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An innovative tool for the evaluation of energy efficiency of merchant ships

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ABSTRACT

The maritime sector, while recognized as the most efficient mode of freight transportation, confronts significant challenges in reducing greenhouse gas emissions and enhancing energy efficiency. These challenges are intensified by the ageing fleet of merchant ships, which often lack the latest technologies intended to minimize atmospheric pollution. This paper aims to introduce an innovative tool designed to evaluate the energy efficiency of merchant ships and monitor their emissions, particularly concerning CO_2 and its relation with the Carbon Intensity Indicator. The tool consolidates essential data into a centralized database to facilitate continuous monitoring of ship efficiency, taking into account both internal and external factors. In particular, it enables the collection and analysis of data for small/medium shipping companies, which typically lack the resources to allocate towards complex, tailored IT solutions for managing their fleet. Key features for this tool include the availability of accurate operational data and adherence to current emissions regulations. However, the applicability of the tool may be constrained by variations in ship types, operational conditions, and the availability of real-time data. The application of the tool to a case study of a tanker ship, designed to validate its functionality, demonstrates that the tool can effectively generate extensive data, which can be used to identify correlations between specific ship factors and GHG emissions. These findings offer a more accessible and self-explanatory approach to evaluating ship performance and efficiency, presenting a practical framework for compliance with evolving climate regulations and identifying the technical solutions to be implemented onboard for improvement.

1. Introduction

Nowadays, the rate of sea transportation represents a significant indicator of the world economy's robustness, as it reflects the continuity of global freight trade [1]. International shipping plays a crucial role in goods transportation, as witnessed by the overall shipment quantity equal to 11 billion tons registered in 2021 [2]. As a negative consequence, the whole shipping sector was responsible for 1076 million tonnes of global anthropogenic GreenHouse Gases (GHGs) emissions in 2018, equal to 2.89 % of the global emissions [3]. Furthermore, although new buildings are more efficient than aged ships (which are the majority in the world fleet), the growing size of the world fleet is leading to an increase in overall GHG emissions.

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Merchant ships can live up to 30 years and their efficiency decreases over the years with a consequent increase in pollution emitted. They may be subjected to refit interventions focused on hull maintenance and restoration during their lifecycle, but these processes are not always environmentally friendly [4] and do not solve the major problems regarding atmospheric pollution.

Due to this issue, the maritime sector is facing a strong revision of the environmental legislation aimed at reducing GHG emissions. The International Maritime Organisation (IMO) has developed regulations that apply to ships, including merchant ships, which are designed to improve energy efficiency and reduce environmental impact. Among these, the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Index for Existing Ships (EEXI) are used to measure the energy efficiency of new and existing ships, respectively and to set targets for reducing carbon dioxide (CO_2) emissions. Especially for existing ships that do not possess construction characteristics capable of ensuring compliance with the required EEXI, finding the most appropriate measure aimed at improving the energy efficiency of the ship is necessary [5].

Besides, the introduction of the Ship Energy Efficiency Management Plan (SEEMP) part I, II and III requires ships to develop and implement plans to improve energy efficiency while the Carbon Intensity Indicator (CII) measures the actual CO_2 emissions of existing ships and sets targets for their reduction [6, 7]. Moreover, The European Union (EU) is leading the way in addressing emissions from maritime transport by incorporating them into the EU Emissions Trading System (EU ETS). The EU ETS will include all emissions arising from voyages and port stays within the EU/EEA (European Economic Area), while 50 % of emissions from voyages to or from non-EU countries will also be included. The regulations require shipping companies to pay for the emissions they reported in the previous year. In 2025, companies will pay for 40 % of the emissions reported in 2024. In 2026, they will pay for 70 % of their 2025 emissions, and starting from 2027, they will be responsible for 100 % of their reported emissions [8, 9]. Another initiative starting from January 1, 2025, is the FuelEU Maritime, which mandates that vessels engaged in trade with or to/from the EU/EEA must comply with annual average GHG intensity limits for on-board energy use. GHG intensity is measured in grams of CO_2 equivalent per megajoule (gCO2e/MJ) of energy, covering emissions from CO_2, methane (CH_4), and nitrous oxide (N_2O). The regulation extends beyond on-board emissions, including the entire fuel supply chain, from extraction to transport. GHG intensity targets are based on reductions from a 2020 baseline of 91.16 gCO_2e/MJ, with increasingly stringent targets set every five years until 2050, starting with a 2 % reduction requirement in 2025 [10].

These regulations and initiatives have the overall aim to improve the efficiency and reduce the environmental footprint of ships. It is however important to note that lower efficiency translates to higher fuel consumption. Consequently, higher fuel consumption results in increased operational costs for shipping companies. The concept of digitalization within ship-owning companies and the increasing reliance on tools for monitoring the operating conditions of ships have therefore become imperative. Thus, improving efficiency and adopting sustainable practices become essential efforts for shipowners in order to minimize costs.

Shipowners are consequently actively seeking enhanced and more efficient measures to improve the environmental performance of their vessels. Furthermore, operators are increasingly demanding climate-neutral technologies, as they aim to mitigate the risks associated with evolving climate regulations and continually escalating expenses [11, 12].

Marine GHG emissions are generated through the utilization of multiple fossil fuels, releasing harmful substances during both their production and use [13]. As a result, there is an increasing emphasis on the necessity to transition to greener fuels. Such fuels are considered to be environmentally friendlier and have a lower carbon footprint compared to traditional fossil fuels. Several fuel options are being developed for the maritime sector to reduce emissions and promote sustainability. Examples of these include Liquefied Natural Gas (LNG), methanol, ammonia and hydrogen [14, 15]. It is worth noting that not all of these mentioned fuels can be considered completely green, and to determine their environmental impact it is important to consider their entire lifecycle, including the production chain, logistic facilities and employment methods [16]. As an example, LNG is a cleaner burning fossil fuel than conventionally used Heavy Fuel Oil (HFO) or Marine Diesel Oil (MDO). However, building LNG-fuelled ships requires careful consideration of several key factors [17] and the use of this fuel still leads to relevant CO_2 emissions [18]. On the other hand, hydrogen has the advantage of not producing CO_2 during its employment as fuel, but it can be produced either from fossil fuels or from renewable energy sources: the first product is called “grey”, while the second one is called “green” [19, 20]. Therefore, it is important to evaluate the full scope of the environmental and social impacts of the fuel before considering it as a green fuel, making it equally essential to ensure that policies in the energy and shipping sectors are aligned [21]. Thus far, inadequate consideration has been given to the logistic aspect, posing a significant challenge due to the deficiency in infrastructure and supply chain required for facilitating the transportation of alternative fuels [22, 23]. Some fuels are e.g., often produced in remote areas, and there may not be adequate transportation infrastructure in place to move them to ports for ship bunkering. Green fuels such as hydrogen and ammonia are not yet widely available and may require significant investment in production and distribution/bunkering infrastructure. Another issue is the limited availability of green fuels in certain regions, potentially making it difficult to plan and execute voyages. The maritime sector encounters particular challenges in this regard, primarily due to the nature of international waters where ships frequently operate. This circumstance presents difficulties in accurately anticipating the availability of fuels in various ports [24]. However, almost half of the currently available green fuels may be promoted by ships, which could facilitate their delivery from production sites to fuel hubs aimed at different purposes such as aviation, road and rail transport; through the development of the necessary infrastructures, maritime transport would represent a key factor in the decarbonisation of land-based industrial sectors [25]. In this context, the adoption of a new fuel onboard a merchant ship must be supported by a detailed analysis of potential alternatives, along with their maturity and availability in terms of quantity, infrastructures, bunkering facilities, environmental aspects and economic impacts [14]. Furthermore, retrofitting vessels to use green fuel is not viable for most existing ships due to very high capital expenditure, which often cannot be amortized during the limited remaining operative life. Previous studies have addressed the possibility of refitting both merchant and passenger ships to several types of green fuels [26, 27] highlighting the drawbacks in terms of technological challenges, ship range and costs.

As a result, short-term measures are the first approaches to achieving emissions reduction goals and climate neutrality. These must aim to optimise and, when possible, increase operational and energy efficiency. Available Energy Efficiency Technologies (EETs) may vary from the reduction of speed and the monitoring of the correct performance of onboard engines [28] to the retrofitting of vessels with energy-efficient technology and innovative propulsion techniques and eventually, in the medium-long term, switching to (net) zero carbon fuels [29-31]. Among the potential EETs, those enabling the improvement of Hydrodynamics, Machinery, and Energy system performances are of significant importance [32-34]. Some of the most discussed alternatives in the literature include Wind Assisted Propulsion Systems (WAPS), air lubrication systems, batteries, and fuel cells. These technologies, individually or in combination, hold significant promise for reducing the environmental impact of maritime operations [35-40].

