.5 V, specifically selected to closely match the 1000 V of the DC bus. Using the specifications discussed above regarding power demand, HT-PEMFC power output, and the characteristics of the chosen ESS, a Simulink-based simulation was carried out. The results validated the proposed energy sizing, demonstrating a neutral energy balance on the ESS and a reduction in MDO consumption, offset by the methanol used to operate the fuel cell. Table II compares the traditional and proposed configurations, highlighting the advantages in terms of reduced weight, fuel consumption, and emissions. Furthermore, preventing the engine from operating at excessively low speeds ensures the complete elimination of SO_x, NO_x and PM5 near the coastal areas.

Table I – Operations during a ride

	Cruising	Transient operations: - Maneuvering - Hotelling - Acceleration
Time	13 min	27 min
Distance	3 nm	0.6 nm
Energy consumption	354.4 kWh	608.6 kWh

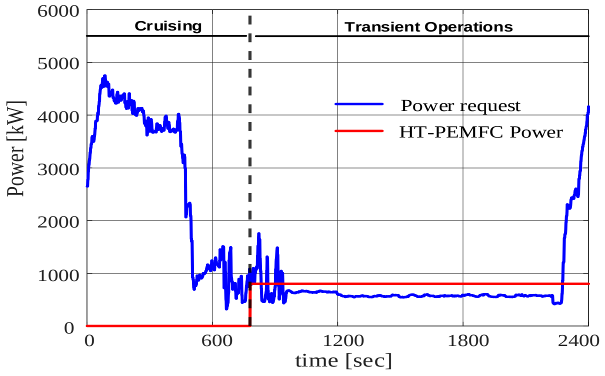

Figure 1 – Powers profile

Table II – Configurations comparison

Parameters	Traditional configuration	Proposed configuration	Reduction
Weight [kg]	~50,000	~45,000	10%
MDO Consumption [kg/ride]	235	128	45%
MeOH Consumption [kg/ride]	/	363.64	/
CO_2 emissions [kg/ride]	753	637	15%

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4E analysis of an ammonia-fuelled solid oxide fuel cell and Rankine cycle integrated power system for an LNG carrier

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Extended Abstract

Greenhouse gas emissions from maritime activities are increasing and threatening the world. To limit greenhouse gas emissions, the International Maritime Organization (IMO) has taken decisions at a level that pushes the techno-economic limits of the maritime sector and has started to put these decisions into effect in various phases. While it is known that ammonia fuel will play an important role in decarbonization in the future, there are problems with its use in internal combustion engines, such as low reactivity and combustion speed, ammonia slipping, and significant N_2O emissions. The use of ammonia in fuel cells can eliminate these problems, and moreover, with newly developed materials, much higher performance levels can be achieved than both conventional power systems and previous-generation fuel cells.

In this study, a proton-conducting solid oxide fuel cell (PC-SOFC) has been modelled electrochemically and thermodynamically and integrated into a Rankine cycle (RC) for a Q-Flex type LNG carrier. Integrated systems are simulated by Aspen HYSYS thermodynamically, and energy, exergy, economy, and environmental (4E) analyses are carried out. The operating temperature of the PC-SOFC is selected as 800°C, the current density is selected as 5kA/m^2, and the operating life is 36,000 hours. The effect of three fuels-green, blue, and black ammonia-on cost was investigated. The power loss caused by degradation has been compensated for by the LNG-powered RC. The results were compared with SOFC integrated alternative systems on the same vessel, which were examined in the author's previous study. Although several studies have investigated ammonia-fueled SOFC-RC systems for marine applications, none have incorporated fuel cell degradation into system-level analyses, reported CO_2 abatement cost metrics, or comparatively assessed different ammonia production pathways. Therefore, this study addresses these gaps and provides a novel contribution to the field.

Various studies in the literature have shown that ammonia can be completely thermally decomposed at 600°C even on a very thin anode layer using Ni catalysis (Ni et al. 2008). Therefore, this study accepts that ammonia is completely decomposed when using a Ni-based anode safely. Ammonia is internally heated and decomposed. The thermodynamic model based on a black-box approach has been developed that predicts the temperature of the SOFC stack will remain constant at 800°C. The cathode-out gas heats the air entering the cathode via a regenerative heat exchanger, while the anode-out gas both heats the anode inlet and superheats steam at 16 bar for the RC. Additionally, fuel that does not react at the anode is burned in a boiler, and superheated steam is produced using a three-stage heat exchanger. Extra power is generated in the RC from the superheated steam produced. Although it is possible to generate more power from the RC due to the increased waste heat resulting from degradation, the power lost in the SOFC exceeds this gain, and this loss must be compensated for. Therefore, required power is generated from the RC by burning LNG fuel in an additional boiler, with the amount of fuel used increasing over time while it is not required at the start of the operation. The air and fuel utilization ratios for the cells are 0.5 and 0.85, respectively. In the cell under study, Ni/BZCYYb1711 was selected as the anode material and LSCF/BZCYYb1711 as the cathode material; the anode thickness is 600 µm and the cathode thickness is 30 µm. An innovative bilayer electrolyte was used, consisting of a 9 µm-thick layer of BZY20 and a 1 µm-thick layer of LWO67 as the interlayer (Yamate & Otomo 2023). The electrochemical model of SOFC is established by subtracting activation, ohmic, and concentration losses from the cell's Nernst potential. Activation loss was determined using the Butler-Volmer equation, ohmic losses were determined using Ohm's law for the electrolyte, and concentration loss was determined using Fick's model (Ni et al. 2008). The loss mechanisms equations are shown in Table 1.

The validation of the developed electrochemical model was performed using experimental data from the literature as a reference, and the error margin was determined to be 6.3% in terms of Root Mean Square Error (RMSE) (Ni et al. 2008). This value indicates an acceptable degree of consistency between the model predictions and the experimental results. As a result of the study, the unit cost of CO_2 reduction using black, blue and green ammonia was calculated to be \$81.4, \$169.8, \$416.4 per ton CO_2, respectively. For all fuel types, the cost is cheaper than previously implemented hydrogen-fuelled SOFC-internal combustion engine (ICE)-RC system and reformed fuelled SOFC-ICE-carbon capture and storage (CCS) systems up to 95% for the same vessel (Güler & Ergin 2024). The CO_2 abatement cost of the compared SOFC-ICE-CCS system is $771.1/ton, with the initial investment cost of the SOFC stack accounting for the vast majority of this cost. The reason for the low cell costs in this study is that using NH_3 instead of reformed fuel, combined with the use of much more advanced materials, results in significantly higher both efficiency and power density (approximately 3.4 times higher). The CO_2 abatement cost of the compared SOFC-ICE-RC system is $1310/ton, with the majority of this cost attributed to H_2 storage tanks' initial investment cost.

Table 1. Electrochemical model equations for PC-SOFC.

Equation	Unit	References	Eq. no
$V_{cell} = V_{Nernst} - V_{act} - V_{ohm} - V_{con}$	V	-	(1)
$V_{Nernst} = E^0 - \bar{R}T/nF\ ln\left(P_{H_2,an} P_{O_2,cat}^{0.5} / P_{H_2O,cat}\right)$	V	-	(2)
$E^0 = 1.2723 - 2.4516 \times 10^{-4} T$	V	(Park et al. 2014)	(3)
$V_{act} = \bar{R}T/nF \times sinh^{-1}\left(i/2i_{0,i}\right)$	V	-	(4)
$i_{0,cat} = \gamma_{cat}\left(P_{O_2}/P_{cat}\right)^{0.25}\left(P_{H_2O}/P_{an}\right)\exp\left(-E_{act,cat}/\bar{R}T\right)$	A/m^2	-	(5)
$i_{0,an} = \gamma_{an}\left(P_{H_2}/P_{an}\right)\exp\left(-E_{act,an}/\bar{R}T\right)$	A/m^2	-	(6)
$V_{ohm} = i\ \delta_{el}/\sigma_{el}$	V	-	(7)
$V_{con} = -\bar{R}T/nF\ \ ln\, y_{1,A/E}\ y_{2,bulk}/y_{1,bulk}\ \ y_{2,A/E}$	V	(Suwanwarangkul et al. 2003)	(8)
$y_1 = y_{1,bulk} - JRTz/nFD_{1,T}^{eff} P$	V	(Suwanwarangkul et al. 2003)	(9)
$D_{1,T}^{eff} = 1/\left(1/D_{1,k}^{eff}\right) + \left(1/D_{1N_2}^{eff}\right) + \left(\left(1/D_{12}^{eff}\right) - \left(1/D_{1N_2}^{eff}\right)\right)\left(1 - y_{N_2}\right)$	A/m^2	(Suwanwarangkul et al. 2003)	(10)
$D_{12}^{eff} = 1x10^{-7} T^{1.75} \varepsilon (1/M_1 + 1/M_2)^{0.5} / P\zeta\left(v_j^{1/3} + v_k^{1/3}\right)$	m^2/s	(Suwanwarangkul et al. 2003)	(11)
$D_{1,k}^{eff} = 97r\ \varepsilon/\xi\sqrt{T/M_i}$	m^2/s	(Suwanwarangkul et al. 2003)	(12)
$V_{cell,t} = V_{cell,ini.}(1 - h)^{t/1000}$	V	(Li et al. 2024)	(13)
$h = 0.365U_f.(\exp(2.50i) - 1)$	-	(Li et al. 2024)	(14)

Additionally, the low storage capacity of these tanks relative to their weight has significantly increased shipping losses and costs; however, these costs are eliminated by using ammonia as fuel. Furthermore, in the comparative study using H_2 as fuel, cell efficiency was 57.2% at the beginning of the operation at 800°C and a current density of 2.5 kA/m²; in this study, under the same conditions, an efficiency of 77.6% was achieved, and at a current density of 5 kA/m², 76.2% efficiency was attained. On the other hand, as a result of degradation in the fuel cell, it was found that after 36,000 hours of operation, the total system efficiency dropped to an acceptable level of 49.0%. At the start of the operation, the exergy loss in the SOFC stack is 3.18 MW, with a total loss of 9.76 MW. By the end of the stack's service life due to degradation, the exergy loss in the SOFC stack reaches 8.24 MW, while the total exergy loss rises to 30.7 MW. Finally, considering the system's lifetime, it reduces CO_2 by 81.5%. These results demonstrate that new materials can drastically reduce the initial investment costs of fuel cells and greatly enhance efficiency, challenging conventional wisdom. It is also clear that the use of ammonia will eliminate the problem of storing H_2. The results hold great promise for the future use of the proposed system in ship energy systems.

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Direct Methanol Fuel Cell for a zero-noise and low-emission system on fishing boats

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Extended Abstract

This study presents a feasibility analysis of a hybrid energy system designed to supply onboard electrical services for fishing vessels under 10 meters in length. Static fishing activities involving extended periods at the anchor may require main engine to remain running in order to supply electrical loads onboard. The investigated hybrid system includes a local zero-emission battery charger based on a direct methanol fuel cell and photovoltaic arrays for charging a lithium iron phosphate (LiFePO4) battery storage system. Photovoltaic panels are an appealing solution for renewable energy generation on vessels; however, they are inherently intermittent due to the variability of solar radiation, which can fluctuate significantly with weather conditions and seasonal changes. This limitation often necessitates integrating the system with an additional energy source to maintain a continuous power supply. In this context, Direct Methanol Fuel Cells (DMFCs) represent a promising technology for small-scale marine power generation applications. Recently, among the alternative fuels proposed for the maritime sector, methanol has gained increasing attention as a potential energy carrier for the transition towards low-emission power systems. Methanol offers several advantages over other emerging fuels, such as hydrogen or ammonia. It can be stored in liquid form under standard conditions, simplifying storage and refuelling operations.

Additionally, methanol has a simple supply chain and can often use existing oil infrastructure. In this scenario, the direct methanol fuel cell can serve as an auxiliary generator to compensate for periods of low photovoltaic output or during the night. The potential of methanol to be fully renewable through direct carbon dioxide capture from the atmosphere and green water electrolysis makes it an ideal candidate for the transition toward low-emission systems where full electrification may not be feasible. The novelty of this study lies in a low-cost energy management architecture, which is based on a Raspberry Pi 4 B (RPi). It is used for real-time monitoring of key operating parameters, including battery state of charge, power, and temperature, managing energy flows. The aim of this work is to develop a compact, silent, and low-emission energy system capable of autonomously powering onboard service loads during static fishing activities when main propulsion motor is turned off.In the long term, solution of this typology could contribute to the development of more sustainable energy systems for specific maritime sector, representing a step ahead into the onboard implementation of potentially renewable fuels. Figure 1 shows the hybrid solar-fuel cell system charging a homemade $LiFePO_4$ battery pack. The implementation of sensor fusion could improve overall system performance by enabling autonomous energy flow management based on different weather conditions, using low-cost GPS sensors. Real-time positioning could enable the integration of weather station data with the edge infrastructure to determine the optimal timing for autonomously switching power generation from solar panels to the DFMC during periods of low solar production.

Figure 1: Hybrid solar-fuel cell charger.

Figure 2 shows a schematic layout of the hybrid solar-fuel cell charger on an 8 meters fishing boat.

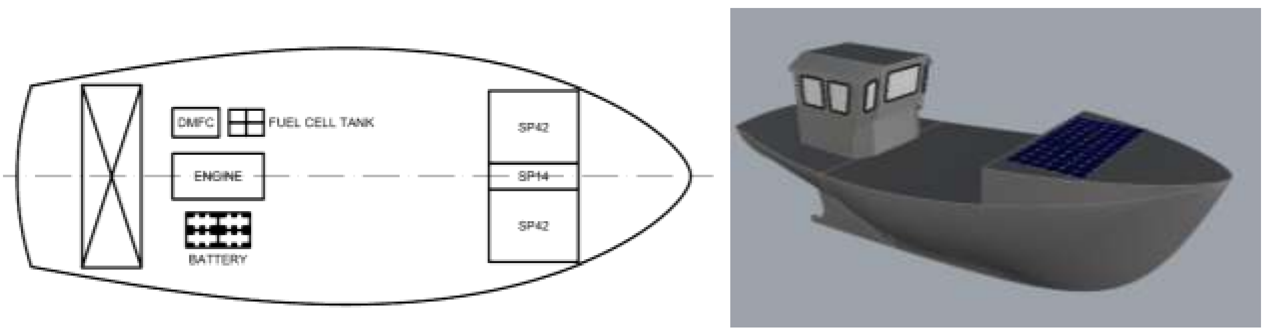

Figure 2. Solar panels and Direct Methanol Fuel Cell installed on an 8 meters fishing boat

ACKNOWLEDGEMENTS

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Theoretical investigation of the methanol fuel cell to recharge a lithium battery

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1 GENERAL INTRODUCTION

Marine transport produces 3% of the global greenhouse gas emissions. The International Marine Organization aims to decrease the emissions of marine transport to net zero by 2050. The combination of the lithium battery with a methanol fuel cell has emerged as a potential technology to reduce greenhouse gas emissions (Yuksel, 2023). This paper presents a theoretical investigation of the capability of the methanol fuel cell to recharge a lithium battery for marine applications through its MATLAB/Simulink modelling.

2 METHODS AND MODEL

The system model for recharging a lithium battery using a methanol fuel cell (**Fig. 1**), consists of "Methanol fuel cell", "Direct current (DC) / DC converter", "Discharging/charging controller", "Lithium-battery" and "DC / alternating current (AC) converter".

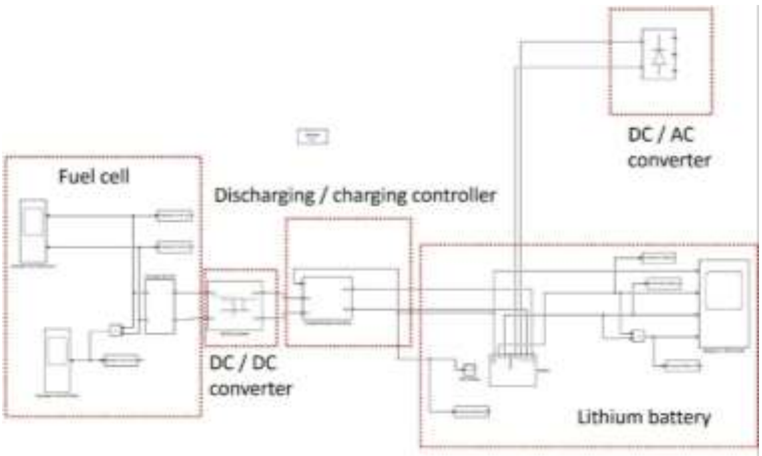

Fig. 1. Schematic drawing of the discharging / recharging model.

The model of the methanol fuel cell was developed based on the Nernst equations (Equation (1)) (Afif et al., 2016).

$$E = N[E_{ocp} + \frac{RT}{Fn_e} ln\left(\frac{[React]^m}{[Prod]^n}\right) - R_{ohm}i - \frac{RT}{Fn_e} ln\left(\frac{i}{i_o}\right) + \frac{RT}{\alpha Fn_e} ln\left(1 - \frac{i}{i_l}\right)] \quad (1)$$

where, E = the voltage of the fuel cell in operation mode, N = the number of the fuel cells in the stacks, E_{ocp} = the voltage of the fuel cell for open circuit mode, R = the ideal gas constant, T = the fuel cell temperature, F = Faraday's constant, n_e= the electrons transferred in the electrochemical reactions, $[React]^m$ = the partial pressure with the stoichiometric power factor (m) of the reactants, $[Prod]^n$ = the partial pressure with the stoichiometric power factor (n) of the products, R_{ohm} = the ohmic resistance, i = the current produced by the fuel cell, i_o = the current of the fuel cell in the open circuit, α = the cathodic slope, and i_l = the current limit of the fuel cell. The methanol fuel cell stack comprised 60 cells, each with 100 cm^2 of active area, and operating with

13.92 atoms of fuel pressure. The model for the lithium battery was further designed based on the electrochemical mechanism as a function of Equation (2) (Motapon et al., 2013).

$$E_{Bat} = E_{nom} - \frac{AQ}{Q - \int i_{Bat} + \int i_{char}} + Be^{-(C \int i_{Bat} - \int i_{char})} - i_{Bat} AQ [\left(\frac{1 - i_{neg}}{Q - \int i_{Bat} + \int i_{char}}\right) - \frac{i_{neg}}{\int i_{Bat} + \int i_{char} - 0.1Q} \qquad (2)$$

where, E_{Bat} = the supplied voltage, E_{nom} = the nominal voltage, A = the polarisation voltage, Q = the maximum capacity, i_{Bat} = the positive current, i_{char} = the charged current from the fuel cell, B = the exponential voltage, C = the exponential capacity, and i_{neg} = the negative values of the current. The lithium battery specifications were sourced from the exiting literature (Yuksel, 2023). Total simulation time was set to 4 days (350000 s), during which multiple discharging / recharging cycles were simulated to ensure the statistical significance of the results. The recharging process began at 0% of SOC and terminated upon reaching 100% of SOC. The inherent charging limitations of the lithium battery and the temporal degradation of both devices were assumed to be as negligible in the present simulations.

3 SIMULATION RESULTS

The temporal evolution of the lithium battery features (voltage, current, power, and SOC) was distinct in function to the charging and the discharging process (**Fig. 2**). The voltage (**Fig. 2(a)**), current (**Fig. 2(b)**), and power (**Fig. 2(c)**) of the battery exhibited comparable dynamic responses during both recharging and discharging processes. Conversely, the SOC trend (**Fig. 2(d)**) for both the recharging and discharging processes differed from that of other battery features.

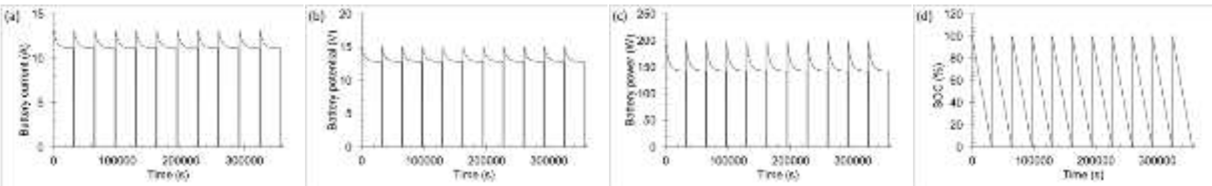

Fig. 2. Temporal evolution of the lithium battery (a) current, (b) voltage, (c) power, and (d) SOC during the charging / discharging cycle stage

The methanol fuel cell features (**Fig. 3**) displayed similar temporal behaviour, with two distinct trends corresponding to the discharging (low value) and recharging (high magnitude) processes of the lithium battery. The recharging process was completed in less than 15 minutes, whereas the supplier specifications for the selected model (Motorola 12.8 V) indicated a typical recharging time of approximately 1 hour (Yuksel, 2023).

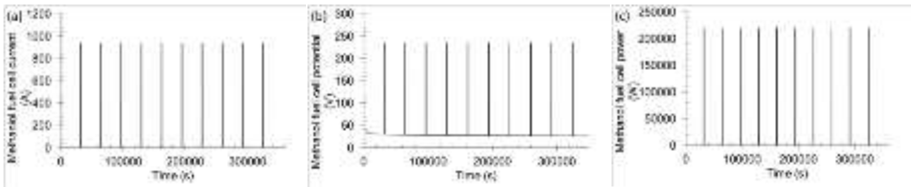

Fig. 3. Temporal evolution of the methanol fuel cell (a) current, (b) voltage, and (c) power during charging / discharging cycle stage.

4 CONCLUSIONS

1. The temporal behaviour of the discharging and recharging processes for the lithium battery and methanol fuel cell can be investigated using the proposed model, capturing the behaviour of their respective features.
2. The methanol fuel cell is able to charge the lithium-battery and its recharging time at 100 % is less than 15 minutes, which serves as an energy source, indicating its potential applicability in the maritime transport sector.

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Ejector H_2 recirculation in marine PEMFC: CFD and geometric scaling

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1 INTRODUCTION

The decarbonisation of maritime propulsion increasingly relies on hydrogen-based technologies, among which proton exchange membrane fuel cells (PEMFCs) stand out for their high-power density and fast dynamic response. In medium and high-power installations, the anodic recirculation system (ARS) is a critical component: hydrogen must be supplied in stoichiometric excess to prevent fuel starvation, and the unreacted fraction must be recovered to maintain acceptable system efficiency.
Ejector based ARS solutions have attracted growing interest due to their fully passive operation, i.e. no moving parts, no auxiliary power consumption (Liu et al., 2021); on the other hand, their performance is strongly correlated to geometric features and is condition dependent, making accurate modelling an essential step in the design process. This work presents a CFD based methodology for modelling, bias correction, and geometric scaling of a hydrogen ejector, targeting a 200 kW PEMFC stack for marine applications.

