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RESEARCH ARTICLE

Benchmarking Reference Bulk Carriers with the Best International Shipping Results Regarding Carbon Intensity Indices

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ABSTRACT

The growing urgency of maritime decarbonization and the efforts toward achieving it are a critical subject of academic debate. This research provides a comprehensive empirical analysis of the operational carbon intensity of a Capesize bulk carrier having 176,859 deadweight tonnage using a full year of noon report data. In addition, a forward-looking scenario analysis was conducted to compare the vessel's performance under alternative fuel options including liquefied natural gas, and Methanol. The findings were then compared with maritime sector data from the period 2008 to 2018. The primary findings confirm the ship's exceptional efficiency in load-dependent metrics, with its Energy Efficiency Operational Index value of 2.78 gCO_2/t/nm significantly outperforming the sector's best value (i.e., minimum) of 17.10 gCO_2/t/nm and its Annual Efficiency Ratio value of 2.57 gCO_2/t/nm securing a critical advantage for the sector's best value which is 6.31 gCO_2/t/nm. Additionally, the time-based indicator (TIME) value of the ship with 2.47 tCO_2/hr remained lower than the 3.64 tCO2/hr, which is the best value of the sector. Conversely, the analysis highlights a key challenge in voyage-based metrics, as the ship's distance-based indicator (DIST) value of 454.2 $kgCO_2$/nm exceeded the sector's best value of 306.46 $kgCO_2$/nm indicating lower performance within the scope of this metric. Additionally, scenario analysis confirms that utilizing LNG or methanol as alternative fuels instead of conventional fuels leads to a substantial improvement across all four indices. The use of LNG and Methanol as marine fuels reduces the EEOI value by 24.82% and 10.43% respectively.

Keywords: Operational carbon intensity, Annual efficiency ratio (AER), Energy efficiency operational indicator (EEOI), LNG, Methanol, Operational efficiency, Decarbonization, Capesize bulk carrier

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1. Introduction

The global shipping industry, responsible for approximately 3% of global greenhouse gas (GHG) emissions, is under increasing pressure to align with international climate targets (Jaramillo et al., 2025; Xing et al., 2025). In a landmark decision, the International Maritime Organization (IMO) adopted the revised 2023 GHG Strategy, setting an ambitious goal of achieving net-zero GHG emissions from international shipping by around 2050 and including intermediate indicative checkpoints for 2030 and

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2040 (Bayramoğlu et al., 2025; Godet et al., 2023). To meet the intermediate target of reducing carbon intensity by at least 40% by 2030, mandatory short-term measures, namely the Energy Efficiency Existing Ship Index (EEXI) and the operational Carbon Intensity Indicator (CII), entered into force in 2023 (Bayraktar & Yuksel, 2023). Compliance with these operational targets requires mandatory data collection, typically derived from daily operational logs known as noon reports (Bayraktar & Sokukcu, 2024; Ha et al., 2023).

The implementation of CII, primarily calculated using the Annual Efficiency Ratio (AER), has prompted a critical discussion within the academic community regarding the suitability of the chosen metrics (Dewan & Godina, 2024; Faber et al., 2020). AER, a supply-based indicator that uses the ship's deadweight tonnage (DWT), is frequently criticized for failing to adequately reflect actual operational efficiency or the actual amount of cargo transported, contrasting sharply with the demand-based Energy Efficiency Operational Index (EEOI) (Barreiro Montes et al., 2024; IMO, 2023). The use of AER leads to inherent volatility, or 'noise,' in year-to-year results, highlighting a key regulatory challenge in ensuring fair and accurate benchmarking across the diverse global fleet (Wang et al., 2022). Moreover, while mandatory carbon intensity compliance is monitored using operational data, current IMO indices are fundamentally Tank-to-Wake (TtW) metrics (Lim, 2025). This is analytically insufficient, as the IMO itself adopted the Life Cycle Assessment (LCA) Guidelines (MEPC.376(80)) in 2023, mandating a Well-to-Wake (WtW) perspective for future fuels (Zincir et al., 2025). Historically, between 2008 and 2018, ship-based efficiency indicators like EEOI and AER showed notable downward trends. However, distance and time-based indicators (DIST and TIME) significantly increased over the same period, indicating a need for more intensive CO_2 reduction activities like slow steaming.