The issue arises from the fact that, depending on the type of vessel, its age, the routes it operates, and other factors, there is no single EET solution that suits all scenarios. Consequently, shipowners are confronted with the challenge of selecting different EETs without a clear understanding of which one would be most suitable for their specific needs. To support this selection, the authors have developed a tool to collect, monitor, and share with the shore-based control centre the emissions and energy efficiency of ships. With only 15 % of merchant ships currently digitalized, the shipping industry relies on unreliable data, underlining the urgent need for digital transformation to improve efficiency and promote sustainable practices [41]. The tool described extensively in this paper is founded upon a data collection procedure encompassing ship information, fuel consumption, and other relevant parameters. The collection of this data can be performed also for aged ships that do not already have specific onboard software for this purpose. In this case, since such operation is not an automatic process, the control box present in the tool will check for potential errors and minimize their potential impact. For new ships or those equipped with advanced technology for automatic data collection, this functionality can be used to fill in parts of input parts of sections more efficiently. Subsequently, this data is processed to derive output parameters measuring emissions and efficiency. Through its application, the user such as the shore staff responsible for performance monitoring and technical operations of small/medium shipowners, can obtain the history of a ship's navigation, which in turn allows extrapolation of the best and worst working conditions in terms of the ship's performance and pollutant emissions. To gain a deeper understanding of these conditions, correlation analyses can be conducted using the extensive database generated, in order to identify key ship parameters that significantly contribute to emissions production and provide especially small/medium shipowners and operators with valuable insights for considering improvements to their vessels. The tool's ability to generate a robust data set could also provide opportunities for integration with AI to further enhance its capabilities. AI could be leveraged not only to analyze the data collected, but also to develop or refine predictive systems for emissions and enabling accurate forecasts even years before a system is implemented [42-44].

While other studies [45, 46] also use real operational data, they typically rely on limited datasets, such as noon reports, resulting in more constrained data coverage. In contrast, this approach not only incorporates noon reports but also integrates higher-frequency data, enhancing both accuracy and robustness. Furthermore, correlation analyses are employed to explore the root causes of reduced energy efficiency and higher emissions more effectively. Additionally, most studies focus on optimizing energy efficiency in specific routes [47] or components, such as engines [48] or ship hulls [49], whereas this approach does not concentrate on a single detailed study area. Instead, the comprehensive dataset allows for the analysis and identification of various potential critical areas, offering a foundation for future targeted optimizations across multiple aspects of operations.

The innovation in this work lies in the integration of real-time operational data to develop a more comprehensive framework for enhancing ship efficiency. This approach addresses the longstanding issue of data scarcity, which has limited deeper insights into maritime operations. It is particularly relevant for small- and medium-sized shipowners, who often lack the resources to invest in large, customized IT projects. The proposed solution is both practical and accessible for these shipowners, who typically manage fleets ranging from 1 to 20 ships. Although fleet sizes vary widely depending on market and regional factors, small- and medium-sized shipowners collectively account for approximately 30–40 % of the global merchant fleet. Their operations are often concentrated in niche markets or specialized cargo segments, underscoring their critical role in the maritime industry [50, 51]. By enabling these shipowners to improve energy efficiency, the proposed tool has the potential to significantly contribute to reducing emissions across the global fleet.

Overall, the tool has the potential to identify areas of best and worst working conditions in terms of ship's performance and pollutant emissions that require improvement, offering significant advantages resulting in reducing fuel consumption, lowering emissions, and improving energy efficiency. Additionally, it is designed to analyze other parameters and ensure compliance, including CII, EEXI, and MRV voyages subject to the EU ETS and Fuel EU Maritime regulations.

2. Energy efficiency improvement

Shipping is responsible for about 2.89 % of total annual GHG emissions according to IMO [31]. The environmental impact of the global merchant fleet is therefore significant, as it is estimated to count about tens of thousands of ships [52, 53].

Many merchant ships are additionally equipped with outdated technology for propulsion, energy generation and auxiliaries, potentially leading to inefficiencies and pollution increase. As mentioned earlier, to address these issues, shipping companies and organizations may perform refitting operations to update their ships. This can help reduce pollution and improve overall energy efficiency.

From the shipowners' perspective, the main reasons for reducing vessels' fuel consumption and, therefore, improving ships' energy efficiency are the following:

1. Reducing fossil fuel consumption is a good way to reduce pollutants emissions and meet more stringent regulations, thus ensuring the right to access special areas such as IMO's Emission Control Areas (ECAs) [54];
2. Considering merchant vessels, fuel is the main operating cost for shipowners, regardless of the employed fuel type: potential solutions are traditional fossil fuels, electricity, LNG, Methanol, or other possible green alternative fuels (Figure 1). Moreover, based on the fuel type chosen, costs may

significantly vary: conventional fossil fuels are less expensive than alternative ones, with green fuels (e.g., ammonia and hydrogen) having the highest price among these [55].

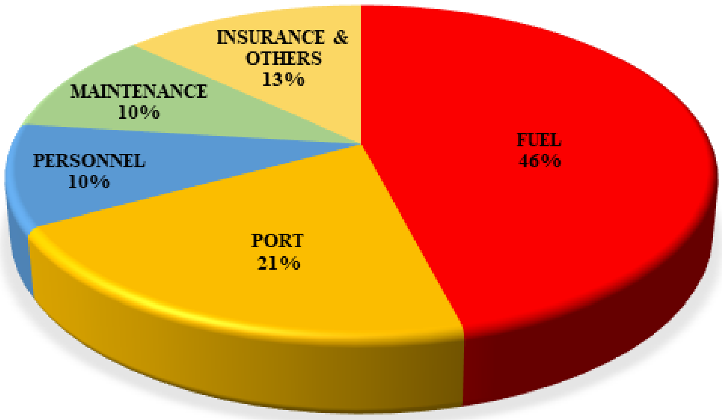


Fig. 1 Breakdown of vessel operating cost [56]

In the construction of new vessels as well as in retrofit projects, the implementation of a continuous optimization process is imperative. This process aims to simultaneously safeguard the environment and minimize or maintain operational expenditure (OPEX) at its current level. Both goals can be achieved through fuel savings, as they imply pollutant emissions reduction and enable to gain an important competitive advantage. In this context, the installation of new EETs may be considered by shipowners and operators.

However, many barriers and obstacles need to be overcome to provide a safe, practical, and achievable solution. The availability of a system to monitor and collect the main data about onboard energy consumption correlated to ship navigation parameters is needed to support the identification of the main features and aspects that can be modified and improved, in order to select and install the most appropriate type of EET or deciding for a fuel switch. Furthermore, in the context of a smart ship, an effective way to improve the ship's energy efficiency management capability is the establishment of a ship-shore collaboration [57]. The aforementioned system should be designed to enable the sharing of collected data among relevant stakeholders onshore (e.g., shore-based control office). This could facilitate the analysis of data and evaluation of significant technical indicators related to energy consumption. Additionally, by carefully selecting and categorizing the issues, it would be possible to differentiate between those that can be resolved through technical solutions and those that require behavioural changes [58].

Consequently, the significance of a tool that can provide a comprehensive assessment of a ship's energy performance in terms of its operating conditions and being able to identify the most relevant parameters that impact CO_2 production becomes evident. In this paper, the authors present a tool specifically designed for merchant ships to effectively tackle this issue.

3. Methodology

The main purpose of the developed tool is to analyse and evaluate the correct performance of ships in a dynamic way: the structure is shown in Figure 2 and is explained in detail in the following paragraphs. The tool is divided into two main sections, defined as input and output. The input sections are used to enter vessel information and data, such as fuel consumption, which are then processed. The output sections subsequently display the computed data, including emissions and efficiency.

In the tool, the quality of the data is the key factor, since it is crucial to rely upon the outcomes of the analysis. To this end, a control box is integrated within the tool, serving as an alert mechanism in instances of erroneous or suspicious data entered. This is particularly crucial for older vessels that may lack modern systems and software for automatic data collection, relying on potentially less accurate data. Conversely, on ships equipped with advanced technology for automatic data collection, this functionality can be utilized to enhance efficiency in entering specific data into the input sections of the presented tool.