2 CFD MODEL AND EXPERIMENTAL VALIDATION

A 2D axisymmetric steady state model was developed, solving the compressible RANS equations under the assumption of ideal gas and single phase. The Realizable k–ε model with enhanced wall treatment was selected for its robustness in flows with strong velocity gradients, separation, and intense mixing. A density-based solver was adopted to handle the supersonic regime downstream of the primary nozzle. The structured mesh (~138,300 elements) was chosen after a three-grid independence study (coarse / base / fine) that monitored the axial Mach number distribution; the three solutions showed substantial agreement, with slight divergence emerging only in the mixing chamber region (see Figure 1).

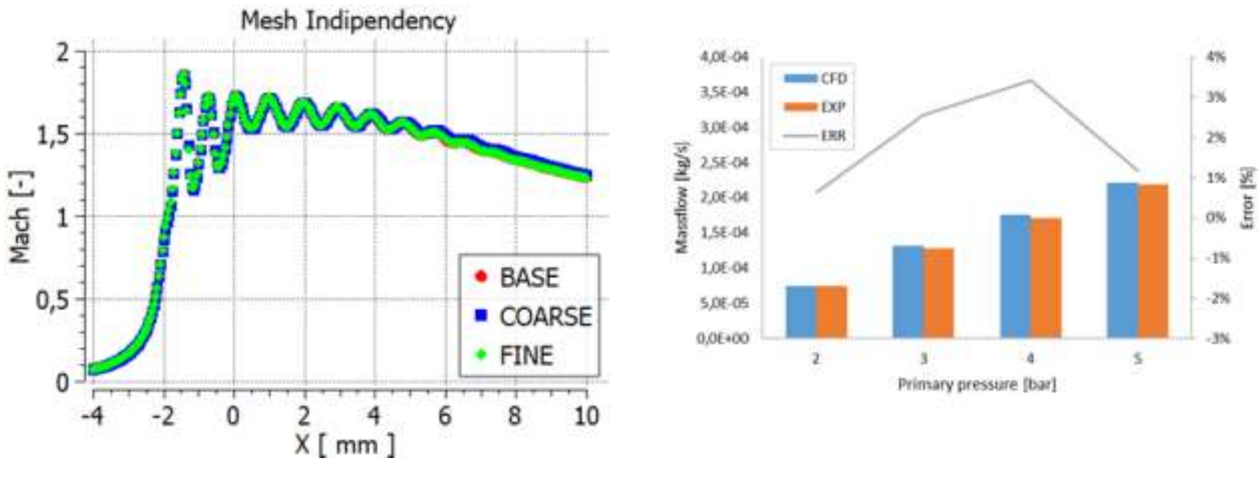

Figure 1. Mach number distribution along the ejector axis for the three tested meshes (left) and comparison between simulated and measured primary mass flow rates (right).

The model was initially validated against experimental data for a 5 kW PEMFC ejector system across several primary pressure levels (Nikiforow et al., 2016). Simulated primary mass flow rates showed good agreement with measurements, correctly capturing the nozzle choking behaviour. A known limitation of 2D axisymmetric models is the systematic overestimation of the secondary (recirculated) flow rate (Mazzelli et al., 2015). In the present case this bias is amplified by the asymmetric geometry of the secondary inlet, which departs significantly from ideal axial symmetry. A linear regression (Figure 2) was therefore fitted on the available experimental data, using primary pressure and pressure difference between outlet and secondary as predictors of the relative error on the entrainment ratio ($R^2 \approx 0.80$). Its structural validity, with updated coefficients, is expected to extend to the scaled geometries properly validated through experimental campaign.

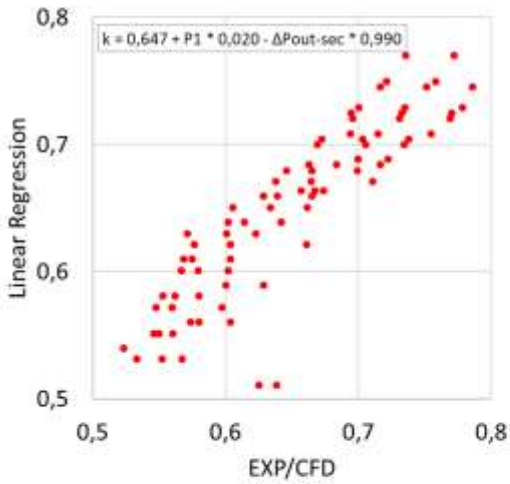

Figure 2. Proposed linear regression to correct axyalsimmetry bias.

3 GEOMETRIC SCALING AND RAPID PROTOTYPING

Ejector performance does not scale linearly with power. The scaling strategy adopted here preserves the key non-dimensional geometric ratios governing entrainment ratio and operational stability (Pei et al., 2019): mixing chamber to nozzle diameter ratio, mixing chamber aspect ratio, nozzle axial position, and diffuser half-angle. Absolute dimensions are anchored by sizing the primary nozzle (D_n) throat via the isentropic flow equation to ensure choked operation at the design point, the condition that decouples primary flow rate from downstream disturbances. The throat diameter scales as $D_n \propto \sqrt{P}$, so the jump from 5 kW to 200 kW yields a diameter roughly six times larger; all remaining sections follow from the preserved non-dimensional ratios.
Given the large power ratio between the 5 kW reference and the 200 kW target, an intermediate 80 kW geometry was assembled by using additive manufacturing. The primary nozzle was made as an independent component, bolted to the main body, allowing the nozzle axial distance to be varied via spacers without reprinting the full assembly.

4 CONCLUSIONS

A structured CFD based methodology has been developed for the design and scaling of a hydrogen ejector recirculation system for high power marine PEMFC applications. A 2D axisymmetric RANS model was firstly validated against 5 kW experimental data, demonstrating reliable prediction of primary flow rates and internal flow field features. A linear regression model ($R^2 \approx 0.80$) was derived to characterise and correct the systematic overestimation of the secondary flow rate inherent to the axisymmetric assumption. Dimensionless scaling rules were applied to obtain a preliminary 200 kW ejector geometry, and an intermediate 80 kW prototype has been manufactured and experimentally tested. The results confirm the feasibility of the proposed approach and provide a scalable, validated framework for ejector-based ARS design in high power fuel cell systems

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Clean hydrogen as a fuel for EU shipping: Legislation and government support

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Extended Abstract

In the EU, maritime transport accounts for 3 to 4% of total CO_2 emissions, or more than 124 million tonnes of CO_2 in 2021 (Fourth Annual Report, 2023). The European Climate Law sets greenhouse gas emission reduction targets for 2030 and 2050 (Regulation (EU) 2021/1119, 2021). To achieve these targets, EU shipping will use renewable energy sources. One such source is clean hydrogen.

Over the past few years, research on clean hydrogen has focused primarily on the technical aspects (Ruhnau & Schiele, 2023; Zeyen et al., 2024). However, the foundation for the more active use of clean hydrogen as a fuel in EU shipping is the existence of an appropriate legislative framework. International classification societies are also adopting their own documents on the use of clean hydrogen in shipping. No scientific research is available.

Another aspect that has also remained unexplored is EU support for the construction of ships that will use clean hydrogen as fuel. Therefore, the aim of this study is to analyse EU legislation on clean hydrogen as a fuel for EU shipping, documents from international classification societies and EU support for ship construction. The result of the conducted study will be shown positive and negative aspects and author recommendations will be proposed. As a result of the conducted research, positive and negative aspects will be shown and the author's recommendations will be offered.

Consideration of EU legislation to achieve zero CO_2 in EU maritime transport: Regulation (EU) 2015/757, Regulation (EU) 2023/1805, Regulation (EU) 2023/1804, Directive (EU) 2023/2413, Directive (EU) 2018/2001, Regulation (EU) 2021/1119… The EU regulations in this area are specified, which require amendments to promote the use of clean hydrogen as a fuel in EU shipping. Documents from international classification societies (IACS Members) on the subject are also analysed and compared with EU legislation. Unregulated issues that hinder the use of clean hydrogen as a fuel in EU shipping are highlighted.

Several programs in the EU related to shipbuilding that should operate on pure hydrogen have been analysed: «Greening mobility and transport», «Maritime industries»... The study was carried out according to the following criteria: 1) EU programme; 2) amount of grant for building or retrofitting a vessel; 3) duration; 4) who could take part in the programme and actual recipient; 5) the operational period of the vessel running on clean hydrogen; 6) any accidents.

The following results were obtained: 1) the recipients are shipping companies; 2) the vessels were built or converted within 2-3 years; 3) information on the actual funds spent; 4) almost all vessels were launched, all vessels passed experimental testing; 5) the actual use of vessels operating on clean hydrogen can be observed among shipowners; 6) the presence of accidents and further operation.

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Working Group 4 on Renewable energy contributions to ship energy efficiency

Operational efficiency impacts of diesel-electric propulsion and controllable-pitch propellers in wind-assisted vessels

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1 INTRODUCTION

Waterborne transportation is currently undergoing a transition toward defossilization, enabling the adoption of innovative technologies such as wind-assisted propulsion systems (WAPS). While these technologies offer substantial potential, they also introduce significant challenges related to system design, performance assessment, and onboard integration. WAPS utilize wind energy to partially or fully provide the thrust required for ship propulsion. Under unfavorable wind conditions that do not allow operation without support from the conventional propulsion system, the propeller operates under off-design conditions. In such scenarios, the application of controllable-pitch propellers (CPP) may enable efficiency gains exceeding those achievable in conventional vessel configurations. Choice of engine type is expected to have severe implications on energy efficiency. Conventional diesel engines cannot be operated for prolonged periods at loads below approximately 10% of their Maximum Continuous Rating (MCR), thereby limiting the efficiency benefits attainable through WAPS.

Only a limited number of studies have addressed the use of fixed-pitch propellers (FPP), CPP, and the influence of engine type in the context of wind-assisted propulsion. Relevant analyses have been conducted by the research groups of Molland & Hawksley (1985) and Reche-Vilanova et al. (2023). Both aim for a preliminary study based on minimal input data, which accounts for the WAPS assistance by subtracting a flat percentage of the vessel calm water resistance, without taking into account induced resistance due to drift or the actual weather conditions. In addition, numerous studies emphasize the critical role of weather routing when evaluating systems incorporating WAPS.

2 METHODOLOGY

In this study, actual weather conditions derived from historical datasets are evaluated for a defined transport task and subsequently employed in detailed, space- and time-resolved analyses. The study focuses on comparative simulations of FPP and CPP configurations combined with either conventional diesel engines or diesel-electric propulsion systems. The investigations are conducted using the in-house Odyssa framework (see, e.g. Fitz et al. (2025)). Performance prediction is based on a steady-state approach with four degrees of freedom (surge, drift, yaw, and heel), accounting for all relevant components, including hull, rudder, propeller, sails, and appendages. Route optimization is performed using a novel method Schwedt at al. (2026) that combines Dynamic Programming and the Dijkstra algorithm, with weather data sourced from the European Union's Climate Data Store.

The objective of this paper is to provide a suitable tool to support investment decisions related to novel energy systems and operational strategies by enabling accurate predictions of energy demand for different system configurations and transport tasks. The results demonstrate that consideration of the actual system specifications and prevailing environmental conditions is essential for conducting meaningful analyses.

3 CASE DESCRIPTION

The present study considers a modern sailing bulk carrier, shown in Fig. 1.

The vessel was originally conceptualized as part of a feasibility study investigating an energy self-sufficient propulsion system; a summary of the approach and findings is provided by Fitz et al. (2025). Primary propulsion is provided by four large Dynarig sails. For the routing calculations, the vessel is assumed to operate on a transatlantic route from Lisbon to New York. Daily departure events throughout the year 2019 are considered for the statistical evaluation, which is presented using box-and-whisker plots (see Fig. 2).

Figure 1: Investigated Vessel

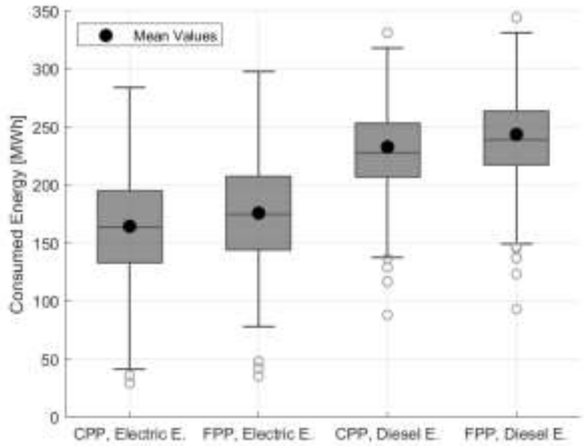

Figure 2: Statistical Evaluation of Consumed Energy during Routing Calcula-tions

4 RESULTS AND DISCUSSION

For both engine types, the use of a CPP results in energy savings, with differences in mean and median values of approximately 11 MWh, corresponding to reductions of about 6% for the diesel-electric configuration and 4.5% for the conventional diesel engine. As these values are comparable to savings reported for conventional vessels (see e.g. Kapsenberg (1964)), the findings indicate that CPP installation does not yield significantly larger efficiency gains for heavily wind-assisted ships. In contrast, comparison of mean and median values between engine types reveals that the use of a diesel-electric propulsion system enables substantial energy savings of approximately 28% and 26% for CPP and FPP configurations, respectively.

Overall, the results indicate that full or partial electrification of the propulsion system is advantageous for wind-assisted vessels. Future research may investigate the integration of power take-off (PTO) and power take-in (PTI) systems in combination with battery storage to mitigate the limitations associated with conventional diesel engines.

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Cost effectiveness of wind-assisted propulsion retrofits for maritime decarbonisation

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Extended Abstract

This paper assesses the cost efficiency of retrofitting existing vessels with wind-assisted propulsion systems (WAPS) as a near-term maritime decarbonisation measure. The international shipping sector emits approximately 3% of global greenhouse gases and faces growing regulatory pressure to decarbonise under the International Maritime Organization's (IMO) revised net-zero target for 2050. With more than 50,000 commercial vessels over 400 gross tonnes currently in service and an average fleet age exceeding 10 years, retrofitting existing ships with WAPS provides an immediate, deployable solution for fuel savings (Huang & Souppez, 2025). Nevertheless, shipowners require compelling economic evidence before investing. This paper quantifies the cost efficiency of WAPS retrofits for existing vessels. It determines achievable payback periods, net present value (NPV), and levelised cost of abatement (LCOA) across three vessel classes – tanker, bulk carrier, and general cargo – on major shipping routes. Results show typical payback periods of 2–6 years, positive 15-year NPV, and a LCOA of \$72-155/t CO_2 for most vessels operating on routes with adequate wind resources. It further identifies the routes and vessel types that maximise cost efficiency and present a simplified decision tool for shipowners. The remainder of this paper is organised into four sections.

In Section 2, it first examines key WAPS technologies and their performance prediction methods. Modern WAPS operate on the same aerodynamic principles as traditional sailing, where sails generate forward thrust by exploiting the incoming wind. However, modern WAPS devices differ substantially in geometry, control systems, and integration complexity. They fall into six main categories: soft sails, rigid wing sails, Flettner rotors, suction sails, kites, and hull-form adaptations. Each device exhibits distinct aerodynamic coefficients determined by its geometry and operating conditions. Installing WAPS introduces aerodynamic forces that the vessel must counter through leeway, heel, and rudder adjustments to maintain course. Consequently, device layout, position relative to the superstructure, and multi-device interference are critical for accurate performance prediction. Performance is typically summarised using polar diagrams – circular plots that present thrust, power, or fuel savings as functions of true wind speed (TWS) and true wind angle (TWA). These diagrams illustrate how different WAPS technologies behave under varying wind conditions and serve as essential inputs for route simulations and operational performance assessments (Wang et al., 2025).

In Section 3, this paper describes our data sources and analytical methodology. Three WAPS technologies, Flettner rotors, wing sails, and suction sails across three representative vessel types– tanker, bulk carrier, and general cargo – on major shipping routes are selected based on the availability of real-world retrofit data on major shipping routes. Our analysis draws on three data sources: (i) literature, published case studies, manufacturer data, and operational data from real retrofits; (ii) simulated performance on major shipping routes, which provides the basis for fuel savings and CO_2 reduction assumptions; and (iii) publicly available cost estimates (Novac et al., 2025).

This paper employs three standard economic metrics: payback period, NPV, and LCOA. The simple payback period – defined as total capital cost (CAPEX) divided by annual fuel and carbon savings – provides a first-order indicator of investment recovery time (Carjova et al., 2025). NPV is calculated over a 15-year operational lifetime with an 8% discount rate, following common practice in maritime retrofit economics (Reche-Vilanova et al., 2025). The LCOA, expressed in USD per tonne of CO_2 avoided, is derived as the ratio of annualised retrofit cost (including CAPEX) to annual CO_2 emission reduction. These metrics are widely used to compare decarbonisation measures consistently. All calculations use published open-access data from real WAPS installations and validated voyage simulations. Table 1 summarises the assumed data required for our cost assessment.

Table 1. The case studies assumptions data.

Vessel	Typical route	WASP	Fuel saving	Annual HFO saved (t)	CO_2 reduction (t/year)	CAPEX	Annual COPEX
Case 1	MR tanker (North Atlantic)	2 Flettner rotors	8 %	960	3,024	\$3.2M	\$96,000
Case 2	Bulk carrier (China–US)	3 Flettner rotors	18 %	3,240	10,206	\$5.0M	\$150,000
Case 3	General cargo (Black Sea)	suction sail	6 %	180	567	\$2.5M	\$75,000

Section 4 presents the results, the discussion, and a simplified decision tool for shipowners. Under the base case assumptions of a fuel price of $600 per tonne HFO and a carbon price of $50 per tonne CO_2. Table 2 presents the results obtained from the cost efficiency assessment presented in the previous section.

Table 2. Cost efficiency metrics for three retrofit cases

Case studies	Annual fuel saving ($)	Annual carbon saving ($)	Total annual saving ($)	Payback (Years)	NPV ($M)	LCOA ($/t CO_2)
Case 1	576,000	151,200	727,200	4.4	+2.20	$155/t CO_2
Case 2	1,944,000	510,300	2,454,300	2.0	+14.73	$72/t CO_2
Case 3	108,000	28,350	136,350	18.3	Negative	

The results demonstrate that route characteristics are the single most important determinant of cost efficiency for WAPS retrofits. Using ERA5 wind data and AIS shipping density maps, vessels on wind-rich routes – such as the North Atlantic westbound, North Pacific eastbound, and South Africa–Brazil corridor – achieve payback periods of 2 to 4 years, whereas equatorial and short-sea coastal routes result in payback exceeding 8 years or negative NPV.

Despite positive cost efficiency, fewer than 100 commercial vessels had installed WAPS as of 2025 due to several barriers. These include first-mover risk, charterer resistance to route deviations (reducing expected savings by 40–100%), lack of standardisation (leading to increased capital costs of 20–30%), and high owner discount rates (15–20% versus the 8% used here) (Chica et al., 2023). Mitigation strategies such as leasing models, pooling on optimised routes, and policy incentives (including CII bonuses) can improve adoption. With carbon prices expected to reach $100–200/t CO_2 under the EU ETS and a potential IMO carbon levy, the economic case for WAPS retrofits will strengthen considerably.

Limitations of this assessment include reliance on published data that may incorporate optimistic assumptions, omission of wave-induced performance degradation, and use of an 8% discount rate that may not reflect higher owner hurdle rates. Nevertheless, the analysis provides a transparent, repeatable framework for estimating cost efficiency using only open-access data.

Based on the quantitative results, a simple four-factor decision framework is proposed for shipowners considering WAPS retrofits. First, the vessel's main route is critical: wind-rich routes are cost-efficient without subsidy. Second, annual fuel consumption is a strong predictor: vessels burning more than 8,000 tonnes of HFO per year (approximately >50,000 dwt) are economically attractive for WAPS retrofits. Third, regarding payback period requirements: only the best wind-rich routes achieve payback within 4 years under high fuel and carbon prices; most good routes yield payback within 6 years; for almost all other routes, the payback period exceeds 8 years. Fourth, for voyage-optimisation potential: owner-operated or flexible-charter vessels can increase fuel savings by 40–100% through route deviations.

Finally, Section 5 presents the conclusions. This paper assessed the cost efficiency of retrofitting existing ships with WAPS using open-access data and standard economic metrics. On favourable wind-rich routes, WAPS retrofits achieve payback periods of 2–6 years and positive 15-year NPV under current fuel prices ($600/t HFO) and moderate carbon prices ($50/t CO_2). The LCOA ranges from $72 to $155 per tonne CO_2, which compares favourably to alternative fuel retrofits. Route dependency is the dominant factor: vessels on low-wind or short-sea routes are not cost-efficient for WAPS. Voyage optimisation substantially improves cost efficiency, often halving payback periods.

With carbon prices expected to reach $100–200/t CO_2 under the EU ETS and a potential IMO carbon levy, this paper concludes that retrofitting wind-assisted propulsion systems is cost-effective on high-latitude and deep-sea routes, offering an immediate solution for reducing CO_2 emissions from the existing global fleet. For shipowners seeking immediate, cost-effective decarbonisation without waiting for alternative fuel infrastructure, WAPS retrofitting on suitable vessels represents a viable investment.

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Holistic evaluation of wind-propelled ships with recuperation using the Odyssa Framework

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1 ABSTRACT

Parameter	**Value**
Vessel type	Cargo Sailer
Length overall	130 m
Total sail area	4000 m²
Deadweight	8700 t
Gross tonnage	12 600 t
Propulsion system	Single screw propeller
Propeller Diameter	4 m
Number of hydroturbines	2
Hydroturbine blade count	4 per turbine
Hydroturbine diameter	4 m
Maximum propulsive power	3.56 MW
Maximum turbine power coefficient	0.39

The integration of wind propulsion systems into commercial shipping is increasing in both quantity and scale as a primary strategy to reduce reliance on fossil fuels and mitigate emissions. However, the implementation of large-scale sail systems alters fundamental ship design requirements, necessitating operational strategies tailored specifically to the complex interaction between wind propulsors, hull hydrodynamics, and hybrid energy systems. Existing assessment tools often isolate these variables—relying on "Velocity Prediction Programs" (VPP) for equilibrium states or statistical averages for weather—thereby failing to capture the dynamic interplay of a full voyage. This paper introduces Odyssa (Fitz et al., 2023), a comprehensive modelling framework designed to bridge this gap by combining vessel performance, powertrain modelling, operational optimization, and techno-economic analysis into a single modular toolbox.