Motivated by this regulatory shift and analytical complexity, this research provides a comprehensive empirical analysis of a Capesize bulk carrier having 176,859 DWT using one full year of high-resolution operational noon report data to assess its performance against the four critical carbon intensity indices defined in the Fourth IMO GHG Study 2020: EEOI ($gCO_2/t/nm$), AER ($gCO_2/dwt/nm$), DIST ($kgCO_2/nm$), and TIME (tCO_2/hr)(Faber et al., 2020). The analysis uses the bulk carrier's real-world operational profile to explore the practical implications of mandatory efficiency targets on ship management and benchmarks the results against sector-wide historical IMO trends. Crucially, the scope is extended to perform LCA-based scenario analysis a TtW fuel transition scenario analysis for two leading alternative marine fuels, liquefied natural gas (LNG) and Methanol (Karatuğ et al., 2023; Sevgili et al., 2025). While LNG offers significant reductions in SO_X, NO_X, and CO_2 emissions, its widespread adoption is controversial due to the serious life-cycle climate penalty imposed by methane slip (CH_4), a potent greenhouse gas (Psaraftis & Lagouvardou, 2023). Conversely, Methanol, particularly bio-Methanol or e-Methanol, presents a pathway to ultra-low or net-zero carbon operations, although its commercial viability is constrained by lower energy density and higher costs (Bayramoğlu et al., 2025; Policano et al., 2024).

This research contributes significantly to the existing literature by offering a unique and integrated perspective. First, unlike studies relying on aggregated data or limited voyage samples, this analysis bases its findings on one full year of high-frequency, real-world operational noon report data from a single ship, providing an unprecedented level of empirical detail for a Capesize bulk carrier. Secondly, TtW operational performance of the ship is assessed based on EEOI, AER, DIST, and TIME, and the contributions that alternative fuels such as LNG and methanol will make to decarbonisation strategies are highlighted within the scope of these indices. This provides shipowners, charterers, and policymakers with evidence-based insights necessary for developing realistic and technically sound decarbonization strategies in the maritime sector. The workflow of research, including its objectives, utilized data, and resulting outputs, is illustrated in Fig. 1.

The research is structured in the subsequent sections so that the methodology is outlined in Section 2, the results are reported in Section 3, the discussion is provided in Section 4, and conclusions are drawn in the final section.

2. Methodology

A precise assessment of ships' carbon intensity is vital for developing effective strategies supporting the sustainability of maritime transport while reducing its environmental footprint. Four different indices have been identified for measuring the carbon intensity of international maritime transport under the Fourth IMO GHG Study 2020. These are EEOI, AER, DIST, and TIME, respectively. The equations employed in calculating these indices are expressed Eqs. (1) to (4), respectively (IMO, 2020).

The EEOI, as highlighted by IMO, enables ship operators to evaluate fuel efficiency based on carbon intensity. In its calculation, the type of fuel utilized,