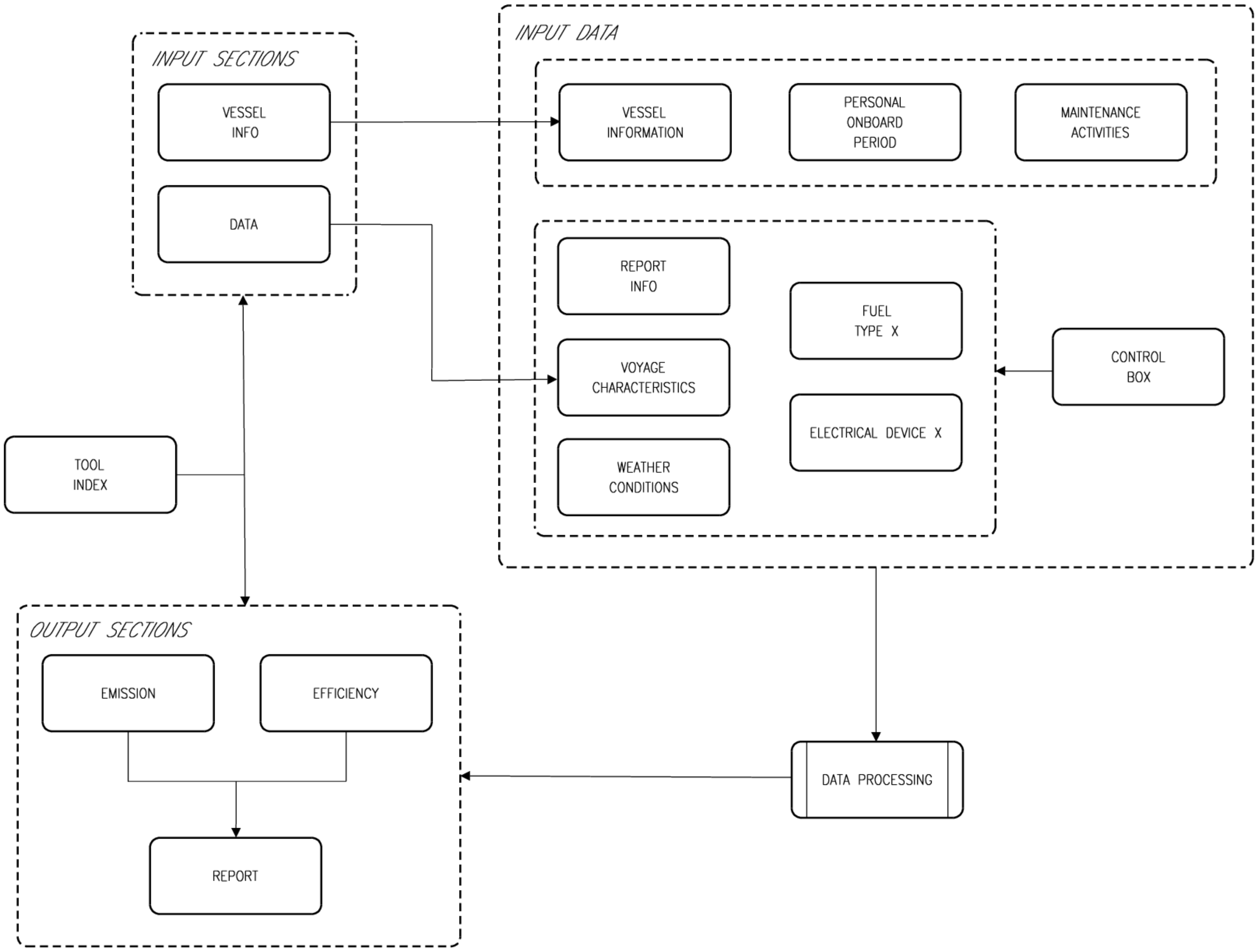


Fig. 2 Tool structure with main components and data flows

3.1 Tool Index

The Tool Index is the main window in which all the tool sections are listed. For each of them, all the information regarding the required data, the frequency of data acquisition and the user in charge of the updating tasks are provided (Table 1).

Table 1 Tool Index

Type of Section	Section Name	To be filled with	Frequency	Compiled by
INPUT	Vessel Info	Vessel Information	..	Ship staff
		Personal onboard period	..	Ship staff
		Works Maintenance Scheduled	..	Ship staff
	Data	Report Info	At least once a day	Ship staff
		Voyage Characteristics	At least once a day	Ship staff
		Weather Condition	At least once a day	Ship staff
		Fuel Type X	At least once a day	Ship staff
		Electrical Devices X	At least once a day	Ship staff
OUTPUT	Emission	N/A	N/A	N/A
	Efficiency	N/A	N/A	N/A
	Report	N/A	N/A	N/A

It should however be noted that only the input sections requiring vessel info and data need to be filled. The output sections are automatically generated as a result of processing the input sections and do not require any additional information to be filled in.

As outlined in Table 1, the responsibility for entering data into the tool lies with the ship's staff, particularly on older vessels that may not have modern systems or software for automated data collection. However, on vessels equipped with advanced automation systems, data collection can be streamlined by interfacing the system and its sensors with the data collection spreadsheet.

3.2 Input Sections

The Input Sections are the ones dedicated to data acquisition, which may be subdivided into the vessel information and the information related to the vessel route and consumption.

In the Vessel Info, the data that shall be recorded are the main information and characteristics of the vessel like age, dimensions, age of Main Engine (ME) and Diesel Generator (DG) (an example of the structure adopted for data collection is given in Table 2); Period of crew onboard assignment (as for structure in Table 3); List of maintenance activities (i.e., dry dock, hull cleaning, propeller cleaning, etc.) and their history (as for structure in Table 4).

The 'open data', represented by 'x' in the tables below, are intended as placeholders to illustrate the structure for data collection.

Table 2 Main input information and characteristics of the ship

Vessel Information				
Characteristic/Features			Characteristic/Features	
Name	..		Tier	..
Type	..		Engine build date	xx/xx/xxxx
Hull type	..		Generator #X build date	xx/xx/xxxx
Length Overall	..	[m]	Boiler #X build date	xx/xx/xxxx
Extreme breadth	..	[m]		
Deadweight	..	[t]		
Displacement	..	[t]		
..	..			
Delivered date	xx/xx/xxxx			

Table 3 Period of onboard stay for personnel

Personal onboard period			
Rank	Surname and Name	Sign On Date	Sign Off Date
Master	.. ..	xx/xx/xxxx	xx/xx/xxxx
Ch. Engineer	.. ..	xx/xx/xxxx	xx/xx/xxxx
..	..	..	..

Table 4 List of maintenance activities

Maintenance activities	
Activity	Last date of performance
Dry dock	xx/xx/xxxx
Hull cleaning	xx/xx/xxxx
Propeller cleaning	xx/xx/xxxx
Others	xx/xx/xxxx

The Control box is designed to flag any values entered that fall outside of predefined acceptable ranges or patterns. It provides three different notifications to the user, as outlined and explained in Table 5. These notifications help the user identify and address potential errors in the data, ensuring that the input remains accurate and within the expected parameters.

Table 5 Control box functionality

Data Quality	Definition	Action
Good	The tool has not identified any unusual parameters related to the input data.	No action is required by ship staff and/or users.
Suspicious	The tool has identified some input parameters that could not be correct. This happens when the values entered fall outside of predefined acceptable ranges or patterns (i.e. the "Distance Reported" could exceed the expected range based on the "Time at Sea”).	The ship staff should immediately review the data entered. If necessary, the user can also verify the data.
Error	The tool has identified some input parameters that are incorrect (i.e., the "Fuel Type X" consumption entered exceeds the available bunker onboard, or the "Cargo Quantity" reported differs from the values entered in the previous Report, despite no discharge or loading activities having occurred.)	The ship staff must input the correct values; otherwise, the tool will not allow additional data entry until the changes are made.

The entered data can be checked on shore by the user using the documentation maintained by the ship. Additionally, certain information may need to be provided by the ship to the shipping company or operators when required. Among these documents, the following are required:

- Engine Log Book: Engine fuel consumption records - the log must record the amount and type of fuel used, typically on a daily or voyage basis, depending on the operational schedule; Engine hours, in terms of the running hours of the main engine and auxiliary engines; Engine parameters, including operational parameters such as engine speed, load, and performance data that could affect fuel consumption; Maintenance records, providing information on any maintenance or repairs performed on engines or fuel systems that may impact fuel efficiency;
- Nautical LogBook: Voyage details, including the start and end points, time of departure and arrival, and any deviations during the voyage; Time at sea, in terms of total hours spent at sea; Ship’s position and distance sailed; Weather and sea conditions;
- Deck Log Book: Ship’s position and course, including latitude, longitude, and course steered; Speed; Operational changes;
- Cargo Log Book: If the vessel is involved in the transportation of cargo the Cargo quantity and type; Loading and unloading detail;
- Fuel Oil Record Book: Fuel type and quantities, in terms of type of fuel used, amounts bunkered, and fuel quantities consumed during voyages; Fuel quality;
- Operational Data from Monitoring Systems: If the vessel is equipped with an Energy Management System (EMS) or other monitoring equipment, data from these systems could be provided.

To ensure continuous monitoring, it is mandatory for the ship to submit a report upon arrival and departure from port. Moreover, the ship will be required to submit a daily report at noon for daily control, irrespective of the ongoing operations. This enables the prompt application of behavioural corrections upon detection of any issues through monitoring.

The data that needs to be entered concerns:

- Report Info consisting of: Report Type (Departure from a port, Arrival at a port, Voyage Noon, Port Stay Noon); Operation (Sailing, Cargo Loading, Cargo Unloading, Bunker, Dry Dock, Ship to Ship transfer (STS) [59, 60]); Date/Time; Time at sea; Time at port; Time at anchorage; Time drifting.
- Voyage characteristics consisting of: Position, Displacement, Draft, Trim, Cargo Amount, Ballast Amount, Distance Reported (i.e., the distance travelled calculated from the difference between the last report time and the new report time), Avg. Ship Speed (i.e., average speed over

ground value).

- Weather conditions consisting of: Wind direction, Wind force, Sea direction, Sea state, Swell Direction, Swell High, Current Type (N/A, Against, With, Abeam), Current Direction, Current Speed. Weather conditions for vessels are evaluated using the Beaufort scale (BF) and the Douglas Scale (SS) (Table 6). Generally, conditions are considered "good" for navigation when the BF scale is 5 or below, and SS is 4, indicating a moderate sea state with fresh breezes. Conversely, conditions are deemed "bad" when the BF scale reaches 6 or above, and SS exceeds 5, reflecting stronger winds and rougher seas. However, it's important to recognize that the impact of these conditions can vary significantly depending on the size and type of vessel. As noted by [61], the aforementioned conditions are typical for small crafts. Larger ships are generally better equipped to handle higher BF and SS values due to their size and power. However, these conditions can still pose challenges for larger vessels, particularly for tankers and bulk carriers. As highlighted by [62], these vessel types are among the most critical in terms of the sufficiency of their installed power for maneuverability in adverse weather conditions, as well as their ability to simultaneously meet the maneuverability requirements under such conditions. For these vessels, the aforementioned range of conditions could also be considered. It is important to note that this assumption should be appropriately adjusted for larger or smaller vessels, taking vessel size into account when data from different vessels are aggregated and analyzed.
- Fuel Type X consisting of: Total ME fuel consumption, DG consumption, Boiler consumption, Other consumption (e.g., Cargo Heating, Tank Cleaning, Pilot Burner), Bunker (in case of a bunkering event, the amount of fuel should be given as input).
- Electrical Device X consisting of: Running hours, Power Consumption, SFOC, Fuel Consumption.