The structure of the simulation environment is illustrated in Figure 1. The framework facilitates a holistic evaluation of windship designs by integrating four distinct submodules in a closed-loop workflow. The vessel performance module employs a 4-Degree-of-Freedom (4-DOF) model that accounts for the aerodynamic and hydrodynamic interaction between the hull, appendages, sails, and propeller. While the framework allows for high-fidelity inputs from CFD or model tests, the current iteration utilizes empirical formulas validated against CFD data, showing a strong correlation in calm water resistance (within 3 %) and a conservative overestimation in drifting conditions. As shown in the schematic, this performance module feeds directly into a route simulation module utilizing time-resolved ERA5 weather data. This coupling allows for the simulation of developing weather conditions along a specific trajectory rather than relying on statistical averages. These operational parameters are processed by the energy system module, which models the efficiency and state-of-charge limitations of hybrid components (combustion engines, batteries, and hydrogenerators), and finally passed to a techno-economic module that evaluates Total Cost of Ownership (TCO), accounting for carbon taxes, system weight penalties, and cargo capacity loss.

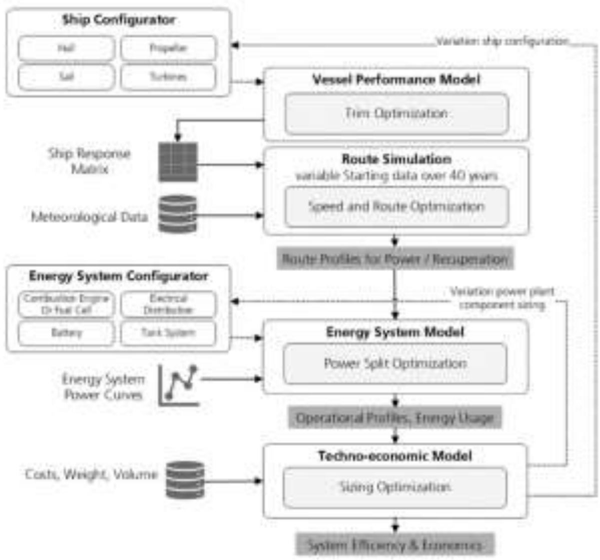

Figure 1: Odyssa Framework: Schematic of the simulation workflow coupling performance, routing, energy systems, and economic analysis.

To demonstrate the framework's capabilities, a case study was conducted on a 130 m sailing bulk carrier operating on a transatlantic route between Hamburg and New York. The proposed design, is a "Cargo Sailer" optimized for high wind fractions. The vessel is equipped with a quad-mast Dynarig (Bordogna et al., 2018) sail system providing 4000 m2 of surface area. To counteract the significant side forces generated by the sails, the hull features a large centerboard for drift stability, clearly visible in the rendering.

The hybrid powertrain comprises a methanol genset and a battery system. Uniquely, the design includes two dedicated hydrogenerators intended to recuperate energy during high-wind conditions for hoteling or self-sufficient operation. The specific technical parameters used for the simulation are detailed in the Table. The study compares this advanced design against two baselines: a conventional vessel with a two-stroke HFO engine, and a vessel equipped with sails but lacking the recuperation and hybrid battery system.

Operational simulations revealed significant variances in efficiency based on speed optimization strategies. Results indicate that at a constant speed of 10 kn, the Dynarig system enables a 36 % reduction in fuel consumption. However, when the framework's dynamic programming algorithm is applied to optimize instantaneous vessel speed—leveraging favorable winds without compromising the average voyage speed—fuel savings increase to 49.3 %.

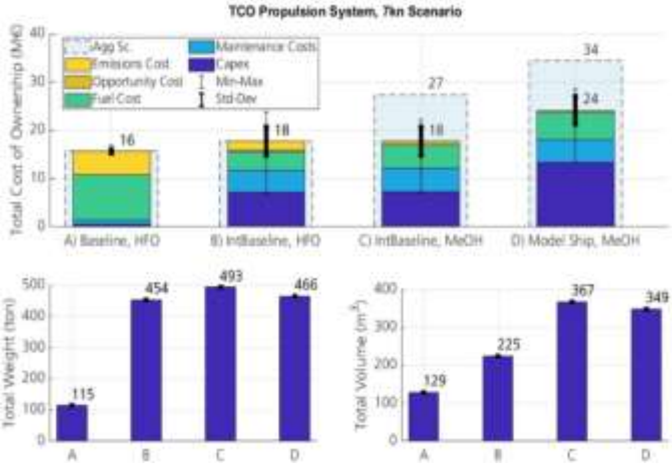

Figure 2: Distance normalized fuel consumption for the three analyzed power train options: Baseline (no sails, diesel); Intermediate Baseline (sails, methanol-electric); and Model Ship (sails, methanol-electric with battery and hydrogenerator).

The study further scrutinized the efficacy of hydrogenerators, a technology often proposed for energy autonomy. The analysis found that hydro-recuperation is highly sensitive to operational speed; it was only effective when the average speed was reduced to 7 kn, unlocking an additional 3.1 % fuel saving on top of the speed optimization results. At higher speeds, the drag penalty of the turbines outweighed the energy harvested. Figure 2 highlights these results, comparing the distance-normalized fuel consumption across the three analyzed powertrain configurations. The graph explicitly demonstrates the diminishing returns of full electrification compared to the "Intermediate Baseline" which utilizes sails without the weight and drag penalties of the recuperation hardware.

From an economic perspective, the Odyssa framework provided a detailed lifecycle TCO analysis, the results of which are illustrated in Fig. 3. Despite the significantly higher investment costs associated with the Dynarig system, the windship designs without recuperation achieved a total cost of ownership comparable to the conventional HFO baseline. This parity is driven by a 48 % to 55 % reduction in fuel costs and the mitigation of emission taxes, which offset the capital expenditures (CAPEX) and increased maintenance costs of the sails. However, the fully recuperating design (including hydrogenerators and larger battery capacity) resulted in a 33 % higher TCO. The powertrain design exploration indicated that, given the specific wind conditions of insufficient to justify the added CAPEX of the turbines and electrification hardware under current cost assumptions. In conclusion, the Odyssa framework successfully captures the complex, coupled dynamics of modern wind-assisted ships, offering a higher fidelity of prediction than standard steady-state models. While wind propulsion proves to be a technically and economically viable solution for the investigated route, the addition of hydro-recuperation requires careful matching of the operational profile to the technology. Future work will expand the design exploration to include varying hull forms and alternative sail technologies to further map the design space of sustainable shipping.

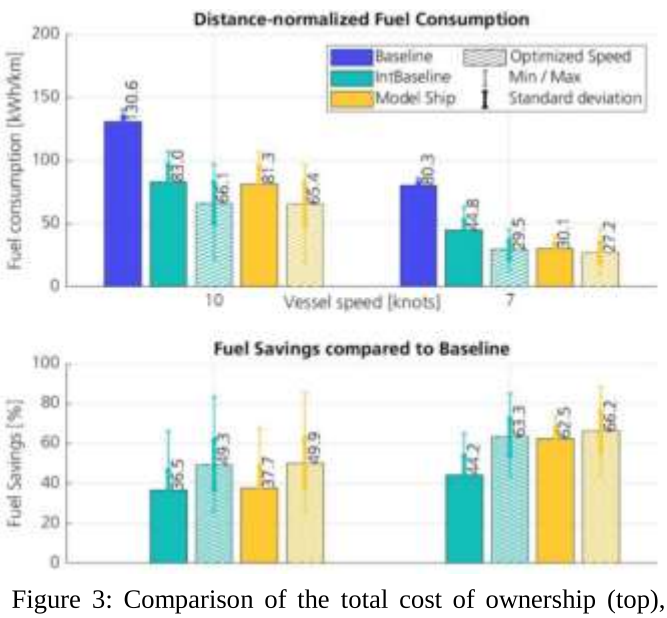

Figure 3: Comparison of the total cost of ownership (top), powertrain weight (bottom left) and volume (bottom right) between the considered powertrain options, at 7kn.

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A comprehensive review of hybrid PV-Wind systems and multilevel converter topologies for greener shipping: Current state and future perspectives

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Extended Abstract

The maritime sector, which carries more than 90% of global trade, is facing unprecedented decarbonization pressure under the International Maritime Organization's (IMO) revised 2023 greenhouse gas (GHG) strategy. This framework mandates at least a 20% reduction in total annual GHG emissions by 2030, 70% by 2040, and net-zero emissions by or around 2050, all relative to the 2008 baseline [1]. Current maritime operations emit approximately 1.1 billion tons of CO_2 annually, accounting for nearly 3% of global anthropogenic emissions, with auxiliary power units (APUs) contributing significantly to port and at-berth pollution (Fadaie et al., 2025). Conventional diesel-powered APUs, operating continuously during berthing periods averaging 6-72 hours depending on vessel type, generate substantial nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter emissions that severely impact coastal communities and port workers (Fadaie et al., 2025). In this context, the transition from fossil-fuel-dependent auxiliary power systems to renewable energy sources through hybrid photovoltaic-wind (PV-Wind) systems integrated with advanced power electronics is critical for sustainable maritime operations while maintaining operational reliability and economic competitiveness.

Integrating renewable energy into ships presents challenges due to the marine environment, space-weight constraints, and dynamic conditions. Modern systems combine flexible photovoltaic panels adapted to curved decks with vertical-axis turbines (VAWTs) that capture directional winds (Zhang et al., 2025). Spatial-temporal coupling of wind and solar energy yields a 20-30% reduction in emissions, while rotary sail technologies increase efficiency (Zhang et al., 2025). However, the marine environment is highly variable: solar panels experience shading from ship equipment, and wind patterns are turbulent due to the superstructure. Corrosion, thermal cycling, and vibration stress power electronics. The transition from conventional AC to hybrid AC-DC microgrids is essential for the efficient integration of DC renewable resources and requires sophisticated energy management capable of real-time load forecasting, battery optimization, and diesel backup coordination to ensure uninterrupted power for critical systems.

The conversion of variable DC power from hybrid PV-wind sources to the ship's AC system is critical. While conventional two-stage inverters are simple, they are limited in medium-voltage applications: high Total Harmonic Distortion THD exceeding 5% requires filtering, high dv/dt causes motor isolation failure, and Electromagnetic Interference (EMI) disrupts navigation equipment (Azizi et al., 2025). Multi-stage converters (MLCs) are the superior solution: they provide a sinusoidal waveform with THD below 2%, >98% efficiency, low voltage stress, and fault tolerance with redundant switching (Azizi et al., 2025; Barros et al., 2024). In marine applications, MLCs continue to operate at reduced capacity after a failure. The cascaded H-bridge (CHB) modular structure is ideal for marine retrofits: it allows for incremental expansion and a natural interface with battery systems. Advanced topologies offer bidirectional power flow for vehicle-to-ship (V2S) charging in ports and active filtering for harmonic loads.

Neutral-Point Clamped (NPC), Cascade H-Bridge (CHB), and Flying Capacitor (FC) have different performance balances with respect to marine criteria (Le et al., 2023). NPC offers the highest power density, requires complex voltage equalization, but uneven loss distribution makes thermal management difficult (Le et al., 2023). CHB stands out with its modular structure and fault tolerance: isolated DC sources interface with separate PV/battery modules, provide N+1 redundancy, and maintain operation even after a complete cell failure (Suresh et al., 2025). The literature reports 98.5% efficiency and THD below 1.5% in CHB systems. Although FC has high flexibility, the large number of high-voltage capacitors is limiting for marine applications in terms of weight, volume, and cost (Mosepele et al., 2024). For ship microgrids, CHB is the optimal choice due to its modular scalability, distributed battery interface, and fault-switching performance that ensures power continuity in severe sea conditions.

Graph Neural Networks (GNNs) capture the graph-theoretic structure of ship electrical grids, enabling topology-aware learning that generalizes to different configurations without retraining (Meng et al., 2025; Suri &

Mangal, 2025). GraphSAGE-GRU hybrid architecture outperforms traditional methods in bus voltage and renewable power estimation (Suri & Mangal, 2025). GNN-powered management optimizes multiple objectives: fuel reduction, battery life extension, power quality, and stability during load transitions. GNN-LSTM integration reduces communication overhead by 55% and improves voltage regulation by 45% (Meng et al., 2025). Physics-aware GNN variants incorporate physical laws into the learning process, ensuring interpretability and safety in critical marine applications. Distributed GNN inference enables edge computing in ship controllers and eliminates dependence on satellite communication.

EV batteries are retired at 70-80% capacity (Aguilar Lopez et al., 2024; Hassan et al., 2023). By 2035, 100 million EV batteries could meet the 2040 maritime BESS needs, offering 500 GWh of capacity in Europe [8]. Second-life batteries offer 60-70% lower cost, reduced embodied carbon, and a contribution to the circular economy (Hassan et al., 2023). Technical challenges: The modular architecture of multilevel converters provides an ideal interface for second-life battery integration, with each module accommodating a battery pack with independent voltage and capacity monitoring, enabling graceful degradation when individual modules fail (Barros et al., 2024). CHB compensates for incompatibility between aging packs with natural voltage equalization. Large-scale demonstration projects have successfully validated second-life battery systems at commercial scale, supporting renewable-powered facilities and proving technical viability (Choudhary et al., 2024). For maritime applications: charging from shore power at a low tariff, discharging for peak reduction at high load.

IMO decarbonization targets require three pillars: hybrid PV-Wind adapted to the marine environment, fault-tolerant MLC topologies, and GNN-based intelligent management. The transition is not just hardware, but a control transformation requiring grid-generating inverter capabilities. CHB is the optimal architecture with modular scalability, a distributed battery interface, and fault-switching. Second-life EV batteries reduce critical material dependency through the circular economy. Future research: hybrid GNN-physics models, open-source marine datasets, and MLC control methods that seamlessly transition between grid-generating/monitoring.

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Experimental C-HIL validation of MPPT algorithms for photovoltaic integration in resilient shipboard microgrids

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1 INTRODUCTION

Shipboard power systems can be regarded as a particular form of microgrid, as they integrate multiple distributed generation sources, energy storage units and variable loads within a controllable and islanded electrical network. Photovoltaic (PV) systems offer a renewable energy solution to improve efficiency and cut emissions in short-sea shipping (Subhashini & Kumar, 2017). Shipboard PV operates under complex conditions as salinity, motion, shading, waves, and variable irradiance (Tang, 2017) making efficient Maximum Power Point Tracking (MPPT) crucial for energy performance (Tang et al., 2017). Conventional MPPT algorithms, including Perturb and Observe (P&O) and Incremental Conductance (INC), continue to be widely implemented owing to their simplicity, robustness and ease of practical deployment (Ali et al., 2025). Under partial shading conditions, the power–voltage (I–V) characteristics of PV system exhibit multiple local maxima, which complicates accurate MPPT (Zheng et al., 2025). Also, to address these limitations, AI and metaheuristic MPPT methods, including reinforcement learning-based hybrids for multi-angle shipboard PV systems, have demonstrated high efficiency in simulation studies (Xiang et al., 2026). This paper presents experimental C-HIL validation of conventional MPPT algorithms under partial shading, enabling real-time performance assessment and analysis of controller–power stage interactions. Unlike pure simulations, the framework connects physical control hardware with a high-fidelity real-time shipboard PV model, supporting systematic evaluation under dynamic maritime conditions before full-scale implementation and operation under realistic operational condition.

2 METHODOLOGY

The C-HIL setup comprises a Typhoon HIL404 real-time simulator and a dSpace DS1103 controller. The HIL 404 simulator models the PV array, power converter, inverter, and loads, while the DS1103 controller executes MPPT, current/voltage control, and grid synchronization algorithms. The system (Fig. 1), comprising a DS1103 controller and HIL 404, operates in a closed loop via PWM and analog signals. Controller-generated PWM pulses drive the inverter model, while feedback signals—DC voltage, currents, and grid voltage—are returned to the controller, ensuring high-fidelity real-time interaction.

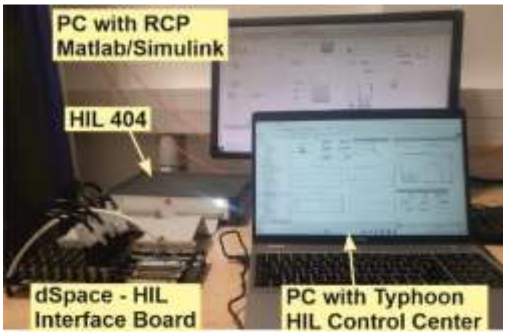

Fig. 1. Experimental setup with HIL 404 and dSpace DS 1104

The modeled PV system represents a 10 kWp array with nonlinear characteristics and time-varying irradiance to emulate fast transients such as partial shading. The inverter is a two-stage, three-phase 7.5 kW converter with an LCL filter, connected to a simplified low-voltage grid and representative loads. The cascade controlled

DC/DC boost converter operates at a switching frequency of 30 kHz. The MPPT algorithm is implemented as a Matlab m-function executed cyclically at 5 ms intervals.

3 RESULTS

To validate the platform, grid-connected test scenarios were conducted under rated and reduced irradiance conditions, emulating clouding, shading, and soiling effects representative of realistic operating environments.

The first experiment was conducted using the P&O algorithm, illustrating the system response during MPPT algorithm tracking under a step change in solar irradiance from 1000 to 500 W/m². The characteristic results are presented in Fig. 2.

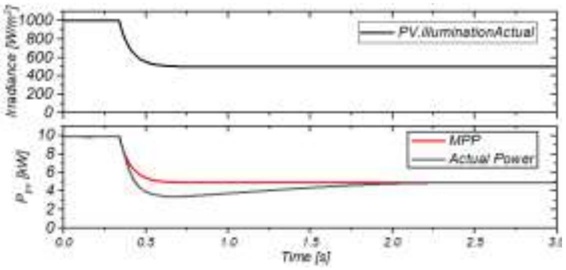

Fig. 2. PV panel output power (bottom) for the P&O algorithm under irradiance (top) variation

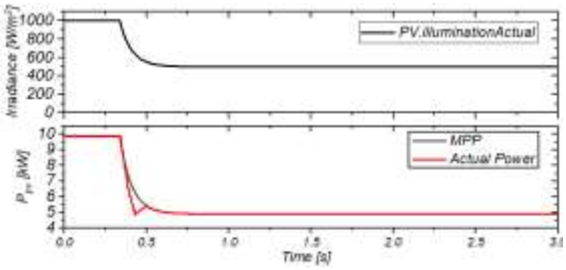

Fig. 3. PV panel output power (bottom) for the INC algorithm under irradiance (top) variation

The next experiment was performed using the Incremental Conductance (INC) algorithm under the same operating conditions, with the corresponding results presented in Fig. 3. The final experiment uses experimentally recorded characteristics where multiple local maxima exist in the P(V) curves. In Fig. 4, characteristic results are shown, highlighting the difficulty of finding the absolute maximum. This outcome underscores the need for further modifications of the MPPT algorithm—such as hybridizing P&O and INC algorithms or using metaheuristic algorithms—which will be implemented on the dSpace platform in future studies.

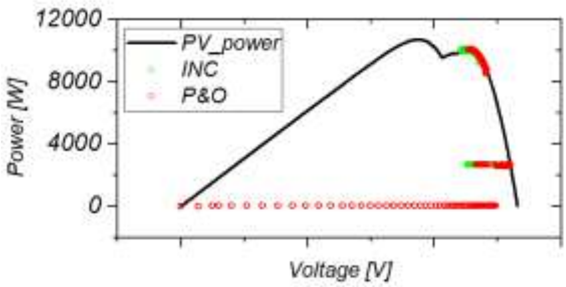

Fig. 4. PV panel output power trace as a function of voltage for the P&O and INC algorithm under shading condition

4 CONCLUSIONS

The presented methodology, based on the use of HIL and RCP devices with accompanying software, enables rapid testing of various MPPT algorithms, not only under ideal conditions but also in realistic scenarios including shading effects. In cases of multiple local maxima, standard P&O and INC algorithms do not provide satisfactory results, requiring their further modification.

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Some aspects of selected renewable energy sources use on ships

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1 INTRODUCTION

The use of renewable energy sources (RES) on ships is one way to improve ship energy efficiency by reducing fossil fuel consumption and thus significantly reducing emissions of toxic compounds contained in exhaust gases and greenhouse gases (GHG).

The current goal of the International Maritime Organization (IMO), expressed in the revised 2023 GHG Reduction Strategy from Ships, is to achieve a total reduction of these gases by 2050. At the same time, a gradual reduction in these emissions is assumed. Thus, by 2030, emissions should be reduced by 20%, aiming for a 30% reduction, and by 2040, by 70%, aiming for an 80% reduction, compared to 2008 levels. In particular, the carbon intensity of international shipping is to be reduced, by an average of at least 40% by 2030 (International Maritime Organization 2023).

Furthermore, in European Union countries, a European Union (EU) regulation (known as FuelEU Maritime), entered into force in January 2025, affecting ships of all flags with a gross tonnage exceeding 5,000 GT calling at EU ports. This regulation supports decarbonization in international shipping. The regulation aims to ensure a 2% reduction in GHG emissions between years 2025 and 2029, compared to the average GHG emission intensity in 2020, with a target of an 80% reduction by 2050. It is worth emphasizing that the GHG emission reduction applies to the entire life cycle of the fuel "well-to-wake" (Det Norske Veritas 2024). However, the use of renewable energy sources on board ships, aimed at reducing and, together with other initiatives, ultimately eliminating the combustion of fossil fuels, faces certain obstacles. These include, first and foremost, the very low energy stream density and the random nature of their availability.

In practice, renewable energy sources such as wind energy, solar energy, and biomass can be used on ships. The use of water energy is currently under investigation. Low solar energy density (density of solar energy stream <1.33 kW/m², density of wind energy stream <3 kW/m²) combined with limited deck area means that the generated power is usually insufficient for ship propulsion, so these sources, also due to the random nature of generation, are considered supplementary. In this situation, good knowledge of all difficulties in their use and intensification of energy conversion processes plays a crucial role.

The aim of the article is to indicate the possibilities of increasing the energy efficiency of ships by intensifying the process of solar radiation energy conversion in photovoltaic (PV) panels and the process of burning biomass as fuel.

2 OPERATION OF PV PANELS IN MARINE CONDITIONS

The operation of a ship-based PV system differs significantly from that of a land-based system due to various disturbances. One of the most disruptive factors to a ship's PV panel operation is its rolling in waves and course changes. The impact of ship motion in waves and course changes on the performance of the photovoltaic system using a unique test stand to simulate ship swinging have been examined. The study showed that the average power generated by the PV panel during rolling is lower than the power generated by the panel in a horizontal position, and the instantaneous power generated by the PV panel changes periodically at the same frequency as the ship's rolling frequency (Zeńczak & Zapałowicz 2022).