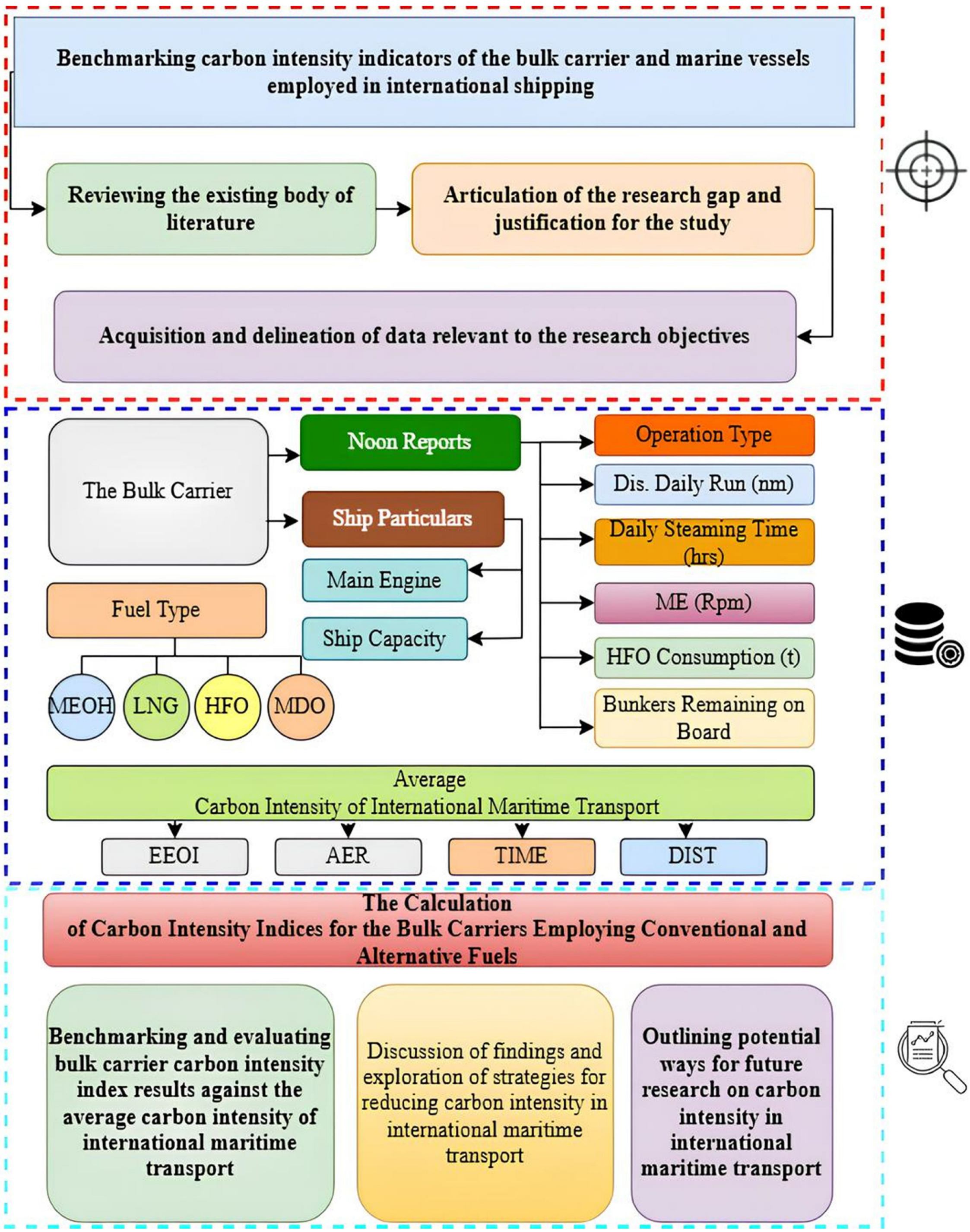

Fig. 1. The workflow of research.

the amount of cargo transported, and the distance travelled are critical because they directly affect the EEOI value of ships (IMO, 2009; Wärtsılä, 2025a).

$$EEOI = \frac{\sum_{i=1}^{n} C_i}{\sum_{i=1}^{n} T_i x\, D_i} \quad (1)$$

C_i represents the total CO_2 emissions in grams sourced from each ship's voyage. The type of fuel utilized, the mass of fuel consumed, and the corresponding carbon emission factors during the voyages are used in the calculation of C_i (IMO, 2009). T_i denotes the cargo weight transported on each voyage in metric tons, and lastly, D_i is the distance travelled in

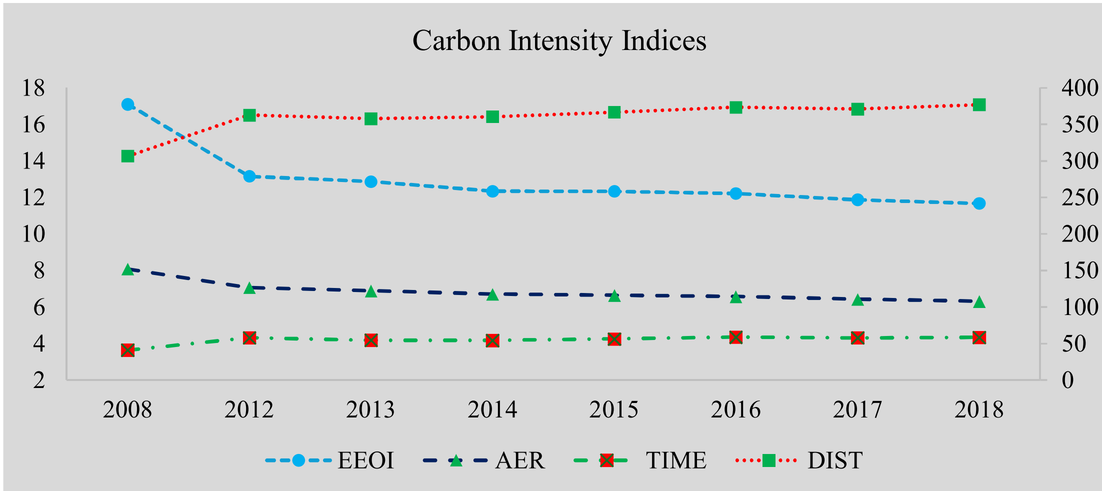

Fig. 2. Carbon intensity and trend line from 2008 to 2018.

nautical miles with the transported cargo. The EEOI is calculated on an annual basis, taking into account all operations and specified variables throughout the year (Wärtsılä, 2025a).