Table 6 Douglas and Beaufort scales [63-65]

Douglas Scale	Significant Wave Height $H_{1/3}$ (m)	Sea State Description	Beaufort Scale	Wind Speed Vw (km/h)	Wind Description
0	0	Calm (glassy)	0	0	Calm
1	0 - 0.1	Calm (rippled)	1	1 - 5	Light Air
2	0.1 - 0.5	Smooth	2	6 - 11	Light Breeze
3	0.5 - 1.25	Slight	3-4	12 - 28	Gentle to Moderate Breeze
4	1.25 - 2.5	Moderate	5-6	29 - 49	Fresh to Strong Breeze
5	2.5 - 4	Rough	7	50 - 61	Near Gale
6	4 - 6	Very rough	8	62 - 74	Gale
7	6 - 9	High	9	75 - 88	Strong Gale
8	9 - 14	Very high	10	89 - 102	Storm
9	>14	Phenomenal	11-12	103+	Violent Storm to Hurricane

In the section Data, all consumptions and travel information are recorded in order to start with the analysis performance. The mandatory input list of information is shown in Table 7. All the entered data are monitored with a Control box that prevents the user from entering inconsistent/wrong data.

Table 7 Data interface

Voyage										
	Report Info		Voyage Characteristics		Weather Conditions		Fuel Type X		Electrical Device X	
Control box	Report Type		Position		Wind direction		ME consumption	[t]	Running hours	[h]
	Operation		Displacement	[t]	Wind force	[BF]	DG consumption	[t]	Power Consumption	[kW]
	Date/Time	[UTC]	Draft	[m]	Sea direction		Boiler consumption	[t]	SFOC	[g/kWh]
	Time at sea	[h]	Trim	[m]	Sea state	[SS]	Other consumption	[t]	Fuel Consumption	[t]
	Time at port	[h]	Cargo Quantity	[t]	Swell Direction		Bunker	[t]		
	Time at anchorage	[h]	Ballast Quantity	[t]	Swell High	[m]				
	Time drifting	[h]	Distance Reported	[nm]	Current Type					
			Avg. Ship Speed	[kn]	Current speed	[kn]				

All the data entered is processed and provides the results obtained in the output sections explained below.

3.3 Data processing and output sections

The data entered in the input sections are processed through three different rule-compliant routines for calculating emission and efficiency parameters. The results derived from the calculations, along with the input parameters, constitute a database for the vessel, which will be utilized for conducting a correlation analysis, as explained below.

Emission (1) is the section where the emissions generated by the ship are calculated. Based on the corresponding Tier level, the emission factors for Carbon Dioxide (CO_2), Carbon Monoxide (CO), Sulfur Dioxide (SO_X), Particular Matter 2.5 (PM2.5), Particular Matter 10 (PM10), Total Suspended Particular (TSP), Non-Methane Volatile Organic Compounds (NMVOC), Nitrogen Oxides (NOx) for different types of engine/fuel combinations and for the various vessel travel phases (i.e., voyage, at anchor, port stay) are elaborated.

As the emission factors depend on the type of vessel and the corresponding Tier, the following formulas are to be employed [66], where the unit of measure identified by * is kg for all the pollutants except for CO_2, expressed in tons.

- Tier 1 calculation:

$$E_i = \sum_{k=1}^{O} \left(FC_k \cdot EF_{i,k} \right) \tag{1}$$

where E is the total emission [*], FC is the mass of fuel used [tons], EF is the specific emission factor [*/tons]; i is the index identifying the i-th considered pollutant, k is the index identifying the k-th fuel type.

- Tier 2 calculation:

$$E_i = \sum_{m=1}^{O}\left(\sum_{j=1}^{O} FC_{m,j} \cdot EF_{i,m,j}\right) \tag{2}$$

where *m* is the index identifying the *m*-th fuel type, *j* is the index identifying the engine type.

- Tier 3 calculation:

$$E_{Trip} = E_{Hotelling} + E_{Manoeuvring} + E_{Cruising} \tag{3}$$

where E_{Trip} is the emission over a complete trip [*], $E_{Hotelling}$ is the emission in hotelling during trip [*], $E_{Manoeuvring}$ is the emission in manoeuvring during trip, $E_{Cruising}$ is the emission in cruising during trip [*]:

$$E_{Trip,i,m,j} = \sum_{p=1}^{O}\left(FC_{j,m,p} \cdot EF_{i,m,j,p}\right) \tag{4}$$

where *p* is the index identifying the phase of the trip (cruise, hotelling, manoeuvring).

In 2024, Methane (CH_4) and Nitrous Oxide (N_2O) were introduced into the tool, as these parameters were integrated into the calculation of Greenhouse Gas Emissions from Monitoring, Reporting, and Verification (GHG_{MRV}). The formulated equation for GHG_{MRV} is articulated as follows, with comprehensive parameters accessible at [67]:

$$GHG_{MRV} = CO_{2_{MRV}} + CH_{4_{MRV}} \cdot GWP_{CH_4} + N_2O_{MRV} \cdot GWP_{N_2O} \tag{5}$$

were $CO_{2_{MRV}}$, $CH_{4_{MRV}}$ and N_2O_{MRV} represent the comprehensive aggregation of emitted CO_2, CH_4, and N_2O, respectively. GWP_{CH_4} and GWP_{N_2O} represent global warming potential of CH_4 and N_2O respectively, over 100 years as referred to in the Annex to Commission Delegated Regulation (EU) 2020/1044. By applying these formulas, all emissions are calculated for each report.

In Efficiency (2), the results of the efficiency indices are shown. These indices can provide an overall picture of how well the ship is performing in terms of energy efficiency and environmental impact. The specific indices and their calculation methods can be either mandatory or voluntary and are determined by the regulations that apply to the type of ship in question. The level of detail of the analysis depends linearly on the number of parameters that are taken into consideration. For the present study, the authors decided to consider only the mandatory CII (Carbon Intensity Indicator), whose formula for all ships to which regulation 28 of MARPOL Annex VI applies is as follows:

$$\frac{\sum_j C_{Fj} \cdot \left\{FC_j - \left(FC_{voyage,j} + TF_j + \left(0.75 - 0.03y_i\right) \cdot \left(FC_{electrical,j} + FC_{boiler,j} + FC_{others,j}\right)\right)\right\}}{f_i \cdot f_m \cdot f_c \cdot f_{iVSE} \cdot Capacity \cdot (D_t - D_x)} \tag{6}$$

where *j* is the fuel type, C_{Fj} is the fuel mass to CO_2 mass conversion factor for fuel type j; FC_j is the total mass of consumed fuel of type *j* in the calendar year; $FC_{voyage,j}$ is the mass of fuel of type *j*, consumed in voyage periods; $TF_j = (1 - AF_{Tanker}) \cdot FCS_j$ represents the quantity of fuel *j* removed for STS or shuttle tanker operation; AF_{Tanker} represents the correction factor to be applied to shuttle tankers or STS voyages; y_i is a consecutive numbering system starting at $y_{2023} = 0$, $y_{2024} = 1$, $y_{2025} = 2$, etc.; $FC_{electrical,j}$ is the mass (in grams) of fuel type *j*, consumed for the production of electrical power; $FC_{boiler,j}$ is the mass (in grams) of fuel type *j*, consumed by the boiler; $FC_{others,j}$ is the mass (in grams) of fuel type *j*, consumed by other related fuel consumption devices; f_i is the capacity correction factor for ice-classed ships; f_m is the factor for ice-classed ships having IA; $\cdot f_c$ represents the cubic capacity correction factors for chemical tankers; f_{iVSE} represents the correction factor for ship-specific voluntary structural enhancement; $Capacity$ is deadweight or gross tonnes depending on specific ship type; D_t presents the total distance travelled (in nautical miles); D_x represents the distance travelled (in nautical miles) for voyage periods which may be deducted from CII calculation.

All the parameters have been entered into the program following the IMO's guidelines [68], with specific reference to the regulations in force at the moment of the analysis.

The tool will require periodic updates to reflect future regulatory changes, such as those adopted during MEPC 82 [69].

As a final output, the tool processes the data provided in the input sections with the results of output sections (1) and (2) to provide a third output (3), that is the Report section in which data from a selected period (Figure 3) are processed, providing an overview of the overall results.

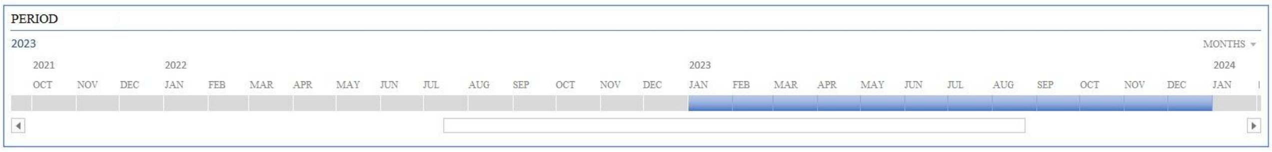


Fig. 3 Example of selected period

Once the selected period (in terms of years, months or days) has been applied to the Report section, a map showing the route of the ship will be illustrated (an example is reported in Figure 4) and all the significant parameters calculated will be provided to the user (as shown in Figure 5).