A way to increase the efficiency of PV panels is to use cooling, which is particularly easy to achieve in the case of a ship due to the unlimited access to seawater as a cooling medium. Theoretical studies have shown that the power increase of a PV panel with a cooling system per square meter of its gross surface area varies significantly, both between days and months of the year. For example, on a single day in May, it was calculated that for designed ferry staying in port, the amount of electricity generated was 13% higher than that obtained for a

PV module without a cooling system. However, on average, during the summer months, the power increases of PV panels with a cooling system ranged from 7 W/m² to 12 W/m² (Zeńczak & Zapałowicz 2021). Experimental panel cooling studies were also conducted using one of the simplest and cheapest methods: simulating natural cooling during increased sea waves and flooding the decks of a ship with PV panels with seawater. Depending on the flooding frequency and the current solar radiation value, the power increases of the cooled PV panel, compared to the reference uncooled PV panel, ranged from 7.2 to 13% [5].

3 INTENSIFICATION OF THE COMBUSTION PROCESS OF SOLID BIOMASS AS FUEL ON SHIPS

One of the most effective renewable energy sources, may be a solid biomass as a fuel. This source hasn't main disadvantages as other RES, such as low power density and periodic interruptions in their availability. Compared to biomass in liquid or gaseous form (bio-oil, biogas), it is characterized by cleaner combustion because its combustion in the engine requires a pilot dose of diesel fuel necessary for ignition. The energy use of solid biomass most often finds its equivalent in coal-burning energy technologies. However, biomass has a lower bulk density and lower calorific value than coal, which means that the fuel volume required to achieve the same energy effects will be larger. Therefore, it is refined through mechanical densification (pellets, briquettes) or torrefaction. Torrefied biomass can also be used to produce second-generation pellets. These pellets are very similar to coal (biocoal). Fluidized bed combustion technology is considered the most efficient and environmentally friendly. This allows for increased heat transfer intensity and a smaller boiler footprint compared to a conventional boiler of the same power output, thus improving the engine room's mass and dimensions. Tests conducted on a physical model of a fluidized bed boiler placed on a cradle simulating the impact of regular waves on the ship revealed a certain sensitivity of the fluidized bed boiler to ship heeling, resulting in a decrease in its efficiency (Zeńczak & Krystosik-Gromadzińska 2020).

Regardless of the engine room design, problems arise related to the operation of the pellet transport system (which is delivered to the engine room from the supply bunker). This article presents selected results of experimental studies conducted on a test stand with a model of the transport system (Zeńczak & Łuszczyński 2025).

Renewable energy sources on ships, particularly PV panels and pellets as fuel, unfortunately also contribute to the emergence of new ship safety hazards, primarily fire hazards. Therefore, the fire hazards resulting from the use of these renewable energy sources on ships were assessed and certain solutions were recommended.

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Decarbonizing anchorage waiting time in EU ports: A scenario analysis of renewable energy options

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Extended Abstract

1.1 Background and Rationale

The decarbonizations of maritime transport has become a central policy priority in both global and European governance frameworks. The IMO's 2023 GHG Strategy calls for at least a 40% reduction in carbon intensity by 2030 relative to 2008 and envisions the uptake of zero- or near-zero-GHG technologies, fuels, and energy sources to reach at least 5%, striving for 10% of the energy used by international shipping by 2030 (International Maritime Organization [IMO], 2023). In parallel, the European Union has extended the EU ETS to maritime transport from 1 January 2024 and has introduced FuelEU Maritime to reduce the greenhouse gas intensity of energy used by ships calling at EU ports (European Commission, 2024) These developments make port-related ship emissions an increasingly important research and policy issue within the EU context.

Although maritime decarbonizations is often examined through voyage emissions and alternative propulsion fuels, emissions generated during anchorage waiting time remain comparatively underexplored. Yet ships waiting offshore before berthing continue to operate auxiliary engines to support onboard electricity demand, hoteling loads, safety systems, and cargo-related services. Recent evidence shows that offshore waiting can be identified and quantified through AIS-based methods and that longer waiting times are associated with additional CO2 emissions (Akakura, 2023). This makes anchorage waiting time an important but still insufficiently addressed component of port-related maritime emissions.

This study aims to assess the decarbonizations potential of renewable-based auxiliary energy options during anchorage waiting time in selected EU ports. More specifically, it examines whether renewable-supported and hybrid auxiliary power configurations can reduce fuel consumption, CO2 emissions, and operational costs compared with conventional onboard auxiliary engine use during pre-berthing waiting periods.

1.2. Literature Basis and Research Gap

Existing studies provide a useful foundation but also reveal a clear gap. First, port-emission studies have developed approaches to estimate ship emissions during port stays, generally relying on auxiliary engine power or fuel-consumption-based calculations (Albo-López et al., 2023). Second, recent work has shown that offshore waiting time can be systematically measured and translated into incremental CO2 emissions at container terminals (Akakura, 2023). Third, the decarbonizations literature increasingly highlights hybrid ship power systems, batteries, and electrification as promising solutions for reducing fuel use and emissions in shipping operations (Chin et al., 2022; Kolodziejski & Michalska-Pozoga, 2023; Yuan et al., 2020). In the port context, studies also show that batteries and onshore power supply can materially reduce emissions from ships in port, especially by limiting auxiliary engine use (Abu Bakar et al., 2023; Albo-López et al., 2024). However, most of this literature concentrates on either general port-call emissions, at-berth electrification, or propulsion-focused hybridisation. Fewer studies isolate anchorage waiting time as a distinct operational phase and assess renewable auxiliary energy options specifically for EU ports, where congestion, environmental regulation, and decarbonization obligations increasingly intersect. This study addresses that gap by focusing directly on pre-berthing waiting time and by evaluating renewable energy options through a scenario-based analytical framework tailored to EU port conditions.

1.3. Methodology

The study employs a scenario-based comparative analysis for four major EU ports—Rotterdam, Antwerp-Bruges, Hamburg, and Valencia. The analytical unit is defined as port–ship type–scenario, focusing on ships' auxiliary energy demand during anchorage waiting time. These ports are selected to reflect variation in geographic location, traffic intensity, port scale, and operational conditions across the EU port system.

The analysis compares a baseline scenario, in which auxiliary energy demand is fully met by conventional marine-fuel-based engines, with alternative scenarios involving renewable-supported options, particularly battery-assisted hybrid systems and, where relevant, renewable-charged battery configurations. The methodological framework builds on established port-emission estimation approaches that assess fuel use, emissions, and cost performance across different technical configurations (Albo-López et al., 2023, 2024).

For each scenario, total auxiliary energy demand during anchorage waiting time will be estimated as:

$$E = P \times T$$

where E denotes total auxiliary energy demand, P is auxiliary power requirement, and T is anchorage waiting time. This energy demand will then be converted into fuel consumption and CO2 emissions using appropriate fuel coefficients and emission factors. Comparative performance will be evaluated using four main indicators: total fuel consumption, total CO2 emissions, total operating cost, and abatement cost per ton of CO2 reduced. A sensitivity analysis will also be conducted by varying waiting time duration, auxiliary load demand, battery contribution ratios, fuel prices, and carbon-cost assumptions. This design is appropriate because hybrid marine systems are known to have performance outcomes that depend strongly on load profiles, system configuration, and operational context (Yuan et al., 2020).

1.4. Conclusions

The results show that anchorage waiting time is a significant source of port-related ship emissions in the selected EU ports. In all scenarios, battery-assisted hybrid auxiliary systems reduce fuel consumption and CO2 emissions compared with conventional marine-fuel-based auxiliary engines. The analysis further reveals that the magnitude of these reductions differs across ports and increases with longer waiting times. Among the selected cases, ports with relatively extended offshore delays exhibit the highest decarbonization potential, indicating that renewable-supported auxiliary energy systems are particularly effective where anchorage congestion is more persistent. Overall, the findings may confirm that anchorage waiting time should be treated as a distinct target area within EU maritime decarbonization strategies.

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Working Group 5 on Onboard decision support systems for energy-efficient ship operation

Emerging green fuel and ESD technologies supporting the development of Digital Twin in shipping

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Extended Abstract

Improving shipping efficiency is essential for reducing energy consumption and emissions across global maritime transport. As international trade grows and so does the transportation demand, the shipping sector remains a cornerstone of worldwide logistics—but it also faces increasing environmental and economic pressures, particularly regarding fuel use and greenhouse gas output. Strengthening efficiency not only decreases operating costs for shipowners but also supports global sustainability goals by shrinking the industry's carbon footprint. To meet these challenges, the maritime sector is adopting a range of solutions, including innovations in vessel design, the use of alternative fuels, advances in digitalization, and more effective logistics management. At the same time, regulatory initiatives—such as the emissions reduction targets set by the International Maritime Organization and the European Union—continue to drive the industry toward cleaner, more energy-efficient operations.

The shipping industry is limited to the traditional modeling approaches in ship design phase, where various hydrodynamic-based models are utilized; see, e.g., Papanikolaou (2019, 2021). The latter adequately perform during the ship design phase, supported by additional scale tests conducted in towing tank and ocean basin type environments, and experimental data that are collected and fed back into simulation models.

In the framework of TwinShip Horizon Europe project (https://twin-ship.eu/), a set of technological elements has been proposed. An important component concerns the development of DT methodology supported by an open-source digital platform that is facilitated by several pilot study vessels with their ship performance data sets. The same digital platform will serve as the hosting foundation for DT development as well as its simulated environment so that a proper Decision Support System (DSS) can bring a significant step toward accelerating the maritime industry's digital evolution. The proposed DT technology can pave the way for greener, more efficient future by setting early greenhouse gas (GHG) emission benchmarks for the world merchant fleet to reduce fuel consumption and emissions; see Perera et al (2025). To support the DT the Engine Propeller Combinatory Diagram (EPCD) is developed for existing vessels with fuel and technologies based on existing domain knowledge through model-based systems engineering and simulations. Furthermore, in the framework of TwinShip DT the modelling of emerging green fuel and ESD technologies is studied as a step supporting the models is discussed; see Fig.1.

In this work, results are presented showing the upgrade of the EPCD with novel domain knowledge as the secondary step towards DT models for selected existing vessels, including experimental evaluations on the updated EPCD using data from emerging green fuel and technology data. In particular, the application of the bow dynamic wing as wave energy device along with WAPs based on suction sails for RoRo and tanker ships are presented and the combined effects on propulsion improvements are discussed.

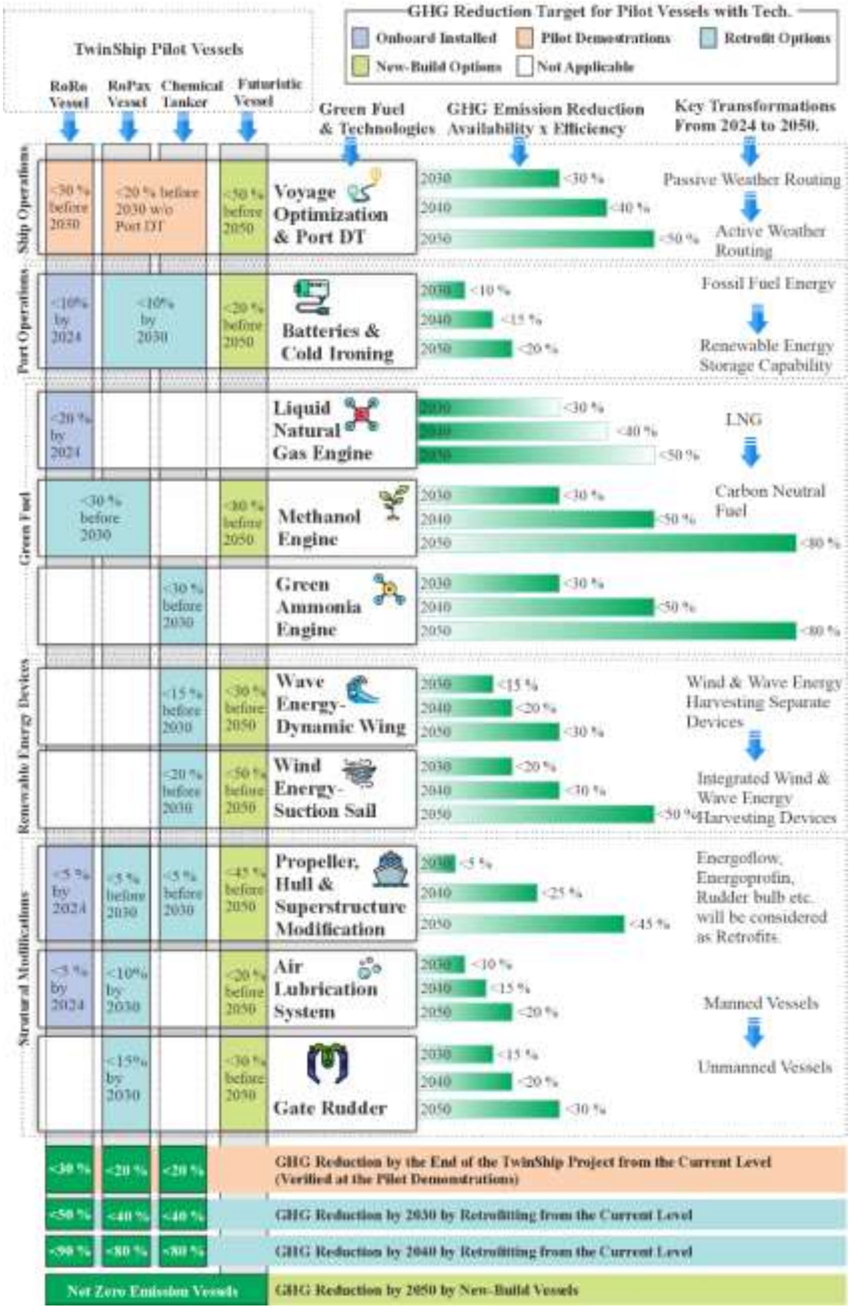

Figure 1. Emerging green fuel and energy saving technologies considered in TwinShip

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DTTEx – Roadmap to Digital Twinning through an IoT Platform

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Extended Abstract

The International Maritime Organization's 2023 Strategy targets net-zero greenhouse gas (GHG) emissions from international shipping by or around 2050, with indicative checkpoints for 2030 and 2040. Meeting these targets requires reliable onboard measurement and decision-support tools that can verify compliance and identify efficiency gains. This paper introduces DTTEx, an Internet of Things (IoT) platform developed by ITEx that integrates live sensor networks with a physics-based simulator to act as a digital twin of a vessel's energy and mass flows. DTTEx couples four interoperable modules (a Microgrid Digital Twin, a Sensor Drift Detection module that logs calibration parameters and enables user to decide to recalibrate or replace sensors, the SNIFFEx gas-quality network and the EMTEx electricity and fuel metering network) into a single platform for real-time monitoring of fuel consumption, exhaust emissions and operational efficiency over a voyage. The paper outlines the platform architecture, the drift detection and anomaly-handling methodology, and preliminary validation results demonstrating the impact of sensor drift on CII calculations and the effectiveness of the correction layer.

1 INTRODUCTION

International shipping is under growing pressure to decarbonise. The IMO's 2023 Revised Strategy commits the sector to net-zero GHG emissions by or around 2050, with indicative reductions of at least 20% by 2030 and 70% by 2040 compared with 2008 levels (IMO, 2023). In parallel, short-term measures under MARPOL Annex VI such as the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII) are already in force (IMO, 2008). Meeting these requirements depends on accurate, continuous, and auditable measurement of onboard energy use and emissions.

Yet onboard instrumentation is noisy, sensors drift over time, and operational data are rarely integrated with the physics of propulsion and power generation (Fonseca & Gaspar, 2021). A digital twin that continuously ingests sensor streams, compensates for drift and models the vessel as a microgrid can close this gap (Coraddu et al., 2019). DTTEx has been developed by ITEx to do exactly this: it couples IoT sensor networks with a browser-based simulator so that shipowners, operators and class society reviewers can test operational scenarios, validate emissions reporting and plan efficiency retrofits against a reliable digital baseline.

The principal contribution of this work is the integration of real-time sensor drift detection with a voyage-aware energy microgrid model inside a single platform: whereas existing ship digital twins typically assume clean input data (Gkerekos et al., 2019), DTTEx embeds an autonomous correction layer that flags and compensates for sensor degradation before it propagates into CII calculations or retrofit analyses. This paper presents the platform architecture, the drift-detection methodology, and preliminary validation results.

2 PLATFORM ARCHITECTURE AND METHODOLOGY

DTTEx is a modular IoT platform built around a central integration database. Four modules interact through this database: (i) a Microgrid Digital Twin that models vessel energy and mass flows along a simulated voyage; (ii) a Sensor Drift Detection engine; (iii) the SNIFFEx gas and air-quality sensor network; and (iv) the EMTEx electricity and fuel metering network. Each module writes to, and reads from, the shared database, which also supplies training data for the machine-learning models.

The Drift Detection Module implements a five-stage pipeline applied continuously to incoming sensor streams:

• Data Acquisition and Pre-processing: sensor streams from the vessel are collected continuously and cleaned to remove noise, outliers and missing values.

• Feature Engineering: relevant features are extracted from the cleaned streams, including sensor age, operating conditions and environmental factors that may indicate drift.

• Drift Detection: machine-learning models (e.g. regression and time-series models) predict expected sensor readings from historical data; the residual between predicted and actual readings signals potential drift.

• Anomaly Detection: statistical and clustering methods flag sensor behaviour consistent with malfunction or failure.

• Recalibration and Correction: a feedback loop applies correction factors to the raw streams in near real time; where recalibration is not feasible, sensors are flagged for maintenance or replacement.

The Microgrid Digital Twin is a browser-based tool that balances onboard power generation against a user-defined consumption load. The vessel is positioned on a dynamic global map with inputs for location, speed and environmental conditions, enabling analysis of operational efficiency and fuel economy along a simulated voyage. Where direct emissions measurements are unavailable, an exhaust-gas submodule estimates CO_2, CO, NO_x, SO_x and particulate matter from fuel type, excess air and piston–cylinder geometry using correlations from the open literature. The twin is updated at each time step with corrected sensor data, ensuring that anomalies flagged by the Drift Detection Module (Brandsæter et al., 2019) do not propagate into CII or emissions estimates.

The sensor layer consists of two IoT networks: SNIFFEx, which monitors exhaust-gas composition and air quality, and EMTEx, which logs electricity consumption and fuel flow. Both feed the shared database that trains the ML drift models and supplies the Microgrid Digital Twin with measured, rather than assumed, input values.

3 PRELIMINARY RESULTS

In this work, we will only assess the platform's ability as a simulator. The platform has been used to model an anonymised coastal vessel's energy flowchart, assess its energy performance, and evaluate the improvements in energy efficiency achievable by integrating renewable energy sources (solar PV) and onboard battery storage. The IoT sensor network and drift correction testing is planned to be validated at a later stage in the development cycle of DTTEx.

4 CONCLUSIONS

DTTEx demonstrates that a modular IoT platform coupling a physics-based digital twin with IoT sensor networks can support decarbonisation decisions at operational and retrofit levels. Preliminary simulations will be performed on an anonymized coastal vessel to confirm that the Microgrid Digital Twin can quantify efficiency gains from solar PV and battery storage integration. Planned work includes validation of the sensor drift detection layer against operational data and extension of the emissions submodule to alternative fuels.

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Operational decarbonisation through port-based Digital Twin intelligence: Decision-support frameworks for energy-efficient vessel operations

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Extended Abstract

1. Introduction

Despite rapid advances in alternative fuels and propulsion technologies, operational inefficiencies during vessel approach, manoeuvring and berthing remain a structurally embedded source of avoidable fuel consumption and emissions. Current decarbonisation strategies largely overlook the port environment as an active optimisation domain. This gap is critical, as low-speed manoeuvring and idling phases can disproportionately contribute to total voyage emissions due to suboptimal thrust allocation, safety-driven conservatism and environmental uncertainty. Decarbonising waterborne transport therefore requires a systemic approach extending beyond vessel technologies toward integrated optimisation at the vessel–port interface. Ports represent complex and dynamic environments where environmental forcing, infrastructure constraints, and operational uncertainty directly influence vessel behaviour and energy use. Traditionally, monitoring systems deployed in ports focus primarily on safety, navigation or infrastructure maintenance. However, integrating real-time monitoring into operational decision-support frameworks offers new opportunities to enhance energy efficiency and reduce emissions. This work shifts the focus from vessel-centric optimisation toward integrated vessel–port intelligence as a previously underutilised pathway for operational decarbonisation.

The proposed framework is designed to support applications across diverse port typologies, facilitating collaborative implementation within European maritime networks and supporting coordinated decarbonisation strategies.

2. Smart Port Monitoring as an External Decision-Support Layer

Vessel manoeuvring in confined waters typically involves conservative operational practices due to uncertainty regarding environmental conditions such as waves, currents, wind and water levels. These uncertainties often lead to increased engine loads, waiting times and corrective manoeuvres, contributing to higher fuel consumption.
The proposed framework integrates multiple monitoring components into a unified operational intelligence system:

- real-time metocean monitoring (waves, currents, wind fields, water levels)
- infrastructure health monitoring of quay walls, breakwaters and critical assets
- bathymetric and morphological monitoring of port basins and approach channels
- vessel trajectory and operational performance analytics

The transformation of monitoring data into actionable operational intelligence enables ports to serve as an externalised decision-support layer, guiding vessel operators in optimising arrival windows, manoeuvring strategies, and speed profiles.

3. Digital Twin Architecture for Operational Decarbonisation

The proposed digital twin framework integrates environmental, infrastructural and operational data streams into a predictive system capable of supporting energy-efficient vessel–port interaction. The architecture comprises three interconnected layers:

1. **Environmental Layer** – real-time and forecasted metocean conditions affecting vessel resistance and manoeuvrability.
2. **Infrastructure Layer** – structural condition indicators and seabed evolution influencing safety margins.
3. **Operational Layer** – vessel motion analytics, scheduling optimisation and energy performance indicators.

Given the nonlinear relationship between vessel speed and fuel consumption (fuel demand scaling approximately with the cube of speed under displacement conditions), even marginal reductions in approach velocity or corrective manoeuvring can translate into disproportionate fuel savings. Therefore, uncertainty reduction through real-time environmental intelligence represents a direct decarbonisation mechanism rather than merely an operational improvement.

The proposed framework reconceptualises port monitoring beyond its traditional safety function, positioning it as an active optimisation tool integrated within broader maritime decarbonisation strategies. It establishes the basis for future quantitative assessment of operational fuel savings by linking environmental uncertainty reduction with vessel energy-demand modelling during port approach and manoeuvring phases.