Although AER and EEOI share similarities, their calculation methods differ. In the case of EEOI, the actual cargo carried on each voyage is considered, whereas AER is based on the ship's DWT, assuming that the ship operates at full cargo capacity continuously.

$$AER = \frac{\sum_{i=1}^{n} C_i}{\sum_{i=1}^{n} DWTx\ D_i} \quad (2)$$

The calculation approach applied in the AER is likewise utilized to determine the ship's attained CII values. Compliance with the required CII value, as well as the corresponding CII rating, is assessed based on this way (DNV, 2021). The meaning of C_i and D_i is the same as in the EEOI equation; however, DWT represents the carrying capacity of a ship. The ship's load factor during operation does not alter its DWT value (Wärtsılä, 2025b).

The DIST is an operational carbon intensity index that expresses the amount of CO_2 emitted per nautical mile travelled by a ship, regardless of its cargo load. In the equation created for DIST, the CO_2 emitted from ships is expressed C_i in kilograms (IMO, 2020; Jaramillo et al., 2025).

$$DIST = \frac{\sum_{i=1}^{n} C_i}{\sum_{i=1}^{n} D_i} \quad (3)$$

The TIME is an operational carbon intensity index that represents the rate of CO_2 emissions per unit of time during a ship's operation.

$$TIME = \frac{\sum_{i=1}^{n} C_i}{\sum_{i=1}^{n} H_i} \quad (4)$$

In the equation, CO_2 emissions are measured in tonnes, and time, denoted as H_i, is expressed in hours.

The carbon intensity of international maritime transport has decreased substantially, reflecting heightened global environmental awareness and the implementation of more stringent international regulations. Fig. 2 illustrates the changes in carbon intensity and the corresponding trend line from 2008 to 2018, based on the four indices.

Between 2008 and 2018, all four ship-based indicators, including EEOI, AER, DIST, and TIME, show notable changes, with higher values generally indicating less favourable performance in terms of environmental. The EEOI decreased from 17.1 $gCO_2/t/nm$ in 2008 to 11.67 $gCO_2/t/nm$ in 2018, marking a reduction of about 31.8%, which reflects that a considerable amount of CO_2 emissions is mitigated from ships. Similarly, the AER declined from 8.08 to 6.31 $gCO_2/dwt/nm$, showing a 21.9% decrease over the same period. In contrast, the DIST rose significantly, from 306.46 $kgCO_2/nm$ in 2008 to a peak of 376.81 $kgCO_2/nm$ in 2018, indicating an overall increase of 18.7%. Likewise, the TIME increased from 3.64 tCO_2/hr in 2008 to a peak of 4.35 tCO_2/hr in 2016, ending at 4.34 tCO_2/hr in 2018, representing an overall rise of 16.1%.

In this research, the carbon intensity of the bulk carrier is analysed through four indices directly related to ship efficiency and emissions performance. The bulk carrier has a DWT of 176,859 and a GRT of 89,603. It is powered by a main engine rated at

Table 1. Noon-report sample of the bulk carrier.