These include information such as: Voyage info (displacement, cargo quantity, ballast quantity, observed speed, observed distance), Weather conditions (wind force, sea force, swell high, current speed), Fuel X Consumption (Total, Propulsion, Generator (including DG, Boiler, Cargo Heating, Tank Cleaning, Pilot Burner), Summary Report (Hours, Observed Speed, Observed distance), Emission (NOx, NMVOC, TSP, PM10, PM2.5, SO_X, CO_2, CO), Efficiency (for this specific case, the value of CII).

This part can be used to monitor important parameters that could affect efficiency and emissions in a single scheme. This scheme is designed to alert users when parameters have values that are not appropriate for the type of operation.

3.4 Correlation analysis

Using the data collected and processed by the tool, an analysis of correlation can be conducted through the generated database. Correlation analysis is instrumental in elucidating the relationship between variables, enabling to discern how alterations in one variable are linked to changes in another. This focus yields valuable insights into the nature, direction, and degree of correlation.

In this context, the Pearson method has been employed. Through the calculation of the Pearson Correlation Coefficient, which ranges between -1 and +1, with positive and negative signs denoting positive and negative correlations respectively, it becomes possible to discern the correlation between two random variables, thereby quantifying their linear interconnection.

The Pearson correlation coefficient for two variables is as follows [70-73]:

$$\rho(A,B) = \frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{A_i-\mu_A}{\sigma_A}\right)\left(\frac{B_i-\mu_B}{\sigma_B}\right) \tag{7}$$

where N is the scalar number of observations of both variables, μ_A and σ_A are the mean standard deviation of A and similarly μ_B and σ_B are for B.

The correlation coefficient matrix of two random variables is the matrix of correlation coefficients for every possible pair of variables within the given set:

$$R = \begin{pmatrix} \rho(A,A) & \rho(A,B) \\ \rho(A,B) & \rho(B,B) \end{pmatrix} \tag{8}$$

As A and B are inherently correlated with themselves, the diagonal elements in the matrix are consistently set to 1:

$$R = \begin{pmatrix} 1 & \rho(A,B) \\ \rho(A,B) & 1 \end{pmatrix} \quad (9)$$

4. Tool test procedures

In order to illustrate the functionality of the tool presented in the previous section and test its use, a test ship was assumed as a real case study: the tool allowed identifying efficiency and emission parameters worthy of consideration. For achieving this goal, all voyages travelled by the test ship starting from 1 January 2023 to 31 December 2023, have been selected.

The simulation will take into account this period to see the CII trend, since this parameter was introduced on 1 January 2023.

4.1 Test ship

The main characteristics and list of maintenance activities of the case-study ship were entered into the input sections of the tool as shown in Tables 8 and 9.

Table 8 Main input information and characteristics of the case study ship

Vessel Information				
Characteristic/Features			Characteristic/Features	
Type	Oil Tanker		Tier	1
Hull type	Aframax		Engine build date	01/02/2008
Length Overall	245.55	[m]	Generator #1 build date	11/12/2007
Extreme breadth	42.01	[m]	Generator #2 build date	11/12/2007
Deadweight	110,295	[t]	Generator #3 build date	11/12/2007
Displacement	17,537	[t]	Boiler #1 build date	01/01/2008
Delivered date	18/09/2008		Boiler #2 build date	01/01/2008

Table 9 List of maintenance activities of the case study ship

Scheduled maintenance works	
Work	Last performed date
Dry dock	09/06/2023
Hull cleaning	07/06/2023
Propeller cleaning	07/06/2023
Engine Overhaul	07/04/2023
Navigation Equipment calibration	09/06/2023

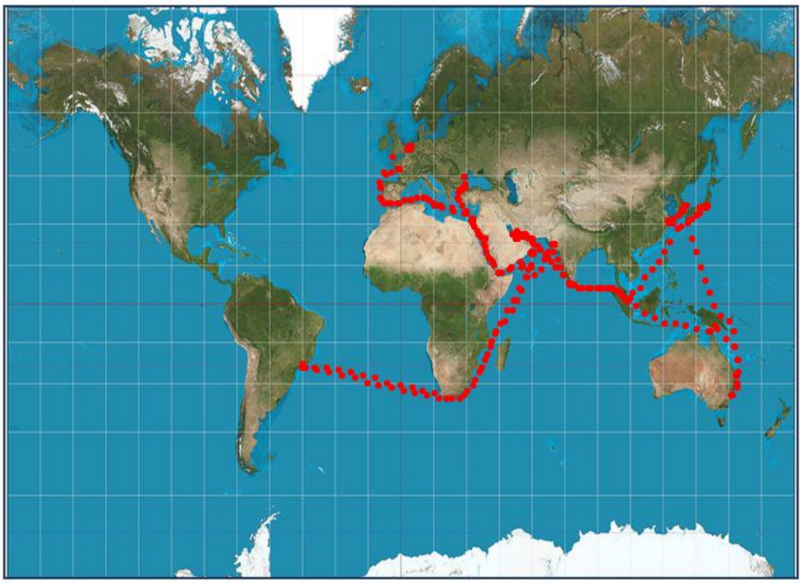


Fig 4 Route of the test ship

4.1.1 Test scenario and outcomes

After the insertion of all the ship's reports for the selected period in the Data section, the Report section shows the map providing the ship's route of operation (Figure 4) and the tool elaborates the calculation for all the interested parameters, that are illustrated for the case study in Figure 5. The tool is able to evaluate the aimed quantities by taking into account two different sets of data, identified with the label Total and Average. Specifically, the label Total refers to all report types, while the label Average refers only to reports reported during navigation. For the test ship, an Aframax Oil Tanker, weather conditions are considered 'good' when the BF scale is 5 or below and the SS is 4 or below. Conversely, conditions are deemed 'bad' when the BF scale reaches 6 or higher and the SS is 5 or above.

A specific focus on the CII values is reported in Figure 6, in which the graph describing the CII trend is shown.

The calculated CII parameters for the year 2023 result in the following ratings: A (0-3.43), B (3.44-3.89), C (3.90-4.52), D (4.53-5.36), and E (greater than 5.37). Specifically, the CII analysis for the year 2023 yields a rating of C being, the calculated value equal to 3.88 gCO2/DWT·nm. A closer examination of this efficiency parameter can be observed from the graph illustrating the CII trend for the year 2023 (Figure 6).

From Figure 6, it can be observed that the CII trend experienced peaks, reaching values D and even E before July, with improvement noted from July onwards.

In order to understand the factors contributing to these peaks, the authors opted to conduct a correlation analysis aimed at identifying elements that exert a negative influence on CO_2 emissions, and consequently, directly impact the CII.

Voyage Info

	Cargo quantity [t]	Ballast quantity [t]	Observed speed [kn]	Observed distance [NM]
Total	46766400	10939500		67900
Average	43500	19650	8.7	

Weather condition

	Wind Force [BF]	Sea Force [SS]	Swell High [m]	Current Speed [kn]
Max	8	5	6	3.8
Average	4	3	1	0.7

VLSFO Consumption

		Total [t]	ME consumption [t]	DG consumption [t]
Good weather (≤ 5 BF)	Total	6870	5755	535
	Average	29.2	2.2	2
Bad weather (≥ 6 BF)	Total	1740	1590	101
	Average	34.4	32.9	32.9

LSMGO Consumption

		Total [t]	ME consumption [t]	DG consumption [t]
Good weather (≤ 5 BF)	Total	574	95	104
	Average	2	1.5	1.1
Bad weather (≥ 6 BF)	Total	24	8.5	7.7
	Average	2	1.1	0.7

Summary report

		Hours [h]	Observed speed [kn]	Observed distance [nm]
Good weather (≤ 5 BF)	Total	4260		50110
	Average		11.76	
Bad weather (≥ 6 BF)	Total	1043		11218
	Average		10.76	

Emissions

	NOX [kg]	NMVOC [kg]	TSP [kg]	PM10 [kg]	PM2.5 [kg]	SO_X [kg]	CO_2 [t]	CO [kg]
Total	728994	24900	54200	49007	49007	87208	29009	70

Efficiency

	CII [gCO_2/DWT·nm]
Total	3.88

Fig 5 Report output section

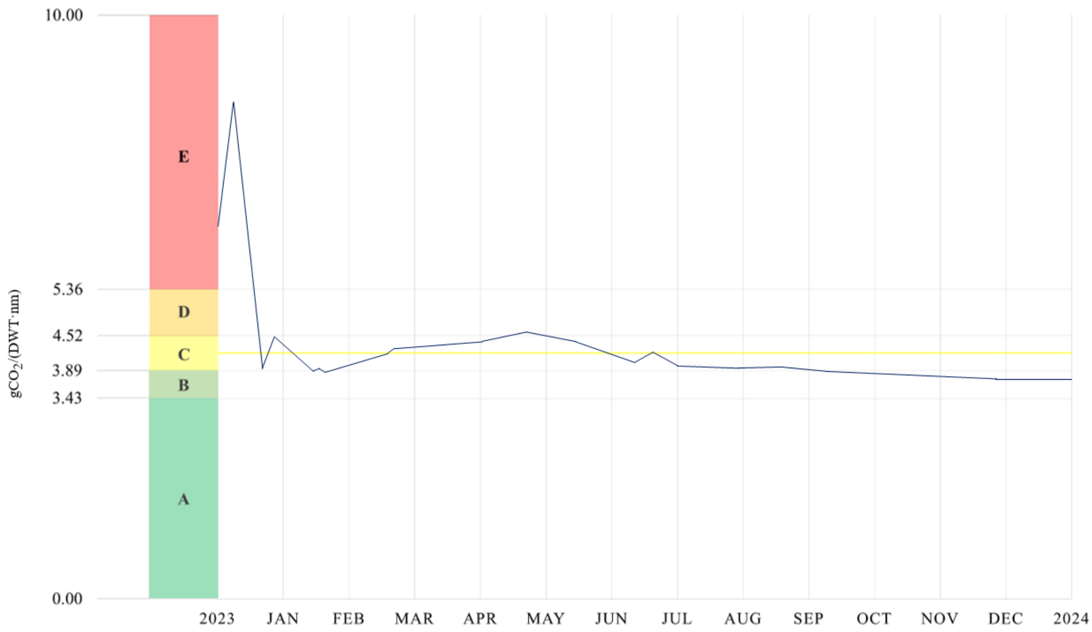


Fig. 6 Output of CII trend 2023

4.2 Correlation analysis

In order to test the tool, a correlation analysis was carried out, based on the results of data obtained from the existing case-study vessel.