4. Coastal Engineering Integration and Monitoring Technologies

Recent advances in coastal and harbour engineering monitoring technologies enable continuous situational awareness within port environments. Autonomous survey platforms, remote sensing systems and in-situ sensor networks allow dynamic tracking of environmental forcing and infrastructure condition. The integration of UAV-based inspections, autonomous bathymetric surveys and real-time environmental observations demonstrates the feasibility of scalable smart monitoring frameworks adaptable to diverse port configurations.

The integration of such monitoring systems into digital twin environments enhances their functionality by shifting toward predictive analysis, improving operational efficiency and infrastructure resilience under evolving climate conditions.

5. Research Contribution

This study introduces a structured digital twin architecture that explicitly links port-based environmental and infrastructure intelligence with vessel energy-demand dynamics during confined-water operations. Unlike conventional port monitoring approaches focused on safety and maintenance, the proposed framework positions ports as active optimisation agents within maritime decarbonisation strategies.

6. Contribution to Maritime Decarbonisation

The proposed approach positions ports as active nodes in maritime decarbonisation pathways. By providing operational intelligence that supports energy-efficient navigation and manoeuvring, smart port monitoring can contribute to measurable reductions in fuel consumption and associated emissions. The framework complements technological advances in propulsion and alternative fuels by addressing operational inefficiencies that remain largely untapped.

7. Conclusions

Decarbonising waterborne transport requires moving beyond vessel-centric solutions toward system-level optimisation. By transforming ports into data-driven optimisation hubs, smart monitoring and digital twin technologies can function as distributed decision-support systems extending onboard intelligence. This integrated vessel–port paradigm offers a scalable and technology-neutral pathway to operational emission reduction, complementing advances in propulsion and fuel innovation.

From sensors to decision support technologies for energy efficiency in ships

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Extended Abstract

International maritime transportation is estimated to move around 80% of the total volume of goods worldwide, thus playing a major role in the working of global economy. In addition, maritime shipping is regarded as the most energy efficient way to transport cargo in terms of energy used per cargo unit transported. Despite its efficiency advantages, the scale and recent growth rate of the shipping industry make it a significant driver of global ecological change. Under long-term economic and energy scenarios, shipping emissions are expected to increase by 90% to 130% by 2050 relatively to 2008 (Bui & Perera 2021).

By acknowledging such environmental impact, the International Maritime Organization (IMO) has introduced progressively stricter regulations aimed at reducing Greenhouse Gas (GHG) emissions from ships, placing increasing pressure on the shipping industry to mitigate its environmental impact. A way to reduce ship emissions from ship fuel consumption and which is an effective approach is to improve energy efficiency (Bui & Perera 2021). Several solutions have been proposed in the literature to reduce fuel consumption in shipping, which in the context of vessel operations include weather routing, optimization of energy systems and speed optimization (Karatuğ et al. 2024).

Nowadays, Internet of Things (IoT) network technologies can interconnect the multitude of sensors onboard ships to collect and transmit real-time operational data. The massive amount of data that can be generated from these sensors may then be used to analyze ship performance and gain further insights. This is challenging, requiring adequate techniques to harness the full potential of this data to help increase energy efficiency during ship operation. Data analytics and Machine Learning (ML) are suitable emerging technologies for this purpose (Bui & Perera 2021). These technologies can power Decision Support Systems (DSSs) to functionally work as a bridge between the large volume of raw data and the human (or machine) operational decision-making processes, particularly regarding ship energy efficiency. The present paper reviews technologies of energy efficient DSSs for ships, covering sensors, IoT and data processing, data analytics and machine learning techniques, culminating with the user interfaces and data visualization aspects of these systems.

The effectiveness of any DSS is inherently and fundamentally limited by the quality and coverage of its sensing layer. Many sensor types and technologies are used to continuously provide DSSs with meaningful real-time data for ship energy efficiency applications and vessel performance evaluation (Spandonidis et al. 2025). As the number of implemented sensors increase, scalable and reliable technologies, such as onboard and onshore IoT solutions can help enhance modern shipping in collecting and managing the large volume of ship operational data streams, enabling continuous and real-time flow of structured data integrating sensors into a monitoring system for DSSs. This means pre-processing data onboard and post-processing it onshore using adequate methods and models to deal with the data handling challenges posed by big data (Perera & Mo 2020). According to Kim et al. (2025), challenges in ship data processing relate to data acquisition and integration, data compression and transmission, and data sources. Approaches have been provided for their mitigation, including statistical filtering and frequent sensor calibration, time synchronization and data assimilation techniques to guarantee accuracy, data compression methods, and systematic data validation and pre-processing measures for data quality improvement. Additionally, data cleaning, missing data, and uncertainty management

are other data processing techniques covered in the literature. The latter, for example, deals with the primary causes of data uncertainty that can compromise the reliability of data analysis results (Kim et al. 2025).

Noisy data or poor-quality data is always a problematic aspect when collecting data from real-world sources using sensors. Therefore, the quality of data related to ship performance and navigation has been a matter of concern. However, this awareness is yet to be fully embraced by the shipping industry and efforts must be made by the sector to value and improve data quality. Additionally, few researchers have addressed this subject in the literature (Bui & Perera 2021). The increasing complexity of ship performance data and inherent imperfections still continuously poses challenges to their processing and managing (Kim et al. 2025).

Conventional approaches such as statistical models have often been studied in the literature, for example to predict ship fuel consumption or engine power. However, these models consider certain assumptions in their distributions, which may imply bias problems and are limited in their ability to deal with complex and non-linear data. As a result, ML models have been extensively developed to deal with these constraints (Bui & Perera, 2021). For example, Perera & Mo (2020) proposed data-driven models incorporating ML technologies to support a data handling framework with pre- and post-processing units to overcome several complex data handling issues faced by the maritime industry during the process of digitalization.

In a nutshell, data acquisition and pre-processing, advanced analytical techniques and ML methods, can be employed to derive insights into ship performance and support decision-making for energy efficiency.

DSSs have been proposed for ship performance monitoring and management to improve vessels energy efficiency using data analytics (Bui & Perera 2021) and machine learning (Karatuğ et al. 2024, Spandonidis et al. 2025) frameworks. Bui & Perera (2021) proposed an advanced data analytics framework for ship performance monitoring under localized operational conditions. The framework architecture comprises domain knowledge, descriptive analytics, diagnostic analytics, visual analytics and prescriptive analytics. The designed functionalities can serve as an operational energy efficiency measure with the capacity to provide data quality evaluation and decision support for monitoring ship performance.

Karatuğ et al. (2024) developed a DSS combining an engine optimization model and an Artificial Neural Network (ANN) to accurately estimate ship fuel consumption using real-time data, providing a cost-effective solution to actively monitor critical engine parameters and improve energy efficiency.

Spandonidis et al. (2025) proposed a ML powered framework for real-time ship performance management focusing on dynamic AI-enhanced Key Performance Indicators (ML-KPIs). The framework starts with collected data from onboard sensors and ends in a DSS. The integration of ANNs with hybrid data fusion methods enabled the evaluation of fundamental operational metrics, such as fuel consumption, engine health, and emissions performance. By supporting adaptive performance monitoring, anomaly detection, and proactive decision-making, it enables the real-time optimization of vessel operations.

It is evident that even advanced data analytical and ML models are limited in their application unless their outputs are effectively communicated to and understood by human operators. According to Perera & Mo (2020) data visualization is a crucial feature for decision-making that enables the identification of optimal ship navigational and operational conditions in energy efficiency applications. However, Nordby et al. (2019) refer that user interfaces of equipment installed on ship bridges seldom have a consistent design as ship bridge systems typically comprise equipment from different vendors. Thus, their operation is cognitively demanding, adding up to the already challenging work performed by operators under constantly varied types of conditions. Moreover, workplace regulations and design guidance are limited, which concerns user interface consistency between different maritime vendors and equipment. Thus, consistency in user interface design across equipment and software in ship's bridges is critical for the development of systems that mitigate human error while also promoting increasing efficiency and user satisfaction. Therefore, the authors have developed a user interface architecture in this context to provide a framework to increase design consistency.

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Risk-aware energy-efficient route planning for summer navigation along the Arctic

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Extended Abstract

1 INTRODUCTION

In recent years, the reduction of Arctic sea ice has made Arctic shipping routes increasingly attractive for improving transport efficiency and shortening voyage distances (Sibu et al., 2026). However, navigation in the Arctic remains highly challenging due to harsh environmental conditions, limited navigational infrastructure, and constrained icebreaker support. These factors significantly increase the risk of accidents such as ship besetting in ice, ship-ice collisions, and grounding (Baksh et al., 2018).

At the same time, the global shipping industry faces increasing pressure to reduce greenhouse gas emissions and improve energy efficiency. Achieving safe and energy-efficient navigation has therefore become a key issue in Arctic shipping.

To address this challenge, this study proposes a minimum-fuel route planning framework for summer navigation along the Arctic Northeast Passage that explicitly accounts for navigational risk. In the proposed framework, navigational risk is incorporated into the route cost function together with fuel consumption, enabling a balance between navigation safety and energy efficiency. An incremental A* algorithm (LPA*) is adopted to efficiently compute the optimal route. The proposed approach provides a practical decision-support tool for safer and more energy-efficient Arctic navigation.

2 METHODOLOGY

2.1 *Fuel Consumption and Risk-Constrained Model*

Fuel consumption is estimated based on the propulsion power required to overcome both calm-water resistance and ice resistance. Calm-water resistance is calculated using the Holtrop-Mennen method (Holtrop and Mennen, 1982), while ice resistance is estimated according to sea ice thickness and concentration (Huang et al., 2021). The resulting propulsion power is converted into fuel consumption using the engine specific fuel consumption. Detailed formulations follow Liu et al. (2026).

Navigational risk is incorporated into the routing model as a penalty term in the path cost function. Risk values are derived from the risk assessment model developed in Liu et al. (2025). By adjusting the risk penalty coefficient, routes with different levels of risk aversion can be generated, enabling a trade-off between fuel efficiency and navigation safety.

2.2 *Routing Strategies*

Four routing strategies are considered in this study, including the minimum-fuel strategy, low risk-aversion strategy, medium risk-aversion strategy, and high risk-aversion strategy. These strategies are designed to represent different operational preferences of ship operators, ranging from purely fuel-efficient navigation to increasingly risk-averse decision-making.

Different levels of risk aversion are implemented through the introduction of varying penalty functions in the routing cost formulation, allowing the model to adjust the trade-off between fuel efficiency and navigational safety.

The routing framework is implemented using the LPA* algorithm, which allows efficient re-planning under dynamically changing environmental conditions. This enables the model to update optimal routes according to different departure dates and evolving sea-ice conditions.

3 RESULTS

To evaluate the effectiveness of the proposed method, a typical summer navigation scenario along the Arctic Northeast Passage was constructed. The starting and destination ports were set as [66.00N, 169.00W] and [69.50N, 33.00E], respectively.

Figure 1 shows the minimum-fuel route together with the optimised routes under low, medium, and high levels of risk aversion under the same environmental conditions. Due to space limitations, only the results for the departure date of 1 July are presented here.

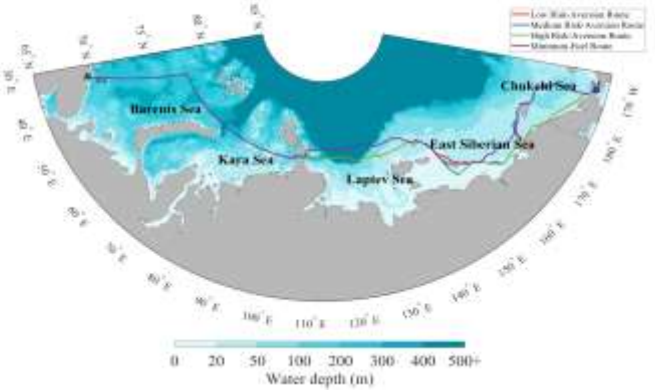

Figure 1. Energy-efficient Arctic routes under different risk-aversion levels (Departure: 1 July)

From the overall spatial distribution, the level of risk aversion has a clear influence on the resulting routes. The minimum-fuel route primarily aims to minimise fuel consumption and therefore tends to follow shorter and more energy-efficient paths. As shown in the figure, this route is generally located closer to higher-latitude area in order to reduce the overall sailing distance and improve energy efficiency.

After navigational risk is incorporated into the optimisation process, the routes gradually adjust their spatial distribution. The low risk-aversion route remains relatively close to the minimum-fuel route. As the level of risk aversion increases, the medium and high risk-aversion routes show more noticeable detours in several sea areas, gradually shifting toward regions with relatively lower navigational risk. This indicates that higher levels of risk aversion encourage the algorithm to avoid potentially hazardous areas, thereby improving navigation safety.

Although risk avoidance may slightly increase the route length, the overall change remains within a reasonable range. The results indicate that route optimisation based on environmental information can help reduce fuel consumption while avoiding high-risk areas. In practice, ship operators can select routes with appropriate levels of risk aversion according to operational requirements, thereby achieving a suitable balance between fuel efficiency and navigation safety.

4 CONCLUSIONS

This study proposes a risk-aware and energy-efficient route planning method for summer navigation along the Arctic Northeast Passage. The proposed approach aims to minimise fuel consumption while accounting for navigational risk through a risk-aversion mechanism, enabling route optimisation that enhances energy efficiency while maintaining navigation safety. In addition, the routing framework allows routes to be updated according to different departure dates and changing environmental conditions.

The results indicate that route optimisation based on environmental information can reduce fuel consumption while ensuring safe navigation, thereby providing potential support for reducing carbon emissions from maritime transportation. Overall, the proposed method contributes to promoting greener and lower-carbon Arctic shipping.

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Energy-Efficient Navigation Risk Evaluation for Polar Escort Ships

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Extended Abstract

1 INTRODUCTION

Global warming causes substantial sea ice melting in the Arctic region. This increase raises the frequency of commercial shipping transits through the Arctic while simultaneously increasing greenhouse gas emissions during cargo transportation (Zhang et al., 2023). During Arctic navigation, most ships select icebreaker escort services to ensure safe passage in polar waters. However, the complex Arctic environment makes icebreaker escort operations full of hazards and uncertainties, and these operations also generate large amounts of greenhouse gas emissions (Lu et al.,2026). Therefore, it is necessary to conduct risk assessments of icebreaker escort operations to improve operational safety. At the same time, such assessments must integrate fuel consumption rates during operations to reduce greenhouse gas emissions.
This paper proposes a comprehensive navigation risk assessment model for polar escort ships that considers energy efficiency characteristics. The study combines System-Theoretic Process Analysis (STPA) with Bayesian networks. This approach accounts for navigation risks and fuel consumption throughout the entire system interaction process and provides decision support for environmentally sustainable icebreaker escort operations.

2 RESEARCH METHODS

2.1 *System-Theoretic Process Analysis for Hazard Identification*

STPA, derived from the STAMP model, serves as a sophisticated safety analysis methodology (Leveson, 2004). Unlike conventional techniques, STPA employs systems thinking to prioritize interactions between components and control inadequacies during operations over individual hardware failures (Takahashi et al., 2025). Within the context of Arctic icebreaker escorts, STPA facilitates the seamless integration of human, vessel, environmental, and organizational elements into a cohesive socio-technical framework. Consequently, the hazard causal factors and unsafe control actions identified through STPA systematically define the topological structure (i.e., nodes and directed edges) of the subsequent Bayesian Network.

2.2 *Specific Fuel Consumption and Navigation Risk Assessment Model*

The navigation risk assessment model for polar escort ships is illustrated in Fig. 1. The fuel consumption node in the Bayesian Network (BN) is derived from physical estimations of ice resistance using Lindqvist's empirical formula. While the original Lindqvist model primarily assumes level ice conditions, actual Arctic environments consist of complex ice features. To address this limitation, the model incorporates ice concentration data to dynamically adjust the resistance calculations, thereby approximating the resistance in mixed ice floes. Furthermore, the inherent uncertainties associated with ridged or compressive ice are statistically captured through the probabilistic distributions of the BN input nodes. By integrating principal ship particulars with these variable environmental data, the total output power is calculated for three speed strategies: low, medium, and high. To account for environmental uncertainties, the resulting power requirements are discretized into low, medium, and high states corresponding to different specific fuel oil consumption (SFOC) levels.

The environmental data, including wind speed, wave height, and temperature, are extracted from the ERA5 hourly dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) in NetCDF format. Ice concentration data are obtained from the ECMWF daily gridded products derived from the SSMIS sensor of the EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI SAF). Additionally, ice thickness data are sourced from the Pan-Arctic Ice-Ocean Modeling and Assimilation System (PIOMAS) reanalysis data released by the University of Washington. Due to the scarcity of detailed historical records regarding human and certain ship-related factors, this study employs a questionnaire-based approach to collect subjective judgments from 12 domain experts. These experts represent a diverse range of stakeholders, including polar shipping enterprises, universities, research institutions, and crew members with practical Arctic navigation experience.

3 RESULTS

To verify the effectiveness of the proposed model, the Newnew Polar Bear is selected as the target vessel to evaluate its navigation risks and specific fuel consumption in the East Siberian Sea. To gain a comprehensive understanding of the overall safety status in the East Siberian Sea, this study defines the Integrated Risk Index (IRI) by averaging the “High Risk” state probabilities of three system-level accidents: collision between the escorted vessel and the icebreaker, collision between the escorted vessel and ice, and ice entrapment of the escorted vessel. This integrated approach enables a macro-level trade-off analysis between comprehensive risk and fuel efficiency, smoothing out local fluctuations of individual nodes to highlight the monotonic decay trend of system performance during the freeze-up period.

Fig. 2 reveals a distinct seasonal divergence among various speed strategies in the East Siberian Sea. The Pareto front highlights September as the ideal decision window, while the high-speed approach in November shifts toward a “high-risk, high-consumption” state driven by intense ice resistance. These results verify the capability of the developed BN model in capturing the dynamic interdependencies between risk and energy efficiency in Arctic waters.

Fig.1. An Integrated Risk Assessment Model for Polar Escort Ships Incorporating Energy Efficiency Characteristics.

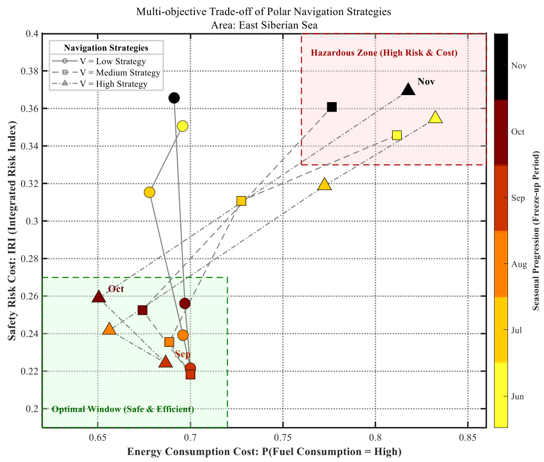

Fig.2. Risk-Fuel Trade-off Trajectory in the East Siberian Sea (June–November).

4 CONCLUSIONS

An integrated risk evaluation framework considering energy efficiency is developed for polar escort missions. It quantifies the interdependencies between navigation risks and fuel consumption rates through a coupled probabilistic approach. Adaptable to various escorted ships, operational speeds, and environments, this model significantly enhances operational efficiency. Findings suggest that integrating fuel consumption into risk assessment enables the simultaneous management of safety and fuel economy, effectively lowering carbon emissions in Arctic shipping.

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Decarbonization as a new challenge for ship routing systems

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Extended Abstract

1 INTRODUCTION

New standards and objectives declared by international regulatory organizations of waterborne transportation (IMO, PIANC etc.) impose strong requirements for significant reduction of greenhouse gas emissions from commercial cargo vessels (Kondratenko et al., 2025a). These ambitious goals (for example, the target of net-zero emissions by 2050) can be achieved in two principal ways. The first involves the development and implementation of various technical solutions – both entirely new designs of "green" and unmanned vessels, as well as retrofitting existing vessels. The latter means transforming them to the use of alternative fuels or equipping them with additional emission-absorbing devices or alternative propulsion systems (Kondratenko et al., 2025b). Such solutions are potentially highly effective, but require significant capital investments and a relatively long timeframe. The second approach concerns significantly improving the operational efficiency of existing vessels. It means the development and widespread implementation of decision-support and information systems, both onboard and onshore (i.e., used in the offices of shipping and logistics companies). This approach requires significantly lower financial investment, while the positive results (fuel economy or reduced emissions) are often comparable to those of more demanding technical solutions.

Weather routing software — advisory tools that enable path finding and route planning based on forecasted environmental dynamics, vessel characteristics, and specified optimality criteria and constraints – explicitly relates to the latter way. Such software is already widely used in shipping practice. Traditionally, it focus on maximizing commercial targets (searching the fastest or shortest route, optimizing profits while taking into account strict delivery constraints, etc.). Sustainable and environmentally responsible shipping, however, poses new challenges for users and developers of this class of software. This report considers the related challenges and presents our vision for promising new methods and approaches to the weather routing service. The issue is demonstrated with the current state and prospective development of the author's software product - a web service for routing transoceanic voyages of transport vessels developed by the "Argestes" company.

2 MATERIAL AND METHODS

Our solution is an open-access internet service (see https://routing.argestses.net/), allowing any user to calculate and analyze the optimal route (both trajectory and mode of movement) for a given ship from a given departure to a given destination point within a given time period. We tried to support a minimal entry threshold in our product – to set the vessel, one needs to set nothing more than an IMO number. The service integrates the following principal modules and functional components:

- Original and fast hybrid cell-wave numerical algorithm of path finding in dynamic and heterogeneous media.). We extend the traditional isocost-oriented approach, and the main idea is the new effective method for eliminating unpromising points at each step of the iterative algorithm of wave propagation (Topaj, Tarovik, 2025)
- Built-in database of ship parameters (tankers, container ships, bulk carriers etc). Over 107,000 simplified ship digital models, sourced from trusted classification societies
- Versatile ship performance model taking into account the full spectrum of environmental influences on resistance, fuel consumption, and seaworthiness parameters. The main advantage of the newly proposed model is its simplicity, which makes it a useful tool in the case when high-fidelity simulators are unavailable or impossible to implement due to the lack of input data.
- Relevant free-access weather forecasts from trustworthy providers (Copernicus, NOAA, ECMWF). Wind, wave, ice, and bathymetry data are seamlessly integrated into our routing engine during the calculation process. Ice and mixed-conditions navigation is also supported.

- Geoprocessor module permits avoiding spatiotemporal zones of prohibited or risky navigation. It also allows accounting for canal tolls, strait queue delays, appointed passage time slots, and other operational constraints.