Operation Type	Dis. Daily Run (nm)	Daily Steaming Time (hrs)	Speed (knot)	ME (Rpm)	HFO Consumption (t)	MGO (t)	Bunkers Remaining on Board HFO (t)	Bunkers Remaining on Board MGO (t)
Departure	0	0	0	0	0.92	0	483.63	147.22
End Leg Report	0	0	0	0	1.12	0	484.55	147.22
Manoeuvring Cast Off	0	0	0	0	0.16	0	485.67	147.22
Discharging	0	0	0	0	4.25	0.1	485.83	147.22
Discharging	0	0	0	0	4.2	0.1	490.08	147.32
Discharging	0	0	0	0	3.71	0.1	494.28	147.42
Manoeuvring All Fast	0	0	0	0	1.92	0.1	483.21	95.68
Anchor Up	0	0	0	0	3.38	0	485.13	95.78
Anchor Report	0	0	0	0	2.16	0.1	488.51	95.78
Anchor Down	0	0	0	0	0.88	0	490.67	95.88
Arrival	143	11	10.82	0	15.23	0	491.55	95.88
Noon Position	274	24	11.42	72.53	39.38	0.1	506.78	95.88
Noon Position	277	24	11.54	72.48	39.42	0.1	546.16	95.98
Noon Position	264	24	11	71.51	39.63	0.1	585.58	96.08
Noon Position	274	24	11.42	70.79	39.42	0.1	625.21	96.18
Noon Position	274	24	11.42	71.72	39.39	0.1	664.63	96.28
Noon Position	288	24	12	71.66	39.26	0.1	704.02	96.38
Noon Position	287	24	11.96	71.48	39.28	0.1	743.28	96.48
Noon Position	296	24	12.33	72.3	39.49	0.1	782.56	96.58
Noon Position	282	24	11.75	72.9	39.45	0.1	822.05	96.68
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Table 2. Lower heating values and CO_2 emission factors of the marine fuels.

Type of fuel	Lower calorific value (kJ/kg)	CO_2 (t-/t-Fuel)
MDO /MGO	42700	3.206
HFO	40200	3.114
LNG	48000	2.75
Methanol	19900	1.375

16,860 kW, operating at 91 rpm, which enables a continuous maximum service speed of 17 knots. The ship has an overall length of 288.97 meters, a breadth of 45 meters, and a depth of 24.4 meters. The evaluation process is grounded in noon reports, which provide the ship's standardized operational and performance data. These noon reports serve as the primary source of information for calculating and comparing the selected indices. To illustrate the type of data employed in the analysis, Table 1 presents a sample of the noon reports used in this research.

It is evident that the number of operational days and marine fuels consumed per year directly influence the ship's annual CO_2 emissions. Key parameters such as SFC, engine power output, the type of fuel utilized, and the duration of operation are critical factors in determining overall CO_2 emission levels. Table 2 represents the lower heating values and CO_2 emission factors of the fuels under investigation in this research.

3. Results

Analysis of the one-year noon report data indicates that the ship operated a total distance of 47,554.61 nautical miles. Over this period, fuel consumption amounted to 6,641.89 tons of HFO by the main engine and 285.84 tons of MDO by the auxiliary engines. Although the ship's design DWT is 176,859, the average annual cargo load was 163,500 tons, corresponding to approximately 92.5% of full capacity throughout one-year operation. The performance assessment and subsequent calculations were conducted based on the noon report records, the ship's technical specifications, and indices that ensured alignment with standard regulatory and operational frameworks highlighted by internationally recognized authorities.

The index values of the ships at the end of the year are calculated based on Eqs. (1) to (4), and the results are shown in the Fig. 3.

The ship's EEOI, AER, TIME, and DIST values have been benchmarked against the best-performing (i.e., lowest) ship-based international maritime transport values ranging from 2008 to 2018 years which is published by IMO that represent the most recent and reliable data available in this field. The ship's EEOI of 2.78 $gCO_2/t/nm$ is considerably lower than the best ship-based international maritime transport of 17.10 $gCO_2/t/nm$ reported for the period 2008–2018. The