The main reasons for choosing to perform the correlation analysis on CO_2 rather than on CII are as follows:

- A database for the vessel has been available since 2020; however, the CII came into effect on January 1, 2023. The implementation of this program with the index began only from this date onwards. Consequently, the available data is limited when correlated with the pre-existing dataset;
- CO_2 is inherently directly correlated with CII. Moreover, it is crucial to examine CO_2 emissions in light of impending carbon taxes, such as the EU Emissions Trading System (EU ETS) and Fuel EU Maritime;
- The vessel in question does not consistently follow the same routes. However, the CII depends on the distance travelled and, consequently, the vessel's route; but the continuous variation in routes encountered during different journeys makes route-specific optimisation impractical, especially considering the dynamic nature of transported cargoes, seasons, and diverse weather conditions. For this reason, it is imperative to analyze its activities throughout its lifespan rather than focusing solely on a single route.

Therefore, considering all the aforementioned aspects, it was decided to conduct an unrestricted correlation analysis not limited solely to the period under study. Nonetheless, this does not exclude the possibility that for ships that consistently follow specific routes, it may be worthwhile to analyze each individual voyage, season by season, and so forth.

As the vessel's routes traverse various regions worldwide, the database contains data from voyages with diverse cargo configurations and varying weather conditions. Understanding which specific aspects of the vessel have the greatest impact on emissions, rather than solely analyzing an isolated single voyage, is essential.

This approach is particularly crucial when considering the implementation of Energy Efficiency Technologies (EETs) aboard the ship. However, it is fundamental to emphasize that parameters that could increase emissions over the entire lifespan of the vessel might not adversely affect the particular voyage under study.

This phenomenon suggests that, although certain parameters seem to be responsible for the worst conditions during a single voyage, a broader analysis of the database might indicate that these parameters are less significant.

To fully understand how specific parameters of the vessel under examination influence CO_2 emissions and consequently directly affect the CII rating, the analysis is based on a database of 7496 reports generated by the tool.

To conduct the correlation analysis, a code based on the Pearson method has been implemented to examine the relationship between various vessel parameters and CO_2 emissions: it is indeed crucial to evaluate the impact of various factors on CII rating.

Before conducting the correlation analysis, a convention was established to correlate the parameters of weather conditions with the ship's direction. The chosen convention is illustrated in Figure 7, providing an example:

- Ψ: angle of ship direction;
- θ: angle of weather condition direction (i.e. angle of wind speed (Vw) or wave celerity (c) direction);
- θ': angle of encounter defined as:

$$\theta' = \Psi - \theta \tag{10}$$

This approach has led to the definition of the categories of encounter angles:

① Bow which angle range is defined as [337.5, 22.5]

② Quartering which angle range is defined as]22.5,67.5[or]292.5,337.5[
③ Quartering which angle range is defined as [67.5,112.5] or [247.5,292.5]
④ Abeam which angle range is defined as]112.5,157.5[or]202.5,247.5[
⑤ Stern which angle range is defined as [157.5,202.5]

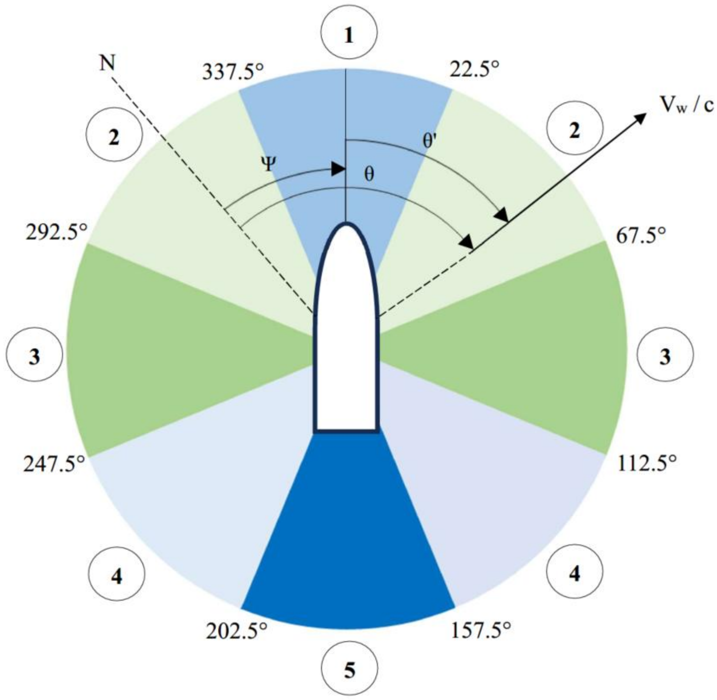


Fig. 7 Categories of encounter angles

The parameters included in the correlation code are:

- Ship speed [*V*];
- Cube of Ship speed [V^3]: as a first approximation, the required propulsive power increases with the cube of the ship's speed;
- Displacement [Disp];
- Wind force on the Beaufort scale [BFW] at different θ': BFW①, BFW②, BFW③, BFW④, BFW⑤;
- Sea State on the Douglas scale [SS] at different θ': SS①, SS②, SS③, SS④, SS⑤;
- Swell Height [SWH] at different θ': BWH①, BWH②, BWH③, BWH④, BWH⑤;
- Current speed in relation to the ship direction:
  - In the same direction, with [CW];
  - In the opposite direction, against [CA];
  - Abeam [CAB];
- Days since the last Dry Dock [DDD];
- Days since the last Hull Cleaning [DHC];
- Days since the last Propeller Cleaning [DPC].

The analysis was conducted by considering the ship's scenarios only during navigation.

The effects of all mentioned parameters on CO_2 emissions are shown in the correlation table (Table 10). Here, the parameter "B", defined as CO_2 emissions per hour of the report (CO_2/h), represents the correlation coefficient for all "A" variables.

Moreover, the most significant correlations are visually depicted in Figure 8.

Table 10 Correlation factor ρ for the considered ship parameters and features

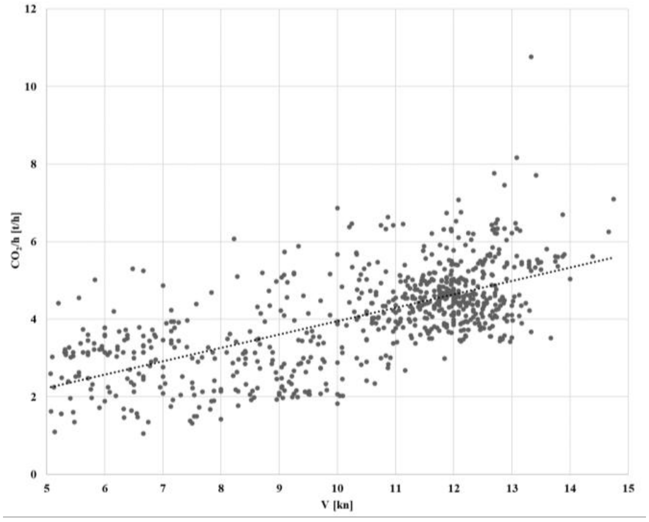
A	$\rho(A, B)$
V	0.6503
V^3	0.6635
Disp	0.2840
BFW①	-0.1130
BFW②	-0.1063
BFW③	0.1333
BFW④	0.0373
BFW⑤	0.1691
SS①	-0.1018
SS②	-0.0737
SS③	0.0987
SS④	0.0487
SS⑤	0.1681

A	$\rho(A, B)$
BWH①	-0.1505
BWH②	-0.1128
BWH③	0.1679
BWH④	0.0994
BWH⑤	0.0886
CW	-0.2285
CA	0.0342
CAB	0.0279
DDD	0.2080
DHC – DHP (case 1)	0.2246
DHC – DHP (case 2)	0.5159

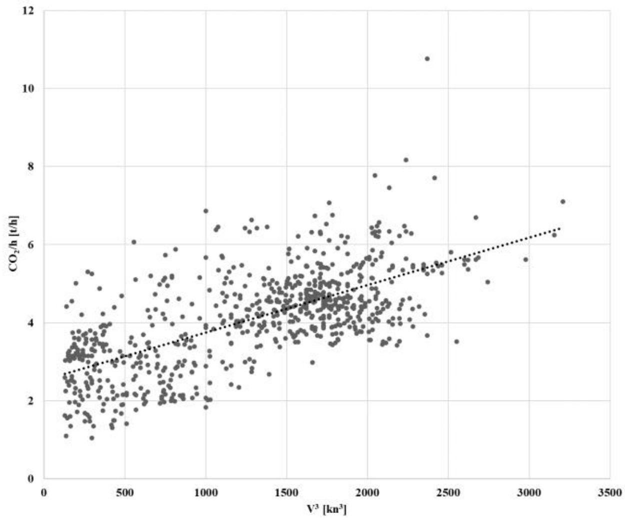
Table 10 presents the correlation factor (ρ) for the analyzed ship parameters and features, while Figure 8 illustrates some of the most significant correlations.