Using our service, one can plan a future voyage for a fixed schedule or a free departure/arrival window. The optimization system intelligently balances parameters to produce results that are both operationally robust and economically sound. The latter is provided by setting one of the pre-defined customized optimization criteria (cost, fuel, time, risk, distance, etc.). As a result, the user obtains a family of recommended routes and can compare them or have a visual playback of alternatives to make the most informed strategic decision.

3 CHALLENGES AND PROSPECTS

In our view, the new functionality for the future automated systems of optimal routing, driven by the decarbonization requirements of maritime shipping, has to cover at least the following issues:

1. Direct calculation of total emissions for main greenhouse gases (carbon dioxide, methane, nitrous oxide) and the CII index per voyage for each alternative route variant. Such functionality is already implemented in the current version of the service.

2. Calculation of sulfur emissions on route segments depending on the explicitly specified fuel type for each voyage and the local operating regime of the ship engine.

3. Implementation of a versatile system for the choice of criteria and constraints in the mathematical optimization problem being solved. Now, the criterion could be minimal emissions, while the constraint could be, for example, the obligation to deliver cargo within a specified time window. The numerical optimization algorithm used in the current version of our system is defined by a single scalar score and an arbitrary number of terminal and integral constraints of any type. So, it seems to be sufficiently flexible for any of the mentioned modifications.

4. Input and taking into account when calculating the optimal route, the emission control areas (ECA) and vessel speed reduction zones (VSR) as specific geo-referenced spatial objects with explicitly defined limits on permissible emissions or velocity limitations.

5. Expanding the list of possible optimization variables. Here, in addition to the trajectory and engine power level, additional variables need to be introduced. One such variable could be the fuel type (really, many modern vessels can switch quite quickly from diesel to LNG, for example, while passing through specially protected natural areas). The temporary switching to purely electric motion on certain sections of the route using energy accumulated on previous sections could also be considered here. The choice of current propulsion from several alternative options could also be a new optimization variable for new-generation vessels. The latter could significantly change the optimal route obtained in weather routing (Sun et al., 2025). While traditional vessels currently strive to avoid storm zones, it's entirely possible that future unmanned vessels equipped with rotor sails will, conversely, seek out strong wind zones to maximize their energy efficiency. All of these potential improvements fit within the semantics of the special discrete optimization variables already implemented in our algorithm—the so-called "statuses". This concept is currently used in the service to find the optimal movement mode for double-action vessels in ice, i.e. fore- or stern forward (Topaj et al., 2019). However, it appears to be completely suitable for the prospective system modifications described above.

4 CONCLUSIONS

The mentioned improvements and extensions should make vessel routing software systems a powerful and user-friendly tool that is in demand in the real practice of sustainable and decarbonization-oriented shipping.

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Meteorological route dynamic optimization method based on improved A-star algorithm

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Extended Abstract

With the rapid advancement of economic globalisation, international maritime trade has expanded substantially, leading to an increasing reliance of global logistics systems on maritime transportation (Xu and Guedes Soares, 2026). As a consequence, greenhouse gas emissions generated by ship operations have continued to rise, posing significant challenges to the decarbonisation goals and sustainable development of the shipping industry. In parallel, the safety and economic efficiency of ship navigation are strongly affected by complex and highly variable ocean–atmospheric conditions, including wind, waves, and ocean currents. These factors directly influence voyage safety, fuel consumption, sailing time, and overall operational costs (Szłapczyńska et al., 2022). Under such circumstances, improving energy efficiency while maintaining navigational safety has become a critical objective for modern ship operation. In particular, meteorological route optimisation has emerged as an effective operational measure to reduce fuel consumption and emissions without requiring major hardware modifications, making it highly attractive for practical onboard applications (Vettor and Guedes Soares, 2016). In recent years, extensive research has been conducted on ship route optimisation considering meteorological and oceanographic conditions(Vettor and Guedes Soares, 2022). Conventional approaches mainly rely on static weather routing methods or graph-based search algorithms, such as Dijkstra and A-star, to determine optimal sailing paths. These methods have demonstrated effectiveness in reducing fuel consumption or voyage time under simplified assumptions (Song et al., 2025).

However, several limitations remain in existing studies. Most approaches rely on static route planning and cannot adapt to time-varying meteorological conditions. Traditional A-star algorithms often suffer from low computational efficiency in large-scale environments, and many optimisation frameworks focus on a single objective while neglecting trade-offs among multiple objectives. In addition, the integration of real-time environmental updates into onboard decision-making systems remains limited.

To address these issues, this study proposes a dynamic, multi-objective meteorological route optimisation method based on an improved A-star algorithm. The method aims to minimise fuel consumption while ensuring navigation safety and operational feasibility. Sailing distance, voyage time, and fuel consumption are jointly considered as optimisation objectives, enabling flexible route planning under different operational requirements. Wind, wave, and ocean current data are incorporated to construct the navigation environment model. The study area is discretised into longitude–latitude grids, where each node is assigned environmental attributes and classified as navigable or non-navigable based on ship manoeuvring constraints.

To ensure computational efficiency and practical applicability in large-scale maritime scenarios, the proposed A-star algorithm is further enhanced by explicitly incorporating ship manoeuvring constraints and navigation-aware directional preferences into the search process. Unlike conventional A-star algorithms that expand nodes uniformly in all feasible directions, the improved search strategy prioritises sailing directions aligned with ship heading, motion characteristics, and favourable environmental conditions. This targeted node expansion significantly reduces the effective search space and improves computational efficiency, particularly for long-distance ocean navigation.

During the route search process, the improved A-star algorithm expands candidate nodes based on navigation constraints and directional preferences. For each node, the total cost is computed as a combination of the accumulated cost from the start node and a heuristic estimate to the goal. The accumulated cost is dynamically

updated by integrating ship performance models and environmental impacts, such as speed reduction and fuel consumption under specific sea conditions.

A multi-objective cost function is formulated to capture the trade-offs among sailing distance, voyage time, and fuel consumption under varying meteorological conditions. Environmental factors, including wind, waves, and ocean currents, are explicitly incorporated into the cost evaluation of each grid node, enabling the navigation environment to be represented in a physically meaningful manner. To support multi-objective optimisation, weighting coefficients are introduced to balance different cost components. By adjusting these weights, the search process can be guided toward different optimisation objectives, such as minimum fuel consumption, shortest sailing distance, or shortest travel time. This mechanism allows the algorithm to generate multiple candidate routes under different operational preferences within a unified framework.

Furthermore, a dynamic route optimisation mechanism is incorporated to handle time-varying meteorological conditions. At each update step, the ship's future state, including position, heading, and speed, is predicted based on real-time navigation data. Correspondingly, updated meteorological information is mapped onto the discretised grid and used to recalculate the environmental cost of each node. The route is then re-evaluated and incrementally adjusted, ensuring that the planned trajectory remains optimal as environmental conditions evolve. Through the integration of environment modelling, ship performance estimation, adaptive cost evaluation, and dynamic updating, the proposed framework establishes a closed-loop optimisation process that continuously refines the route throughout the voyage. **The overall framework of the proposed dynamic meteorological route optimisation method is illustrated in Fig. 1.**

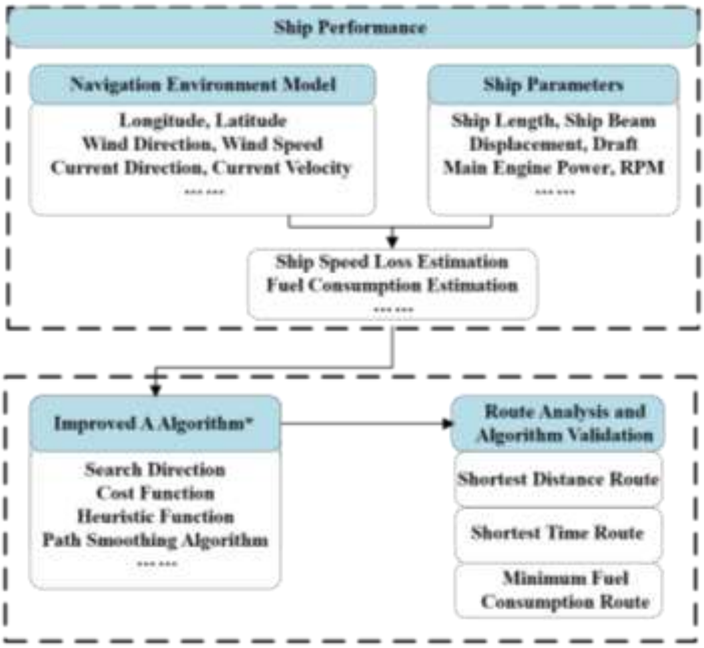

Fig. 1 presents the workflow of the proposed method.

Simulation experiments are conducted on both eastbound and westbound ocean routes using MATLAB. The proposed optimisation method is evaluated by comparing the optimised routes with initially recommended meteorological routes.

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Decision-support approach for selecting ship energy efficiency measures

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Extended Abstract

1 INTRODUCTION

The shipping industry is currently experiencing significant pressure to move forward with decarbonisation and air pollution reduction efforts and the International Maritime Organization (IMO) is leading this process, Tadros *et al.* (2023). A very large number of energy efficiency measures is available, but its applicability to different ship types varies substantially, and the economic and efficiency gains are also variable. DNV (2024) has recently presented a framework that standardizes the assessment of the different measures, but shipping companies decision-making is still difficult.

It is thus useful if such framework can be further developed into a proper decision support system, taken as a computer-based information system designed to support managerial decision-making by providing tools, models, data access, and analytical capabilities, Power (2020). The objective of this paper is to present such numerical tool for supporting decision making in the field of energy efficiency in shipping, based upon, and expanding, the framework of DNV (2024). The contributions of this paper consist of a detailed economic analysis of each measure, enabling a ranking procedure for the measures according with several economic merit parameters.

2 METHODOLOGY FOR RANKING ENERGY EFFICIENCY MEASURES

The approach of DNV (2024) is further developed by quantifying all aspects of this framework, considering that certain aspects are not entirely clear in the original document. In addition to the general approach, additional elements are supplied detailing aspects related to investment and operating costs and applicability to different ship types, sizes and ages. Calculation methods for assessing multiple energy efficiency techniques in terms of measures of merit are developed and implemented into a decision support tool, which comprises aspects related to parameter input, implementation of calculations and presentation of results. The adopted measures of merit are the net present value (NPV), return of investment (ROI), pay-back period (PP) and total efficiency gains (TEG). These measures of merit are applied to rank 39 different energy efficiency measures, taking in consideration is suitability to a specific ship type and size.

3 NUMERICAL RESULTS

3.1 *Characteristics of ship selected for case study*

The decision-support tool is applied to a large containership currently in operation, with a capacity of 13,100 TEU and with an age of, at the time of this analysis, 14 years, operating as a retrofit candidate with an expected remaining service life of 11 years. The vessel's propulsion system relies on HFO for the main engine, while MGO is used for both auxiliary engines and the boiler. Annual fuel consumptions data for that ship has been obtained from MaritimePage (2025) while fuel prices are based on market values, with HFO priced at USD 405 per tonne and MGO at USD 781 per tonne. The economic analysis incorporates an 8% discount rate, alongside an annual OPEX of USD 7,000,000, a time charter rate of USD 50,000 per day, and annual revenue of USD 100,000,000.

3.2 *Selection and ranking of energy efficiency measures*

A first analysis is conducted using the concept of Selective Compatibility Threshold (SCT) of 10, representing a balanced filtering level that excludes clearly incompatible measures while maintaining a comprehensive evaluation set. With this value for SCT, the tool identifies 28 applicable energy efficiency measures for this specific ship, from the complete database of 39 available measures. Table 1 presents the top five of the rankings of measures, for the containership, considering the four different measures of merit.

Table 1. Ranking of energy efficiency measures for SCT of 10.

Rank	NPV	ROI	PP	TEG
#1	M031	M031	M034	M031
#2	M035	M010	M036	M035
#3	M019	M033	M035	M017b
#4	M010	M008	M031	M005
#5	M007	M019	M010	M019

M005 - Wind-assisted propulsion systems
M007 - Bulbous bow retrofit
M008 - High performance coating
M010 - Hull and propeller cleaning
M017b - Batteries (Full electrification)
M019 - Engine de-rating
M025 - Shore power
M031 - Deadweight/ draught increase
M033 - Trim optimization
M034 - Port optimization
M035 - Speed optimization
M036 - Weather routing

3.3 *Sensitivity analysis to changes in composite index weights*

Taking in consideration that rankings shown in Table 1 are related to different measures of merit, a composite index of these four rankings has been created. It merges the rankings into a single unified ranking using a set of weights. This index depends on this weighting system and a sensitivity analysis is presented in Figure 1 showing the changes occurring in the ranking (as per the composite index) of the first six measures, due to different weighting of the four measures of merit. Higher values of the composite index indicate a better overall performance of the measure (higher ranking location), but weight variations show little influence on ranking.

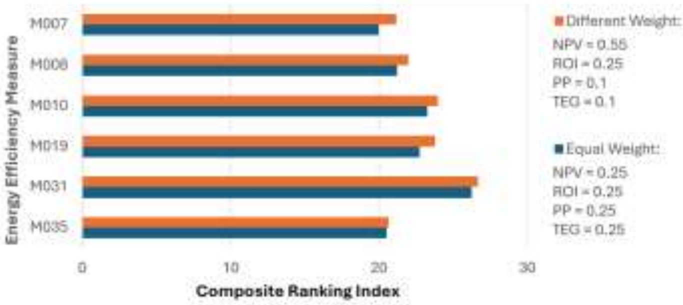

Figure 1. Composite ranking of energy efficiency measures.

3.4 *Scenario analysis considering different economic conditions*

The ranking results are also related to a number of economic parameters that are likely to produce changes in ranking. These economic parameters are the operating expenses (OPEX), time charter rates and fuel costs. Therefore, three scenarios are considered. Case 1 corresponds to the baseline scenario presented in section 3.1. Case 2 simulates a weak market condition, characterized by a 15% increase in OPEX costs and a 30% reduction in both time charter rates and fuel costs relative to Case 1. Case 3 represents a strong market condition, with OPEX costs decreasing by 10% and time charter rates and fuel costs rising by 30%.

Despite these variations, the top five ranked measures remain consistent across all three scenarios, with only minor differences emerging from the sixth position onwards. This stability is particularly relevant in the context of a potential retrofit of this container ship, as it demonstrates that top-ranked measures are robust to economic fluctuations. More pronounced parameter variations are expected to produce greater shifts in the rankings.

4 CONCLUSIONS

A decision-support tool for selecting suitable ship energy efficiency measures is presented. Preliminary results for a container ship indicate that the robustness of rankings is good and the energy efficiency measures for containerships are in line with industry practices. The scenario analysis further confirms that the top-ranked measures remain stable under different economic conditions, demonstrating the reliability of the decision-support tool for retrofit vessel applications.

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Decision-support tool for promoting port decarbonisation

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Extended Abstract

1 INTRODUCTION

Port decarbonisation involves studying the different types of port emissions, the technical characteristics of emission control measures, their applicability, the required investments and operational costs. Styhre et al. (2017) provides a cross-continental comparison of greenhouse gas (GHG) emissions from ships in port areas and evaluates the reduction potential of a set of port decarbonisation measures. Monios et al. (2024) introduce a climate-change-centred governance framework for ports, as well as a stakeholder/action mapping tool that highlights patterns of collaboration and conflict. Santos (2025) provides a comprehensive and updated overview of issues related to port pollution and the associated mitigation and prevention measures. A number of EU funded research projects have developed significant work on individual measures but it can be argued that a systematic approach to enhancing the decision-making process of port emissions reduction is lacking. Namely, port authorities are lacking a decision support tool that, based on port specific characteristics, proposes an optimum set of decarbonisation measures (those leading to the highest emissions decrease) which should be incentivized using a restricted budget. Nevertheless, the paper only describes the preliminary phase of the tool's development.

2 METHODOLOGY

The decision-support tool mentioned above is developed as a modular and entity-specific architectural approach using Python within the Tkinter library for the graphical user interface (GUI). The approach adopted to develop the tool starts by organizing the port's diverse infrastructure by entities, into four distinct computational modules, each handling a specific set of terminals and operational logics:

1. Commercial Terminals Module: facilitates the processing of merchant shipping operations, focusing on ships calls. It is designed to assess emissions from large merchant vessels and cargo handling operations. The terminal complex is comprised of ten distinct terminal typologies, thus ensuring coverage for the entire spectrum of commercial traffic:
   - Freight: Container Terminal, Liquid Bulk, Dry Bulk, General Cargo, Ro-Ro (Car Carrier), and Cargo Ro-Ro.
   - Passenger & Specialized: RoPax Terminal, Cruise Terminal, River Ferry Terminal, and Fishing Port.
2. Port Services Module: focuses on the resident fleet that is managed by the port authority or concessionaires. The present study address two specific categories:
   - Pilot Stations: Modelling pilot boats and service ships.
   - Port Authority Assets: Covering harbour tugs, escort tugs, mooring boats, workboats, patrol/police vessels, dredgers, and pollution control vessels.
3. Recreational Marina Module: designed to model leisure navigation and address the specific energy profiles of marinas. This model enables marina managers to estimate emissions based on the statistical distribution of boat size types and their typical operational profiles.
4. Renewable Energy Module: evaluate the generation potential of two technologies:
   - Solar PV
   - Wind Power

The algorithm processes each selected entity independently, applying specific baseline formulas and decarbonisation measures before aggregating the results into a consolidated port-wide report. Figure 1 presents the workflow of the decision-support tool.

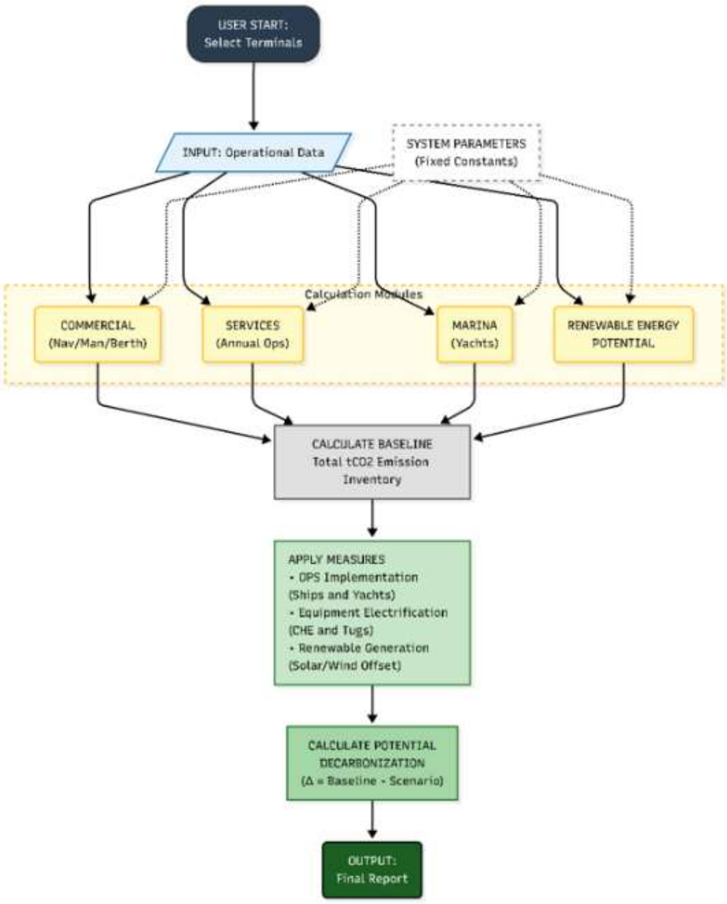

Figure 1. Workflow of the proposed decision-support tool.

3 APPLIED MEASURES

In view of the considerable opportunities for emission reduction, measures for the transition of the port's energy source from fossil fuels to renewable sources are selected for further analysis. Consequently, the direct electrification of equipment and fleet, and the onshore power supply (OPS) for ships, are measures that must be given due consideration. In addition, the potential for port to generate energy from renewable sources is analysed.

4 CONCLUSIONS

The paper's primary objective is to present the development of a computational decision support tool for port decarbonisation. The result is a functional, modular, Python-based framework that quantifies greenhouse gas emissions and evaluates mitigation measures across various port environments. The tool's modular structure provides a comprehensive overview of the port's carbon emissions. It clearly distinguishes between direct emissions from fossil fuel combustion and indirect emissions from electricity consumption. This enables the development of strategies customised to the operational reality of the port.

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Onboard decision support for energy-efficient hybrid ship operation: EMS–PMS setpoint strategy and interface design

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Extended Abstract

An Energy Management System (EMS) operating on a slow time scale computes energy-optimal setpoints for power split among gensets, battery and shore charging, while a Power Management System (PMS) operates on fast time scales to ensure stability and enforce constraints. The methodology is grounded in the EMS definition and EMS–PMS interface datasets specified in FLEXSHIP (OPS/shore charging, battery, genset, and propulsion-demand signals). The Atatürk configuration (3 MWh BESS; 750 kVA primary and 300 kVA backup genset) is used to frame setpoint generation and KPI-based evaluation.

1. INTRODUCTION

Hybrid ships can reduce energy use and emissions, but benefits depend on how onboard sources are scheduled during operations [1]. Onboard decision support is therefore needed to translate measurements into feasible power-split recommendations that respect safety and mission constraints [2]. EMS is defined as the optimisation layer that manages power distribution and usage to reduce fuel consumption/costs and greenhouse-gas emissions by selecting best operating points considering efficiency, emissions, and costs [3-5]. This work focuses on the Atatürk hybrid demonstrator, representative of longer-range hybrid operation with a 3 MWh battery and 100–300 nm routes and an onboard architecture with a 750 kVA primary genset, a 300 kVA backup genset and a 3 MWh battery system integrated through power electronics and switchboards.

2. METHODOLOGY

2.1 EMS–PMS control architecture and time-scale separation

Modern electrified marine vessels separate responsibilities across two supervisory layers [6]. EMS runs a slow loop (minutes) to determine an optimal power split among energy components and sends suggested setpoints to PMS. PMS runs on seconds–milliseconds to ensure power availability and stability, monitors and controls distribution, and returns real-time feedback to EMS. PMS follows EMS setpoints whenever possible, which supports stable operation and reduced power fluctuations [7-9].

2.2 EMS strategy class and setpoint computation

EMS strategies can be rule-based or optimisation-based. Rule-based EMS implements mode-dependent setpoint maps (harbour/transit/peaks) with constraint checks. Optimisation-based EMS computes setpoints in a constrained, receding-horizon manner using component limits and reserve policies. In both cases, the decision support outputs are requested setpoints for battery power, genset power, and OPS charging power [10].