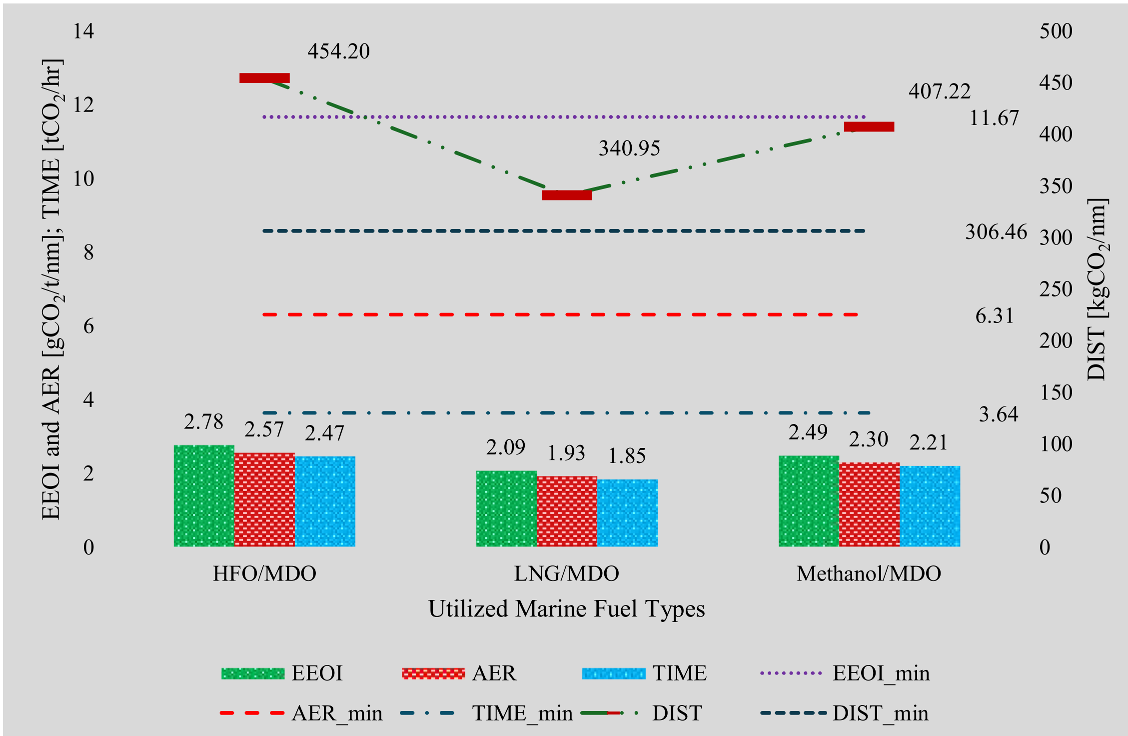

Fig. 3. The index values of the ships.

EEOI values of the ship acquired from using LNG and methanol in main engines instead of conventional fuels are 2.09 and 2.30 $gCO_2/t/nm$, respectively. These values are well below the ship-based international maritime transport value and ship's current EEOI value.

In contrast to the EEOI, which accounts for the amount of cargo carried, the calculation of the AER is based on the ship's design DWT. Consequently, the ship's AER value of 2.57 $gCO_2/t/nm$ is comparatively lower than its EEOI value. Like the EEOI, the employment of alternative fuels such as LNG and methanol in main engine operations is provided to reduce AER values further, and new AER values are 1.93 and 2.30 $gCO_2/t/nm$, respectively, thereby enhancing the ship's performance relative to the global best value.

Compared to the best ship-based international maritime transport value of 3.64 tCO_2/hr for maritime transportation, the investigated bulk carrier exhibits favourable performance with a TIME value of 2.47 tCO_2/hr. This indicator can be further improved through alternative fuel usage, with LNG and methanol reducing the TIME value to 1.85 tCO_2/hr and 2.21 tCO_2/hr, respectively. However, while the ship exhibits notable advantages in terms of EEOI and AER, its superiority having lower values in terms of TIME performance is less pronounced when compared to the best ship-based international maritime transport value.

The bulk carrier's DIST value is calculated as 454.2 $kgCO_2/nm$, considerably higher than the best ship-based international maritime transport value of 306.46 $kgCO_2/nm$ recorded between 2012 and 2018. Indeed, this result exceeds the best ship-based international maritime transport DIST values reported for every year within that period. When LNG is used as the primary fuel, the DIST value decreases to 340.95 $kgCO_2/nm$, surpassing all annual best ship-based international maritime transport values except 2008; however, it remains well above the 2008 level. In contrast, while the employment of methanol in the main engine contributes to a reduction in TIME, it does not yield improvements sufficient to outperform any of the established ship-based international maritime transport DIST values.

4. Discussion

The ship-based EEOI values have been steadily decreasing between 2008 and 2018. Considering this declining trend, the EEOI value is projected to fall by around 10 $gCO_2/t/nm$. In particular, the 2.78 $gCO_2/t/nm$ EEOI value of the ship significantly contributes to the environmental sustainability of maritime shipping and lowers the annual average EEOI values.