A correlation factor of $\rho > 0.5$ indicates a strong relationship between the analyzed parameter and CO_2 emissions. Among the examined variables, ship speed (both V and V^3) shows the highest correlation, followed closely by case 2 of days since the last hull and propeller cleaning [DHC – DHP (case 2)]. This suggests that increasing the frequency of hull and propeller cleaning could significantly reduce emissions for the Aframax Tanker under study. Alternatively, slow steaming could be implemented, as Figure 8(a) highlights a particularly strong correlation between emissions and speeds of 11–13 knots. However, each approach presents trade-offs. More frequent cleaning incurs additional costs and ship downtime, whereas slow steaming reduces operational efficiency and revenue.

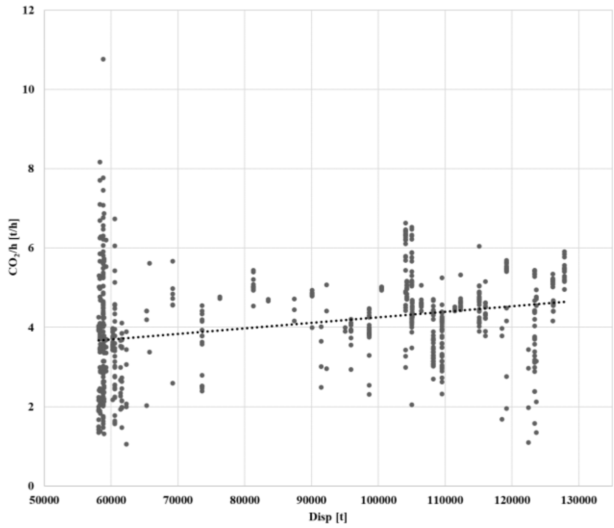
For correlation values in the range of $0.2 < \rho < 0.4$, the relationship is weaker compared to the previously discussed cases but should not be overlooked. Table 10 highlights such instances, including days since the last dry docking (DDD) and case 1 of days since the last hull and propeller cleaning [DHC – DHP (case 1)]. To ensure accurate results, two separate analyses were conducted to assess the impact of hull and propeller cleaning on CO_2 emissions, preventing one from influencing the other.



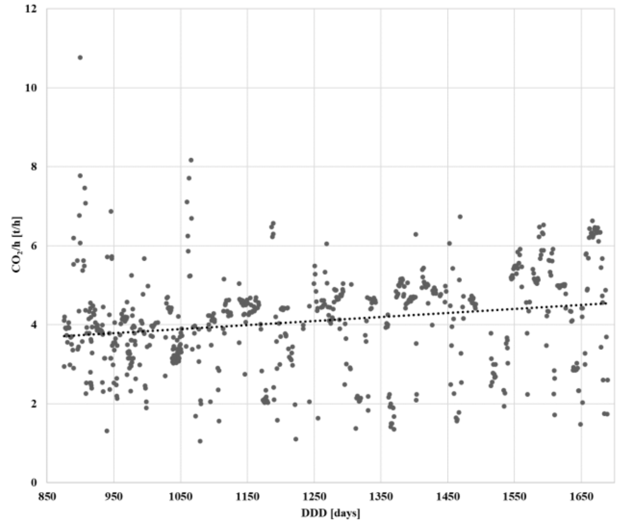
(a) Ship Speed - CO_2/h



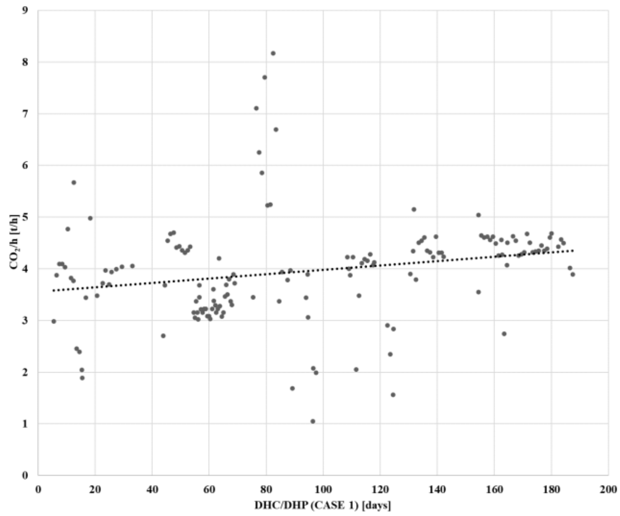
(b) Ship Speed Cubed - CO_2/h



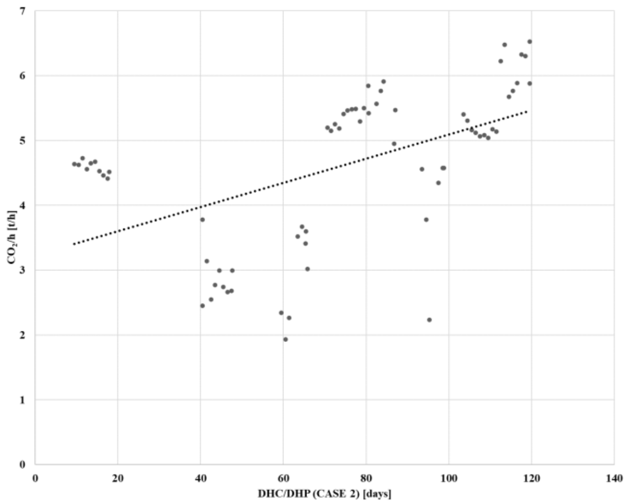
(c) Displacement – CO_2/h



(d) Days from last Dry Dock– CO_2/h



(e) Days from last hull/propeller cleaning (case 1) - CO_2/h



(f) Days from last hull/propeller cleaning (case 2) - CO_2/h

Fig. 8 Correlation Analysis

As previously mentioned, case 2 exhibits a strong correlation, suggesting that increasing the frequency of hull and propeller cleaning would be beneficial. Conversely, in case 1, the correlation is weaker, indicating that a full hull and propeller cleaning may not always be necessary. However, since a non-negligible correlation exists, considering also the similar correlation observed for days since the last dry docking, this further reinforces the importance of antifouling measures. These findings confirm that antifouling efforts are the second most influential factor in CO_2 emissions after speed. Given this, exploring efficiency-enhancing technologies, such as air bubble lubrication, may be a worthwhile consideration. Overall, monitoring hull and propeller maintenance is a critical factor, and the tool provides this functionality as shown in Table 9.

In the same correlation range, displacement (Disp) also exhibits a correlation, as illustrated in Figure 8(c). The figure highlights the impact of loading conditions on CO_2 emissions, showing that ballast conditions in the Aframax Tanker vessel lead to higher emissions due to increased hydrodynamic resistance.

In contrast to the previously mentioned correlations, ocean currents moving in the same direction as the vessel (CW) exhibit a negative correlation with CO_2 emissions, indicating a clear reduction in emissions.

The correlations considered above are the most influence and tend to reduce the other factors, although they are still present. This suggests the possibility of taking specific measures in certain wind, sea, and swell conditions to optimize the ship's environmental performance. For instance, it is not only essential to devise strategies for addressing adverse situations, but also to leverage favourable conditions, such as current, wind, and sea conditions, to optimize outcomes. A correlation analysis reveals a noteworthy finding: when the wind blows in the same ship's direction, there is a negative correlation with CO_2 emissions exceeding 0.1. This indicates that the vessel is likely to experience advantageous wind conditions during its voyages, contributing positively to emission reduction and in this context exploring the installation of technologies like wind rotors becomes a plausible consideration. This proposition gains merit as it aligns with the observed correlation, emphasizing the potential positive impact on CO_2 reduction. Contrastingly, pursuing such implementation might be less justifiable if the preliminary analysis indicated an absence of correlation between the ship and favourable wind conditions.

5. Results and discussion

The tool enables the monitoring of ship emissions and efficiency parameters and facilitates the identification of areas for the implementation of corrective measures aimed at improving the performance and efficiency of the ship. The results obtained and illustrated in Figure 5 can signal when a maximum threshold (that is input by the user based on the Regulations in force) is exceeded, by highlighting the troublesome values. Thus, the fundamental parameters of the ship during its operative lifecycle can be checked and maintained under the prescribed limits. In this context, CII assumes particular significance in assessing emission indexes and mitigating potential financial consequences. For this reason, the tool provides a more comprehensive figure regarding the CII rating over time (Figure 6) and alerts the user when the value of the CII exceeds the maximum threshold calculated according to the Regulation, pointing out that corrective measures should be applied to decrease the index.

Since the assessment of emission indexes is a mandatory step for ships to operate without financial consequences, it is therefore clear that the proposed tool helps to simplify the analysis and represents a valid tool to shipowners and operators. By exploiting it, they can perform a thorough data collection that enables the identification of the voyage situations in which energy efficiency, emissions, indexes and operative parameters are unfavourable.