2.3 Implementable EMS–PMS interface (data model)

A communication interface is required for EMS–PMS data exchange. FLEXSHIP specifies component-wise signal sets that enable direct implementation on Atatürk: (i) OPS/shore charging status and nominal/actual power plus requested charging setpoint; (ii) battery max charge/discharge power, actual power, SoE, nominal energy, and requested battery power setpoint; (iii) genset min/max available power, actual power, fuel input power, and requested genset setpoint; and (iv) propulsion treated as mandatory demand, with PMS-to-EMS propulsion actual and maximum power signals.

3. CASE STUDY: ATATÜRK HYBRID DEMONSTRATOR

Atatürk's hybrid configuration (3 MWh BESS with 750 kVA primary and 300 kVA backup genset) creates a continuous trade-space for energy-efficient decision support: shifting genset operating points away from inefficient low-load regions, using the battery for peak shaving/smoothing, and planning OPS charging when available. An implementable EMS decision-support layer can be structured around slow-loop modes: harbour/port (charge planning and departure SoE targets), transit (efficient genset loading with battery smoothing and SoE reserve band), and peaks/manoeuvring (increased battery contribution within power limits while PMS manages fast stability).

4. EVALUATION METRICS

The proposed decision-support concept can be evaluated on Atatürk using the EMS–PMS interface signals during representative operational profiles. A compact KPI set is:

- Fuel-input reduction proxy: compare genset fuel input power against delivered electrical power under different power-split policies.
- Energy efficiency: energy per nautical mile derived from propulsion demand and integrated energy flows (battery, gensets, OPS).
- Battery utilisation intensity: SoE trajectory and charge/discharge power, including peak power events and reserve-margin violations.
- Setpoint feasibility/tracking: fraction of time PMS can follow EMS targets under power and safety constraints, highlighting robustness.

5. CONCLUSION

This paper proposes an onboard decision support blueprint for the FLEXSHIP Atatürk hybrid demonstrator, grounded in (i) an EMS definition focused on efficiency, emissions, and cost-aware optimisation; (ii) a clear EMS–PMS time-scale separation supporting safe execution; and (iii) an implementable EMS–PMS interface specification across OPS, battery, gensets, and propulsion-demand signals. The concept supports energy-efficient hybrid operation by generating feasible setpoints and transparent KPIs for operators while PMS preserves stability.

FUNDING

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Speed and engine load management within energy-efficiency decision support systems for maritime decarbonisation

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Extended Abstract

1. INTRODUCTION AND MOTIVATION

Decarbonisation of maritime transport is a central objective in achieving global climate targets. While long-term solutions such as alternative fuels and propulsion technologies are being developed, immediate emission reductions must be achieved through operational measures applicable to existing fleets.
Among these, speed optimisation and engine load management are the most effective short-to-medium-term strategies (Psaraftis and Kontovas, 2013). Their integration within energy-efficiency Decision Support Systems (DSS) enables a shift from heuristic operational practices to data-driven, optimisation-based decision-making aligned with evolving regulatory frameworks (Bal Beşikçi *et al*., 2016; Farag and Ölçer, 2020).

2. OBJECTIVE

This work examines the role of speed and engine load management as core functional components of decarbonisation-oriented DSS, focusing on their capacity to reduce fuel consumption and greenhouse gas emissions, support regulatory compliance, and enable adaptive real-time operational decision-making.

3. FRAMEWORK AND APPROACH

The proposed framework integrates operational data, performance modelling, and optimisation layers within a unified DSS architecture. Speed optimisation is treated as a dynamic problem influenced by environmental conditions and routing constraints (Fagerholt *et al*., 2015), while engine load management ensures operation within optimal efficiency regions.

Data-driven models and digital twin approaches further enhance prediction accuracy and enable adaptive optimisation under uncertain conditions (Moreira *et al*., 2021). These components collectively enable the transition from descriptive monitoring to predictive and optimisation-based decision support.

4. KEY FINDINGS

Ship speed remains the most influential operational control variable due to the nonlinear relationship between speed and propulsion power. Engine load optimisation improves energy efficiency by maintaining operation within optimal specific fuel consumption ranges.

Recent DSS developments increasingly integrate regulatory and economic signals, including carbon pricing and emission indicators, into optimisation frameworks (Koundouri *et al*., 2025).

5. CHALLENGES AND IMPLEMENTATION CONSIDERATIONS

Despite their potential, DSS-based strategies face several challenges, including model uncertainty under variable environmental conditions, dependence on high-quality operational data, and operational constraints such as schedule reliability.

Integration challenges also arise from the need to ensure interoperability with existing shipboard systems and adaptability to evolving regulatory frameworks.

6. CONCLUSIONS

Speed optimisation and engine load management are key operational mechanisms for translating decarbonisation targets into practical shipboard actions. When embedded within DSS architectures, these strategies enable significant improvements in energy efficiency while maintaining operational reliability and ensuring compliance with evolving environmental regulations. Effective deployment requires integration of accurate performance models, reliable real-time data, and adaptive optimisation frameworks capable of responding to both environmental variability and evolving regulatory constraints.

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Multi-fidelity transfer learning for energy-aware autonomous ships using RL

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Extended Abstract

Inland waterway vessels offer a low-carbon alternative for the transportation sector. In spite of their potential, adoption remains limited due to significant operational costs, including personnel costs. As a result, autonomous shipping has recently attracted significant research interest. Reinforcement learning (RL) is a particularly promising approach, as it can adapt to dynamic, complex environments through direct interaction. However, current approaches require significant computational resources to train and fail to consider the energy efficiency of the ship. In this work, a multi-fidelity transfer learning-based approach is proposed, which starts training in a low-fidelity shipping simulator, and transfers the RL agent to a high-fidelity simulator after learning converges. Preliminary results indicate that this approach achieves comparable performance to standard RL, while requiring only a fraction of the training time.

1 INTRODUCTION

The recent trend towards decarbonization of the transportation sector provides a tailwind for the adoption of inland waterway vessels. Against this favorable backdrop, the maritime sector is faced with increasing operational costs and a growing staff shortage, largely caused by an aging workforce. Additionally, safety remains an area of concern, with recent work advocating for autonomous ships to reduce human casualties (de Vos et al. 2021). These developments highlight the need for greater autonomy in the maritime sector. Reinforcement learning (RL) has recently gained attention as a promising approach for the autonomous control of ships, owing to its ability to adapt to dynamic and complex environments (Chen et al. 2019). However, training RL agents using high-fidelity maritime simulators is computationally expensive due to the need for extensive interactions with the environment during training (Eloot et al. 2025). Although extensive research has been conducted on the application of RL for path following and collision avoidance (Wang et al. 2024), there is still a lack of studies that incorporate the energy efficiency of the ship into the RL optimization. To address these limitations, this research introduces a multi-fidelity transfer learning-based approach using reinforcement learning for path following, while considering the energy efficiency of the ship during the trip. Rather than relying on a single high-fidelity simulator, RL training is performed in a staged manner. First, training commences in a low-fidelity simulation environment, allowing the agent to learn basic ship dynamics while requiring minimal computational effort. Next, training is transferred to a high-fidelity simulator, which enables the agent to adapt to more realistic ship responses.

2 METHODOLOGY

During this work, we used two shipping simulators, a custom low-fidelity simulation environment in Python based on the Fossen model (Fossen, 2011), and a high-fidelity simulator developed by Flanders Hydraulics (Chen et al. 2021), which considers environmental disturbances, including wind and current. Experiments are conducted using two vessel models, Tripoli-Deseo and Myzako. For both vessels, the hydrodynamic coefficients used in the low-fidelity Fossen model are derived from the high-fidelity tabular models provided by Flanders Hydraulics. This calibration strategy minimizes the sim-to-sim gap between the two environments. The RL agent starts training in the low-fidelity environment and, once it demonstrates satisfactory performance in following the predefined trajectory, is transferred to the environment from Flanders Hydraulics. Furthermore, we formulate the path following task as a Markov decision process (MDP), which defines the observation space, the action space, and the reward function. During our experiments, the observation space comprises the velocity of the ship, the cross-track error, the distance to both the current and the next checkpoints, and the heading towards the current and the next checkpoints. Additionally, the RL agent can control both the rudder position and the thrust delivered by the engine of the ship. The reward function is designed to closely follow a predefined path while considering the energy efficiency of the ship. Although energy consumption represents a key optimization objective, relying solely on this term would lead to suboptimal or degenerate behaviors. Therefore, additional terms are introduced to properly constrain the agent's behavior. The reward function is defined as (1) where v_f is the forward velocity aligned with the path, preventing the agent from trivially minimizing energy consumption by reducing its speed, while e_y is the cross-track error and ψ_e is the heading error between the current heading of the ship and the heading of the next checkpoint. In particular, these terms ensure that the learned policy follows the path consistently, rather than exploiting other routes that deviate from the intended trajectory and may violate operational constraints. Lastly, E_e is the energy consumption of the engine of the ship, which can be approximated by incorporating the hydrodynamic drag experienced by the vessel. $\lambda_{forward}$, $\lambda_{cross-track}$, $\lambda_{heading}$, and λ_{energy} are the weighting coefficients for the forward velocity, cross-track error, heading error, and energy consumption, respectively.

$$R = \lambda_{forward} \cdot v_f + \lambda_{cross-track} \cdot e_y + \lambda_{heading} \cdot \psi_e + \lambda_{energy} \cdot E_e \quad (1)$$

3 PRELIMINARY RESULTS

We have already implemented the low-fidelity Python simulator and successfully trained an RL agent to follow a predefined trajectory within this environment. The performance of this agent was tested in the high-fidelity simulator of Flanders Hydraulics without retraining in this new environment. As demonstrated by Figure 1, the RL agent closely follows the predefined trajectory, albeit with some slight oscillations around the optimal path. We attribute these deviations to the remaining sim-to-sim gap between the low-fidelity Python simulator and the high-fidelity simulator of Flanders Hydraulics. These preliminary results indicate that RL agents trained in a low-fidelity simulator can be transferred to high-fidelity simulators with minimal retraining, significantly reducing the computational costs of training RL agents for autonomous shipping.

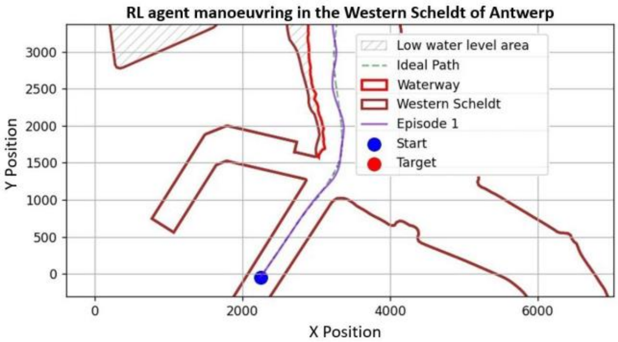

Figure 1. Visualization of the path followed by the RL agent in the shipping simulator of Flanders Hydraulics

4 CONCLUSIONS

In this work, we expect to significantly reduce the RL training by applying transfer learning between shipping simulators of different fidelity levels. Furthermore, this approach is expected to enhance the agent's ability to generalize and operate effectively under dynamic real-world conditions.

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A multi-scale simulation framework for zero-emission IWT planning

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Extended Abstract

The decarbonisation of inland waterway transport (IWT) requires not only advances in zero-emission propulsion, but also decision-support tools capable of assessing the operational viability of such vessels under real-world constraints. Battery-electric and hydrogen fuel cell propulsion introduce hard range limits that are highly sensitive to vessel loading, waterway geometry, current conditions, and infrastructure constraints that existing generic simulation tools are not designed to handle at the granularity required for Class I and II waterways. This paper addresses that gap by presenting a multi-scale simulation framework developed within the EU Horizon Europe FOREMAST project, applied to a novel class of Small, Flexible, Automated, Zero-emission (SFAZ) vessels designed for urban and peri-urban waterborne logistics.

The framework integrates three complementary modelling scales. At the macro scale, a Total Cost of Ownership (TCO) tool evaluates the long-term economic viability of SFAZ deployment relative to road and diesel vessel freight, accounting for vessel capital costs, energy, maintenance, and labour under varying fleet configurations. At the meso scale, an agent-based simulation (ABS) models multimodal freight flows, simulating vessel movements, cargo transfers, lock passages, and modal interactions across multi-layered network data drawn from OpenStreetMap and EuRIS. At the micro scale, three physics-based modules – a route evaluator, a cargo optimiser, and an energy consumption model – provide vessel-specific operational intelligence: infrastructure-constrained routing, cargo placement based on constraint satisfaction, and CFD-grounded range prediction for both battery-electric and hybrid battery/hydrogen fuel cell configurations. The three scales share a common data backbone consisting of two interoperable Neo4j knowledge graph instances: a vessel taxonomy encoding hull geometry, hydrodynamic performance curves, propulsion specifications, and energy storage parameters; and an IWT network ontology representing waterway infrastructure with RIS-compliant constraints on depth, bridge clearance, lock dimensions, and terminal capabilities. All simulation modules are exposed as standardised API services and integrated within the FOREMAST Digital Twin platform, where binding to real-time telemetry streams enables continuous synchronisation between physical vessels and their virtual counterparts, extending the framework from planning tool to live operational decision-support.

The framework is validated against FOREMAST's Living Lab 1 in Ghent, Belgium, a city characterised by an intricate network of Class I–IV rivers and canals. The specific scenario is the multi-year renovation of the Royal Opera House, with delivery routes reaching the Ketelvaart, a Class II inner-city canal within the Low-Emission Zone, across both demolition waste removal and construction material delivery phases. Results yield four operationally significant findings. River current dominates zero-emission range: a 2 m/s favourable current increases final battery state-of-charge by 15%, while a 2 m/s opposing current reduces it by 64% – a variation rule-of-thumb modelling cannot capture, and that directly determines whether a swap stop is required. Cargo configuration under draft and bridge clearance constraints produces non-intuitive fleet selection outcomes: smaller vessels outperform larger ones on specific routes due to dimensional restrictions that force longer detours on vessels with greater air draft. A macro-economic analysis identifies a breakeven point at approximately 26 tonnes of daily transported cargo, below which SFAZ carries a cost premium over both electric and diesel trucks. Fleet configuration analysis, comparing single-vessel operations with coordinated multi-vessel missions,

reveals significant trip count reductions with comparable per-trip costs when labour savings from reduced crewing are accounted for, with SFAZ waterborne logistics becoming cost-competitive with road freight beyond a modal shift threshold of approximately 62%. Cross-validation between the ABS and micro models confirms complementarity: the ABS addresses modal shift and system-level cost comparison; the physics-based micro model resolves operational detail on range, cargo, and energy management. Scenario inputs and outputs are further structured using a standardised application and performance template, providing a replicable reporting format for SFAZ use cases across living labs.

The primary contribution is a reusable, vessel-agnostic simulation architecture in which operational parameters are decoupled from model logic through a knowledge graph data layer, allowing the framework to be applied to any zero-emission IWT vessel class and any European waterway network for which RIS-compliant infrastructure data is available. Its realisation as a Digital Twin system, connecting simulation models to live physical assets, further positions the framework as an operational decision-support tool accessible to vessel operators, port authorities, and logistics planners navigating the transition to zero-emission urban waterborne freight.

Human-centric physics-informed framework for maritime energy optimization

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Extended Abstract

1 GENERAL INTRODUCTION

The maritime sector is navigating a structural transformation to meet International Maritime Organization (IMO) greenhouse gas reduction targets. Onboard Decision Support Systems (DSS) have transitioned from data-logging tools into predictive intelligence hubs. However, a significant "trust gap" often prevents crews from implementing AI recommendations. This paper presents an original framework that couples high-fidelity "grey-box" modeling with Explainable AI (xAI) and Augmented Reality (AR) to ensure predictive insights are actionable and trusted.

2 METHODOLOGY AND MODELING STANDARDS

To enhance energy efficiency, this study moves beyond traditional "black-box" models. We integrate physical laws into the learning process using Physics-Informed Neural Networks (PINNs) and hybrid architectures.

2.1 Literature-Based Benchmarks:

Existing research in maritime hydrodynamics indicates that PINNs can improve the coefficient of determination (R^2) by up to 21.97% [Oh 2026]. Furthermore, validated hybrid engine models utilizing a single hidden layer with five neurons have achieved a Mean Absolute Percentage Error (MAPE) of 0.0647 [Gunes et al. 2023].

2.2 Original Contribution:

Our methodology extends these accuracy gains by integrating a human-centric interface. We developed an original AR-IoT synergy that superimposes these high-fidelity data overlays directly onto physical engine components, using xAI to provide decision transparency.

3 RESULTS AND ORIGINAL VALIDATION

The primary novelty of this work lies in the field evaluation of the integrated interface. While literature focuses on algorithmic precision, our study validates human responsiveness.

Table 1. Performance metrics for literature-based engine optimization [Gunes et al. 2023].

Performance Metric	Hybrid Engine Model Score	Significance
Coefficient of Determination (R^2)	0.99697	Indicates nearly perfect correlation with experimental data
Root Mean Square Error (RMSE)	0.00035	Reflects minimal variance in prediction error
Mean Absolute Percentage Error (MAPE)	0.06470	Demonstrates extreme accuracy in fuel and emission estimates

4 CONCLUSIONS

While existing literature establishes high mathematical accuracy (R^2 = 0.996) for maritime predictive models, this research concludes that such accuracy is functionally irrelevant if it remains trapped behind opaque "black-box" interfaces. The primary finding of this study is that closing the "trust gap" through xAI and AR-IoT is the critical catalyst required to translate theoretical efficiency into real-world fuel savings. By transforming abstract sensor data into an intuitive digital advisor, this framework provides a validated roadmap for 2026 compliance, where human expertise and physics-informed intelligence work in a seamless socio-technical synergy.

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Implementation of ship berthing maneuvers by using artificial neural networks: Analysis of calm water condition

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Extended Abstract

1. INTRODUCTION

Ship berthing maneuvers are among the most complex operations in maritime transportation due to their inherent nonlinear dynamics and the impact of various environmental factors. This study proposes an Artificial Neural Network (ANN) based model to automate ship berthing maneuvers. Within the scope of the study, data were collected from maneuvers performed by an expert ship captain using a full-mission bridge simulator. This paper summarizes the maneuvers conducted specifically under calm water (no wind) conditions, the network architecture employed, and the system performance in these scenarios.

Within the field of ship control, berthing maneuvers hold critical importance due to their inherent challenges, the multiplicity of unpredictable factors, and their reliance on the knowledge and experience of pilots and captains. While studies in the literature began with rule-based controllers and progressed to fuzzy logic and expert systems, optimum solutions have not been fully achieved. Today, in parallel with developments in artificial intelligence technology, ANN models that simulate the learning ability of the human brain stand out as a solution for this complex problem.

2. MATERIALS AND METHODS

The data used in this study consist of simulation outputs of a fixed-pitch propeller container ship berthing at the Keppel Terminal in the Port of Singapore. During the data collection phase, an ECA Sindel Mistral 4000 full-mission bridge simulator was utilized to create a realistic operational environment.

2.1. Mathematical Model and Dynamics

The Maneuvering Modeling Group (MMG) mathematical model, presented by the Japan Towing Tank Committee, was adopted for modeling ship maneuvers (Ogawa and Kasai, 1978). In this model, hydrodynamic forces are characterized separately by the contributions of the hull, propeller, and rudder. Under the calm water assumption, the ship's horizontal movements (surge, sway, and yaw) are expressed by a set of equations with three degrees of freedom. Both a ship-fixed moving coordinate system and an earth-fixed global coordinate system were used to analyze ship motions (Aksu, 2017).

2.2. Artificial Neural Network Architecture

The Multi-Layer Perceptron (MLP) model was preferred for solving highly nonlinear problems such as ship berthing (Minsky and Papert, 1969). The following structural features were utilized in the trained network model:

- Input and Output Parameters: The input layer consists of 7 parameters, including ship position (x, y), heading (psi), velocity (u, v), and angular velocity (r). The output layer contains 4 control parameters: rudder angle, propeller speed, bow thruster, and tugboat force.
- Learning Algorithm: The Levenberg-Marquardt Learning Algorithm (LMA) was selected due to its fast and stable convergence characteristics (Kızrak, 2019).
- Activation Function: The hyperbolic tangent (tansig) function was preferred in the hidden and output layers to increase the learning capacity of the network and optimize the output range (Haykin, 1994).

3. MANEUVERS PERFORMED UNDER CALM WATER CONDITIONS

Expert captain maneuvers were carried out in calm air and water conditions where the wind was absent (0 knots) for the training and validation of the network model.

3.1. Operational Data Collection

The expert maneuver performed in calm weather lasted a total of 28 minutes and 31 seconds. During the maneuver, 1712 rows of data were obtained from the simulator. In these maneuvers, since external factors (such as wind drift) were absent, the ship's inertial forces and hydrodynamic resistances were the primary determinants. It was recorded that during the maneuver, the ship first approached the pier from the bow shoulder, and the parallel berthing was completed in the final stage using tugboats and the bow thruster.

3.2. Performance Analysis

The performance of the network trained with calm water data was evaluated using the Mean Squared Error (MSE) method (Turban and Aronson, 2001). In tests conducted for the scenario without wind effects, it was observed that the ANN model could imitate expert captain behavior with an accuracy of over 95%. Especially in the final berthing phase where the ship speed is low, the control signals generated by the network were found to be damped and stable.

4. DISCUSSION AND CONCLUSIONS

This study demonstrates the effectiveness of the ANN method in automating ship berthing maneuvers specifically for calm water conditions. The high accuracy rates obtained under calm water conditions indicate that the model has a high capacity to learn ship hydrodynamics. However, maintaining safe distances and conducting risk analyses during ship maneuvers are critical for operational safety (Zhang et al., 2015). In future studies, the robustness of the system can be increased by adding different current and wind loads to this base model (Zhang, 2012).

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A Bibliometric assessment of the evolution and research trends of maritime decision support systems

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Extended Abstract:

The accelerating digital transformation of the maritime sector, frequently framed within the Shipping 4.0 paradigm, has significantly strengthened the role of Decision Support Systems (DSS) in enhancing navigational safety, operational efficiency, and environmental sustainability (Gil et al., 2020). Despite continuous technological progress, maritime accidents remain largely associated with human error, emphasising the need for intelligent systems that support and augment human decision-making rather than replace it. Over the past decade, DSS research has evolved from rule-based navigational support tools toward data-driven, AI-enabled frameworks capable of predictive analytics, real-time risk evaluation, and multi-objective optimisation (Perera et al., 2011; Pietrzykowski et al., 2017). Given the rapid growth and interdisciplinary nature of this research domain, a systematic mapping approach is required to identify its structural foundations and emerging trajectories.