Similarly, the ship-based AER average values of maritime transportation are projected to be around 5 gCO_2/t/nm, given the decreasing trend. The 2.57 gCO_2/t/nm AER value of the ship is below the ship-based AER average, contributing to the achievement of maritime transport carbon reduction targets (Cullinane & Yang, 2022). Since the AER formula is directly related to the CII formula, ships with low AER values also help to exceed the CII reference value thresholds that become difficult over the years and enable ships to be rated as A or B grade with high CII ratios (Sandberg, 2024).

Although there is no trend over the years regarding the ship-based international maritime transport TIME value, the ship's 2.47 tCO_2/hr TIME value is superior, i.e., numerically lower, to the annual values. Unlike the three indices, the DIST value has increased over the years. It is expected to average roundly 400 $kgCO_2$/nm by the end of 2025. Although the calculated 454.2 $kgCO_2$/nm DIST value of the ship is beyond projections, it is essential to implement various reduction strategies for the ship-based DIST value in maritime transport (Chen & Mao, 2024). Foremost among these is weather routing, which employs predictive analytics to identify optimal routes minimizing resistance and time in adverse conditions, thereby directly reducing fuel consumption up to 30% and, consequently, CO_2 per nautical mile (Borén et al., 2022). Furthermore, regular hull and propeller cleaning to mitigate biofouling, trim and draft optimization, which save up to 1.2% of total fuel consumption, can yield substantial gains in DIST performance by improving hydrodynamic efficiency and reducing the required power for a specific speed (Yu et al., 2024). While slow steaming is a known effective strategy for reducing TIME value, a careful speed/engine power optimization is necessary to find the optimal balance that also lowers the DIST index, as the relationship between speed and power is exponential. Integrating these focused operational management practices is essential to leverage the vessel's high EEOI and AER performance and achieve holistic compliance and industry leadership in all core carbon intensity indices. Within the scope of alternative fuels, LNG and methanol, which are gradually becoming more widespread in ships to conventional fuels, have significantly lowered all four indices (DNV, 2023). LNG's high calorific value and methanol's low carbon content are major factors contributing to this decline.

It is important to note that these findings and discussions are based on a TtW analysis, which assesses direct emissions and operational efficiency at the ship level. Consequently, the four investigated indices have been developed exclusively from a TtW perspective. It is important to note that a more comprehensive environmental assessment would require a WtW or LCA to account for upstream emissions from fuel production and distribution. However, the implementation of such an analysis is currently hindered by a lack of verified and consistent data and the absence of relevant regulations.

5. Conclusion

This research provides a comprehensive empirical analysis of a Capesize bulk carrier's operational carbon intensity, utilizing a full year of high-resolution noon report data across four key IMO metrics: EEOI, AER, DIST, and TIME. The research uniquely integrates this operational performance assessment with a forward-looking fuel transition scenario analysis for LNG and Methanol.

The primary findings demonstrate the ship's superior efficiency in load-dependent metrics. The calculated EEOI with 2.78 gCO_2/t/nm and AER with 2.57 gCO_2/dwt/nm values significantly outperform historical sector averages, confirming that high operational load factors are crucial for achieving compliance with stringent carbon intensity requirements. However, the analysis highlights a vulnerability in voyage-based metrics, as the ship's DIST 454.2 $kgCO_2$/nm and TIME 2.47 tCO_2/hr results were less favourable against benchmarks. This disparity underscores the importance of implementing targeted operational emission-reduction strategies, such as slow steaming, to effectively manage CO_2 output per unit distance or time. The scenario analysis confirms that adopting alternative fuels significantly reduces all four operational indices.

This research significantly contributes to the metric debate by offering unparalleled empirical detail from a single-ship, full-year dataset. It provides shipowners and policymakers with evidence-based insights for developing robust decarbonization strategies that balance immediate regulatory compliance with long-term transition planning.

Future research should focus on extending this empirical methodology to diverse fleet types to validate the performance correlations observed. Additionally, it is essential to integrate these alternative fuel emission results with full-life cycle cost analyses for enhanced investment clarity. Finally, dedicated empirical studies are needed to quantify the isolated impact of various operational strategies on the voyage-based DIST and TIME indices.

Data available statement

The data are not publicly available due to commercial restrictions.

Conflicts of interest

The authors declare no conflicts of interest.

Ethical approval

Not applicable.

Use of AI for writing assistance

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Author contributions

Alper Seyhan: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing.

Coşkan Sevgili: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing.

Murat Bayraktar: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing.

Onur Yüksel: Conceptualization, Supervision, Writing – Original Draft Preparation, Writing – Review & Editing.

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