With specific reference to the case-study ship under investigation and its CII rating, it has been observed that for the year 2023, the ship is rated as C. However, it is worth noting that the ship experienced significantly high peaks of D and E ratings, having a negative impact on the overall CII value. Indeed, the correlation analysis reported in Table 10 and Figure 8, indicates a noteworthy connection between dry dock activities, hull and propeller cleaning, with CO_2 emissions. This relationship is further evidenced by the CII trend (Figure 6), showcasing an improvement in the rating after the dry dock maintenance conducted in June (Table 9).

As a result, having highlighted the situations in which the vessel is most adversely affected by CO_2 emissions and concurrently desiring an improvement in the CII rating, exploring alternative Energy Efficiency Technologies (EETs) appears to be a viable solution. A possibility one could consider implementing air bubble lubrication to be activated when the vessel begins to accumulate an excessive number of days since hull cleaning. Additionally, exploring technologies to be activated in the event the vessel encounters adverse wind, sea, and swell conditions identified in the correlation analysis could be a worthwhile undertaking.

Technologies aimed at reducing CO_2 emissions could give a solid advantage: particularly, the latest technologies based on Carbon Capture System (CCS) have proved to be very promising and can potentially lead to CO_2 emissions reductions between 11 % and 75 % [74]. Considering that the ship currently has an acceptable CII rating, it may be worth considering the implementation of a small CCS to be used only when the CII value experiences peaks as illustrated in the case study. It is however important to also take into account that CII will become more stringent in the coming years, potentially causing situations that are currently acceptable to exceed the parameters. In this case, the implementation of a bigger CCS would be useful to avoid CII exceeding the limits also during navigation. To determine whether to implement a large or small CCS, several factors need to be considered, such as the age of the ship and its operational requirements. One potential option could alternatively be a first installation of a smaller CCS and, perhaps in the future, a consequent upgrade to a larger system in case the ship no longer meets the predetermined CII values. This approach would allow better flexibility and adaptation based on the ship's operational requirements.

Furthermore, the tool could support the opportunity to evaluate efficiency and emissions using alternative types of fuel. For this case-study ship, one viable approach could be the use of a fuel blend. Instead of using only conventional fuels such as VLSFO and LSMGO, it might be worthwhile to explore the incorporation of a 30 % biofuel blend. By blending biofuels with traditional fossil fuels, existing engines can be fuelled without requiring significant capital investment, which is usually required for alternative decarbonisation measures such as retrofitting engines for dual-fuel capability [75].

The findings emphasize the importance of continuous monitoring for optimizing ship emissions and operational efficiency, aiding shipowners in avoiding financial penalties due to non-compliance with emission regulations. The tool's capability to track performance parameters, such as the CII rating, provides proactive management of ship operations, highlighting areas for improvement like hull cleaning and energy efficiency technologies. In contrast to existing studies that rely on historical route data to model, for example, the relationship between fuel consumption and meteorological conditions, this tool collects extensive real-time data, offering more accurate and dynamic insights and analyses [76, 77]. This comprehensive data collection enables the identification of parameters that might otherwise be overlooked. For istance, initial findings from the application and data collection through the developed tool highlight the importance of further investigating ocean currents, particularly in the context of voyage planning. It appears that favorable currents have a more significant effect on emissions reduction compared to wind and sea state, which, while showing reasonable correlation coefficients, remain extremely weak. Notably, while wind and wave height are typically considered the primary environmental factors in weather routing [78], the results of the present study, focusing on an Aframax tanker vessel, suggest that current optimization could play a more substantial role in improving fuel efficiency and reducing emissions.

This functionality enables the prompt identification of issues and the application of targeted measures, such as Energy Efficiency Technologies (EETs), to effectively address these challenges.

A possible limitation of the tool is its reliance on the quality and consistency of input data, which may occasionally be compromised by human error, affecting its overall accuracy. Additionally, the tool requires manual input of regulatory thresholds, which may change over time. While the tool can suggest improvements, it does not evaluate the feasibility or cost-effectiveness of implementing these changes.

With the advancement of AI technology, this type of analysis could soon be integrated into the tool, enhancing its functionality and adaptability, particularly for real-time decision-making and operational efficiency improvements. The incorporation of AI-driven data analysis would also support broader digital transformation initiatives within the maritime sector, facilitating new research opportunities and unlocking advanced capabilities. A promising direction involves integrating AI-calibrated physical models with real-world data, enabling more accurate fleet management, cost forecasting, and risk assessment. This evolution would allow shipowners to move beyond reactive compliance and towards predictive optimization, ensuring long-term sustainability and competitiveness in an increasingly regulated industry.

It is therefore evident that the proposed tool streamlines the analysis of emission indexes, providing shipowners and operators with a comprehensive grasp of energy efficiency, emissions, indexes, and operative parameters. This tool underscores the imperative for ongoing monitoring, optimization, and exploration of alternative technologies to adhere to evolving regulations and enhance the environmental performance of the ship. Through this tool, it becomes feasible to ascertain the most suitable EETs and potential alternative fuels that align with the specific type and purpose of the selected ship. Consequently, shipowners and operators can contemplate retrofitting interventions based on real-established data.

6. Conclusion

The growing awareness of climate change within the shipping industry is expected to bring significant changes in energy generation and propulsion systems. This shift aims to reduce pollutant emissions in the coming years. Shipowners are now seeking transition plans that can adapt to an uncertain future, while also prioritizing safety and carbon dioxide reduction through flexible fuel solutions. As a result, vessel efficiency enhancement is expected to be a priority in the short term, leading to a gradual transition from fossil fuels to alternative fuels in the long term.

In any case, it has been shown that fuel saving is an essential goal to achieve. Fuel, regardless of the used type, now represents the single biggest operating cost item for shipowners and its saving can significantly reduce emissions as long as non-zero-emission solutions are still in place. As a result, the possibility of monitoring the efficiency performance of ships is important more than ever, and digital solutions appear to be promising in this regard.

The tool developed and tested in this study wants to address this problem, offering a two-fold aim.

Firstly, it allows a systematic collection of onboard detailed data, that can be used by shipowners and operators to define a perfect image of the working conditions of the ship and can be recorded to make comparisons among different ships belonging to the same category and fleet. However, the potential limitations of the tool should be acknowledged. Its accuracy depends on the quality and consistency of input data, which can sometimes be affected by human error. Despite the procedures and checks outlined in the methodology section, such issues can still arise. For future improvements, integrating automation or leveraging metocean models supplied by various data providers—such as the EU's free Copernicus service—would help minimize human error and enhance reliability.

Secondly, through in-tool performed calculations, it enables the identification of the specific situations in which the considered vessel offers its best and worst performances along with the level of atmospheric emissions released. In particular, it allows correlation analyses to be conducted using a vast database to identify crucial navigation and maintenance parameters that have a significant impact on emissions production. With the progress of AI technology, this type of analysis could soon be integrated into the tool, enhancing its functionality and adaptability, particularly for real-time decision-making and operational efficiency improvements on new ships equipped with modern automation systems for automatic data collection and sharing. The incorporation of AI-driven data analysis would also support broader digital transformation initiatives within the maritime sector, facilitating new research opportunities and unlocking advanced capabilities.

Specifically, the methodology was applied to a case study ship, considering factors such as days from last dry dock, hull and propeller cleaning, and environmental variables like wind, sea conditions, and swell, and their effect on CO_2 emissions. The results obtained suggest the possibility of implementing specific measures in distinct and real circumstances. Therefore, this integrated approach provides a deeper insight into the interplay of various factors influencing both vessel performance and emissions. However, while most factors in the presented tool were analyzed in detail, the influence of ocean currents was evaluated in a more simplified manner, considering only three categories: currents moving in the same direction as the vessel [CW], opposing currents [CA], and currents abeam to the vessel's direction [CAB]. Despite this limitation, the correlation analysis revealed a significant relationship between currents moving in the same direction as the vessel and CO_2 emissions. This correlation should not be overlooked, as it highlights a positive impact, leading to reduced emissions for the studied vessel. Therefore, future research should aim to incorporate more detailed characteristics of ocean currents to enhance the understanding of their effects on ship emissions and operational efficiency.

The tool's capability to monitor performance parameters enables proactive ship operation management, identifying areas for improvement and facilitating the implementation of targeted measures, such as Energy Efficiency Technologies (EETs), to effectively address operational challenges.

The integration of EETs into the tool is a key step for future development, which will allow the system to directly estimate how the adoption of EETs influence the performance and efficiency of the ship under various operating conditions. By assessing the impact of different solutions, the aim of the tool is to provide valuable insights and recommend the most suitable and cost-effective measures to further enhance the energy efficiency of ships, in line with the overall goal of sustainable maritime practices. This aids shipowners and operators in making informed decisions regarding refitting interventions, supported by comprehensive and consolidated data.

In terms of global contributions, this study demonstrates the potential of digital tools to assist the maritime industry in achieving more sustainable practices. The developed tool is an enabling technology—a fundamental prerequisite for collecting reliable and precise data to conduct a meaningful EET assessment, thereby mitigating the risk of making inappropriate investments. By allowing more precise tracking of emissions and performance, the tool supports the maritime sector's broader efforts to comply with increasingly stringent environmental regulations and reduce its carbon footprint. Future studies should explore how this tool can be further refined, including integrating AI.

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