This study presents a comprehensive bibliometric analysis of maritime DSS research published between 2010 and 2025. The dataset consists of 902 peer-reviewed documents indexed in Scopus and analysed using Bibliometrix (R) and VOSviewer to examine publication trends, collaboration networks, influential sources, citation structures, and thematic evolution. The results reveal a strong annual growth rate of 15.83%, confirming the dynamic expansion and increasing interdisciplinarity of the field.

Co-occurrence analysis of keywords in the selected papers, depicting the major divisions of the field, identifies several interconnected research streams in Figure 1. One dominant division centres on maritime safety and risk modelling, encompassing studies on collision avoidance, risk assessment methodologies, and probabilistic decision frameworks. A second division focuses on operational decision-making and optimisation, integrating navigation planning, energy efficiency, emission control, and multi-criteria decision-making approaches. A third major division reflects the technological transformation of DSS through artificial intelligence, machine learning, automation, and AIS-based data analytics, supporting predictive and autonomous navigation capabilities. Together, these co-occurred thematic structures demonstrate the convergence of safety engineering, digital technologies, and sustainability-driven operational strategies.

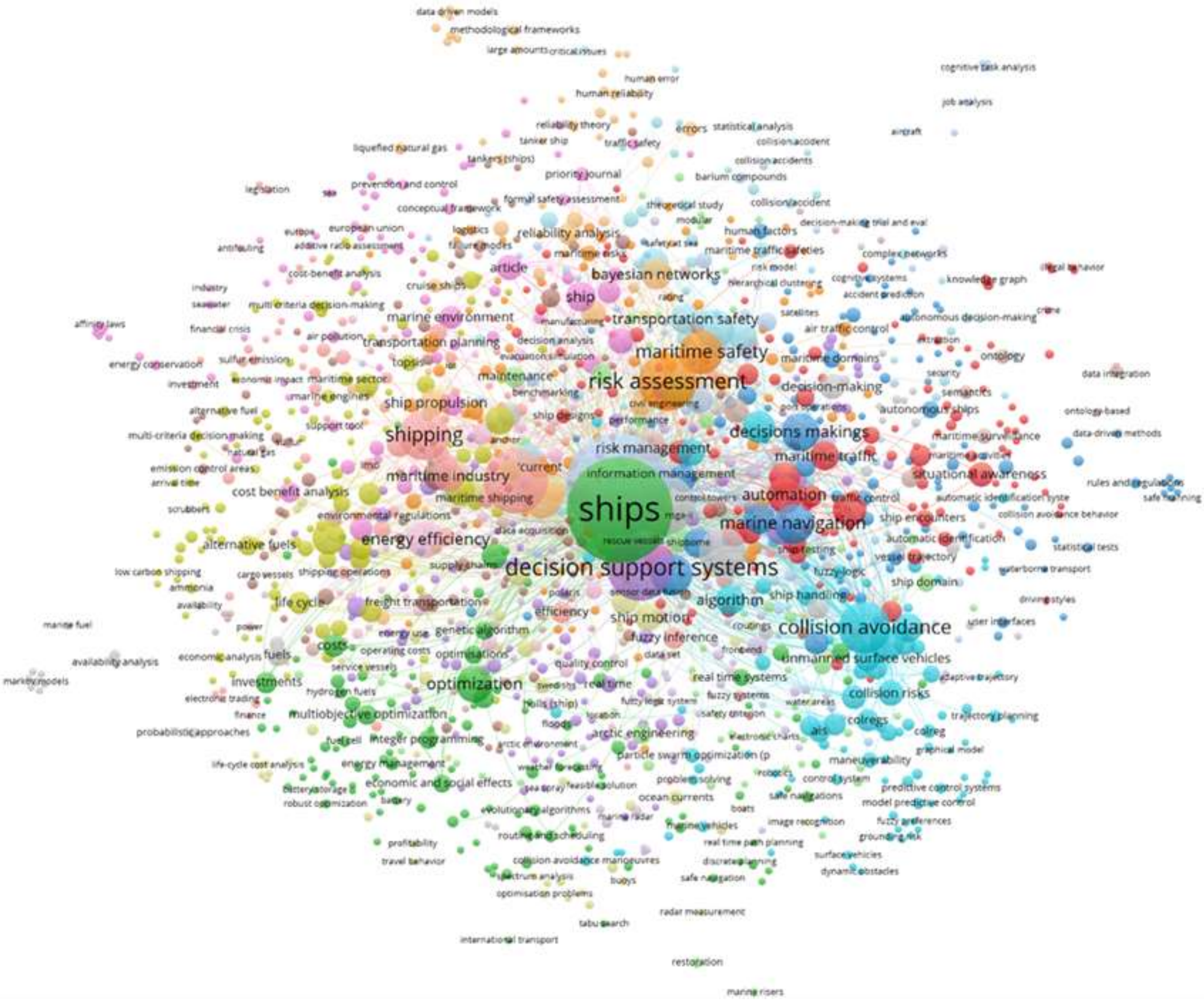

Figure 1. Co-occurred terms in the selected papers depicting the major divisions of the field. https://app.vosviewer.com/?json=https%3A%2F%2Fdrive.google.com%2Fuc%3Fid%3D15WtsHH_FWBi-3IAZ_XC69VPsLYMSUZWe.

Temporal trend analysis indicates a clear progression from early safety-oriented and rule-based systems toward intelligent, predictive, and autonomy-supporting architectures in recent years. While maritime safety remains the central and persistent theme, increasing emphasis on artificial intelligence and environmental performance signals a paradigm shift toward proactive and data-centric decision environments.

The findings confirm that maritime DSS research is transitioning from reactive post-event analysis to integrated, real-time, and predictive support systems aligned with autonomous shipping and decarbonization objectives. However, challenges remain regarding explainability, human–machine collaboration, regulatory integration, and validation in real-world operational settings. By systematically mapping the intellectual and thematic evolution of maritime DSS research, this study provides a structured foundation for future investigations and contributes to the development of reliable, transparent, and sustainability-oriented decision support architectures for next-generation maritime operations.

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Design for agility: Enabling vessel readiness for the energy transition

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Extended Abstract

The global maritime industry is navigating a critical transition driven by the urgent imperative to decarbonize. Escalating global warming concerns and tightening greenhouse gas regulations have accelerated the pursuit of Net Zero Fuel scenarios, yet profound uncertainty remains regarding future fuel availability, regulatory timelines, and technology maturity. Commercial vessels typically have operational lifespans of 25 to 30 years, meaning assets ordered today must be capable of operating in an energy landscape that is not yet fully defined. The capacity to efficiently switch between fuel pathways has consequently become a central driver in asset renewal strategies. To manage this uncertainty, classification societies have introduced "fuel readiness" notations intended to denote a ship's potential to be retrofitted to alternative fuels later in its lifecycle. However, a critical problem persists: the industry lacks a standardized definition of what "readiness" truly entails. A vessel designated as "ready" may merely possess concept approval, or it may have undergone significant physical preparation such as structural reinforcement for tanks or the installation of convertible engine systems. This ambiguity makes it difficult for stakeholders to assess whether the current global fleet and orderbook are genuinely prepared for a fuel switch. This paper addresses this gap by analyzing the current state of vessel readiness and proposing a rigorous Design Structure Matrix (DSM) framework to operationalize engineering agility.

We first establish a taxonomy of agility drawing on engineering design literature. Within naval architecture, Andrews (2003) argued for adaptability over flexibility and defined agility as the capacity for a design to be more readily modified through life. Christensen et al. (2018) considered agility as one aspect of changeability that explicitly addresses the temporal dimension of change, and Lagemann et al. (2022) defined agility as a modifier of flexibility, the ease or speed with which a change can be executed. Building on these foundations and the broader taxonomies of Fricke & Schulz (2005) and Ross et al. (2008), we define agility as a system's capacity to react to both internal and external shifts (adaptability, flexibility) through modifiability, scalability, and robustness. This definition is then operationalized through a standardized five-level readiness framework (Level 0–Level 5) derived from notations from six major IACS classification societies: ABS, Bureau Veritas, CCS, ClassNK, DNV, and Lloyd's Register. By mapping the diverse class notations to these standardized levels, the framework enables consistent cross-society comparison of preparedness, from vessels with no preparation (Level 0) through concept approval (Level 1), physical preparedness (Level 2), convertible systems (Level 3), operable systems (Level 4), to fully converted dual-fuel vessels (Level 5).

A comprehensive analysis of the global commercial fleet (≥5,000 GT), conducted using Seaweb and Clarksons' Shipping Intelligence Network data as of December 2025, reveals two key trends. First, dual-fuel adoption is accelerating: dual-fuel vessels comprise 15% of the in-service fleet but account for 30% of the orderbook. LNG dominates the current alternative fuel landscape, while methanol has surged to 19% of dual-fuel orders, gaining traction particularly in the container ship, vehicle carrier, and bulk carrier segments. Second, and more critically, our analysis exposes a significant "Readiness Gap." Among 778 vessels carrying a readiness notation, 87.9% possess only Concept Approval (Level 1). Physical readiness in critical subsystems is rare across all levels: only 14% have tank preparations, and 19% have main engine preparations. This dominance of "paper readiness" indicates that the majority of the "ready" fleet lacks the physical preparation required for cost-effective retrofitting. Fuel-specific analysis reveals that LNG and ammonia show some higher-level readiness

(16.5% and 14.9% at Levels 2–4, respectively), while methanol readiness is almost entirely conceptual (98.5% at Level 1).

To bridge this gap, we develop a functional DSM methodology based on the Design Structure Matrix framework of Eppinger & Browning (2012). The framework decomposes a vessel into eleven core functions: Energy Onboarding, Energy Storage, Energy Transfer, Energy Preparation, Propulsion Energy Conversion, Ship Service Energy Conversion, Structural Integration, Maintenance Accessibility, Waste Management, Safety Management, and System Control. The DSM maps the readiness of interactions between original and target fuel configurations, with hierarchical agglomerative clustering used to identify functionally related groups and design hotspots.

Application of this framework to prioritized case studies, Kamsarmax Bulk Carriers and Feeder Container Ships converting from Fuel Oil to Methanol and Ammonia, and LNG to Ammonia, demonstrates that functional dependencies are universal across ship types and fuel pathways, differing only in readiness levels rather than structural relationships. The clustering analysis identifies Structural Integration and Energy Preparation as initial hotspots for retrofit complexity. We show that targeted investments in these clusters, specifically space reservations, structural foundations, and modular system-on-sled designs, can eliminate all Level 0 interactions and significantly raise overall vessel readiness from Level 1 to Level 2 (Physical Preparedness). These design changes leverage robust, modifiable, and scalable agility principles: foundations that serve both current and future systems (robust), fuel oil systems that can be downsized or removed (scalable), and alternative fuel systems that can be added to existing structural provisions (modifiable).

We conclude that for the industry to move beyond administrative readiness, stakeholders must adopt an approach that prioritizes physical preparedness in high-impact subsystems. The universality of the observed functional dependencies suggests that standardized solutions for these critical clusters are achievable across multiple vessel classes and fuel types. The transition to Net Zero requires more than administrative approval; it demands a shift to active engineering agility. By adopting the DSM framework presented here, designers can transform “readiness” into a genuine strategic asset.

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Navigating the net-zero framework: Optimal investment pathways for container fleets under tiered penalties and operational constraints

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Extended Abstract

Maritime transport is a major contributor to global trade but also to greenhouse gas (GHG) emissions, accounting for a non-negligible share of global emissions and requiring substantial reductions to meet climate targets (IMO, 2020). Recent regulations, particularly the IMO's short-term measures (EEXI and CII), introduce technical and operational requirements that directly affect ship-level decision-making and impose non-trivial compliance costs.

The literature highlights that compliance with these measures is complex and depends strongly on vessel characteristics, operational profiles, and available technologies. In this context, two legacy studies form the foundation of this paper. Schroer et al. (2022), in an evidence-based assessment of IMO's short-term measures, investigate the techno-economic implications of EEXI and CII compliance options across six container ships using actual operational data and a bottom-up approach. Their results show that engine power limitation (EPL) is the most cost-effective option but can impose substantial operational constraints (including increases in sailing time of up to 793 hours per year), with effectiveness being highly dependent on vessel size and engine load profile. Building on this, Lehmann et al. (2025) extend the analysis to a fleet of 16 container ships, introduce alternative fuels as compliance pathways, and develop a two-stage MILP optimization model covering a broader regulatory environment encompassing EU ETS, FuelEU Maritime, a global fuel standard, and a levy. Their results demonstrate that while current regulations incentivize energy efficiency and alternative fuel adoption, an IMO mid-term technical–economic measure combination offers greater flexibility and cost-effectiveness in achieving reduction targets.

However, both studies address regulatory frameworks in largely sequential rather than simultaneous terms. Neither account for the specific architecture of the IMO's Net-Zero Framework (NZF), its two-tier deficit penalty structure, and Zero/Near-Zero (ZNZ) fuel reward mechanism, leaving a gap in understanding how this emerging framework interacts with existing EU regulations to shape fleet-level investment decisions.

This paper addresses this gap by placing the IMO NZF and its dual-penalty system at the center of the analysis. The framework shifts carbon accounting from Tank-to-Wake efficiency metrics (CII) to a Well-to-Wake GHG Fuel Intensity (GFI) approach, and its two-tier penalty structure creates non-linear economic signals whose interaction with the already binding EU ETS and FuelEU Maritime regulations is the primary object of study. The case study covers a highly diverse fleet of 21 container ships, ranging from 3,000 to 19,000 TEUs, built between 2006 and 2018, encompassing both fossil fuel and methanol-powered vessels operating across EU and non-EU scopes, using high-resolution operational and fuel-consumption data provided by a cooperating liner company. The modeling horizon extends to 2050 and incorporates ship replacement decisions: when a vessel reaches the end of life, a newbuild of equivalent size continues in operation, with the model optimizing the choice of propulsion system among LNG engines paired with onboard Carbon Capture and Storage (OCCS) or dual-fuel engines capable of running on green ammonia or methanol. Rather than employing complex physical modelling of the propulsion systems, the optimization framework utilizes an energy equivalency approach; this ensures that the baseline energy demand is strictly conserved across different propulsion choices and expanded technical interventions. For the existing fleet, the model explicitly evaluates the attractiveness of OCCS retrofits as a compliance lever, assessing under which regulatory and economic conditions retrofitting current vessels becomes cost-competitive relative to fuel switching or continued penalty absorption. Retrofit timing is grounded in physical reality by encoding mandatory dry-docking intervals as the binding windows for major technical upgrades. To systematically address the still-evolving nature of the NZF, particularly its recent one-year postponement and the currently undefined Zero/Near-Zero (ZNZ) fuel reward mechanism, a key analytical output is a scenario-based sensitivity analysis. This analysis determines the minimum ZNZ reward price required to shift a fleet from passive penalty absorption to proactive green fuel adoption.

The results are expected to outline several structural patterns rather than precise forecasts. First, compliance remains highly dependent on vessel characteristics and prior technology adoption. Second, operational measures are likely to dominate short-term compliance due to their cost-effectiveness but will be insufficient for long-term targets. Third, the interaction of multiple regulations is expected to create non-linear investment behavior, particularly affecting retrofit timing and fuel transitions. Finally, coordinated fleet-level strategies are expected to outperform isolated, ship-level compliance decisions.

Overall, this paper builds on the ship-level frameworks of Schroer et al. (2022) and Lehmann et al. (2025) while extending them toward a more comprehensive perspective that reflects the increasing complexity of maritime decarbonization policies, with a particular focus on the economic implications of the NZF's dual-penalty architecture and the long-run asset decisions it incentivizes.

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Energy system optimization and emissions pricing - Comparing alternative generation concepts

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Extended Abstract

1 INTRODUCTION

Maritime transport is the backbone of global trade, representing a highly efficient mode of transport in terms of energy per ton-kilometer. However, due to the massive scale of the industry and a projected continuous increase in shipping volume, it remains a significant contributor to global anthropogenic greenhouse gas (GHG) emissions. In response to the escalating climate crisis, regulatory bodies have introduced increasingly stringent environmental targets. Most notably, the International Maritime Organization (IMO) has revised its strategy, setting a clear trajectory towards net-zero GHG emissions from international shipping by 2050.

European Union regulations, such as the inclusion of shipping in the EU Emissions Trading System (EU-ETS), further intensify the pressure on ship operators to reduce their carbon footprint.

A vast array of measures for direct efficiency improvements is available to ship designers and operators, ranging from alternative carbon-neutral fuels and hybrid-electric propulsion concepts to energy storage implementation and extensive sector coupling on board [Bouman2017]. While the integration of these technologies significantly expands the design space and offers immense potential for drastic efficiency gains, it also increases the complexity of the ship design process dramatically and creates an interconnected architecture where isolated component optimization is no longer sufficient.

Ships designed today will have to operate efficiently throughout a 40+ year lifespan, necessitating a design process that effectively navigates the complex, highly interconnected solution space while accounting for future developments in fuel pricing, emission pricing, and component costs.

While contemporary literature provides rigorous component-level analyses, these often isolate specific technologies without accounting for the interconnectedness or cost uncertainty. Recent studies evaluating Solid Oxide Fuel Cell (SOFC) and Internal Combustion Engine (ICE) hybrids demonstrate significant fuel reductions but highlight that capital cost remains the primary economic barrier [Elkafas2026]. Similarly, investigations into the life-cycle cost (LCC) and environmental performance of alternative marine fuels—such as methanol and liquefied natural gas (LNG) compared to conventional fuel oils—emphasize that volatile future fuel prices and carbon pricing drastically affect architectural viability [He2025].

Furthermore, research explicitly addressing cruise ship environments highlights the necessity of optimizing both system topology and energy management strategies to handle highly variable load demands effectively, yet frequently relies on fixed battery storage without considering long-term degradation and capital replacement costs concurrently with component configuration [Cao2023]. Moreover, while studies have investigated waste heat recovery (WHR) and hybrid battery/fuel cell plants using long-term economic forecasting to demonstrate substantial decarbonization potential [Yuksel2025], integrating these models and combining diverse gensets, multiple fuel cells, variable thermal and electrical storage, and alternative fuels—into a unified decision-making optimizer remains a critical gap.

Consequently, this paper proposes the use of the MESO [Molinski2024], a holistic framework designed for the automated optimization of complex ship energy system architectures, to bridge this gap.

2 OPTIMIZATION SETUP

The goal of this study is to investigate the effect of emission taxation, fuel price volatility and component cost variations on both the process of ship energy system optimization and the resulting optimal configurations. Optimization is done with MESO, a modular Python platform designed to optimize the architecture, dimensioning, and operation of sector-coupled ship energy systems.

The proposed investigation bases its technical parameters on contemporary studies from literature and use demand data from measurements on an existing cruise ship with the fundamental assumption of using electric propulsion. The configuration options include:

- Generators of different size ranges with various fuels (Diesel, HFO, LNG, methanol, ammonia, hydrogen), each with different performance parameters - e.g. partial-load efficiency curves, start-up time, ramping capabilities, waste-heat recovery potential,etc.
- High-temperature fuel cells of different types (SOFC, MCFC, HT-PEMFC) with different fuel options and performance parameters.
- Renewable energy sources, mainly PV, since WASP is not viable without route optimization.
- Different types of thermal and electrical energy storage, parameters include e.g. charge/discharge power and efficiency, capacity ranges, degradation and self-discharge rates, etc.
- Shore power connection for zero-emission port operations, with different power ratings and availability profiles.

The variation of economic parameters includes a range of fuel price scenarios, emission taxation levels, and component cost variations, based on projections from literature and market analyses. MESO is used to optimize the energy system configuration for each scenario, evaluating the resulting configurations based on performance indicators such as total cost of ownership, fuel consumption, emissions, and system reliability. The effect of varying the economic parameters on the optimized configurations is then analyzed to identify trends and thresholds where certain technologies or configurations become more favorable. This analysis provides insights into how future economic conditions could influence ship energy system design and the potential for different technologies to contribute to decarbonization efforts under varying market conditions (see Figure 1).

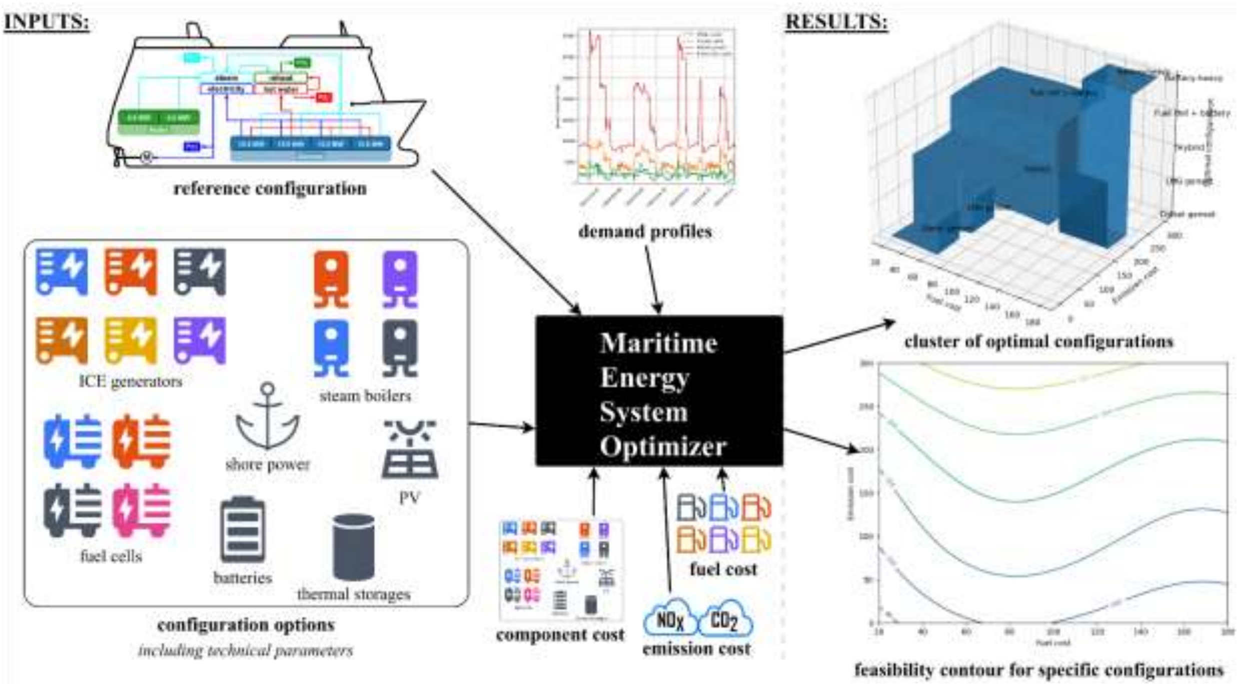

Figure 1: Concept of the proposed study: investigating the effect of emission pricing, fuel price volatility and component cost variations on ship energy system optimization

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