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Achieving EEDI Compliance Through Air Lubrication Technology: A Case Study of a 38,400 DWT Self-Unloading Bulk Carrier

Abstract

The International Maritime Organization (IMO) introduced the Energy Efficiency Design Index (EEDI) as a mandatory technical measure to reduce greenhouse gas emissions from ships. This paper presents a preliminary analysis of EEDI for a 38,400 DWT self-unloading bulk carrier designed at 3. Maj Shipyard. Calculations were performed according to resolution MEPC.245(66), considering the main engine characteristics (7 M 43 C, 7000 kW MCR), auxiliary engines, shaft generator, and reference speed of 13.06 knots. Initial calculations yielded an attained EEDI of 5.866 g(CO₂)/t·nm, exceeding the required value of 5.63 g(CO₂)/t·nm determined for Phase 1 implementation (2015-2019) with a 10 % reduction factor. Analysis identified the hydrodynamically non-optimized hull form characteristic of bulk carriers as the key limiting factor. To achieve compliance, optimization was conducted through implementation of an air lubrication system, based on empirical models predicting 13.1 % friction drag reduction. Implementation of this technology resulted in an effective power reduction of 365.46 kW, achieving an EEDI value of 5.46 g(CO₂)/t·nm. Results indicate the necessity of integrating innovative energy-efficient technologies during early design stages of bulk carriers to meet increasingly stringent environmental standards, particularly considering future implementation phases requiring up to 30 % reduction by the end of 2025.

Keywords: EEDI, bulk carrier, energy efficiency, air lubrication, maritime emissions, IMO regulations

1. Introduction

Shipping represents one of the most cost-effective and efficient modes of cargo transportation globally, accounting for approximately 90% of international trade by volume. However, the extensive global merchant fleet holds significant responsibility for its environmental impacts through the emission of large quantities of greenhouse gases (GHG) into the atmosphere. According to the International Maritime Organization (IMO)'s study conducted in 2007, global maritime transport produced 1,046 million tons of CO₂, corresponding to 3.3% of global emissions of this gas [1]. This substantial contribution to global GHG emissions has prompted the international maritime community to develop and implement comprehensive measures aimed at reducing the environmental footprint of shipping operations.

In response to these environmental concerns, the Marine Environment Protection Committee (MEPC) of the IMO introduced Resolution MEPC.203(62) [2], which amended MARPOL Annex VI: "Prevention of Air Pollution from Ships" by adding Chapter 4: "Regulations on Energy Efficiency for Ships." These amendments, which entered into force on January 1, 2013 [2], mandated the implementation of the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) for all ships in international navigation of 400 GT and above, excluding vessels with turbine, diesel-electric, or hybrid propulsion systems. The new regulations apply to all newly built ships and ships undergoing major conversions, requiring that the calculated Attained EEDI for each vessel must fall within the specified values of the Required EEDI [2,3].

The EEDI is essentially a measure for enhancing ship energy efficiency, serving as a tool for calculating the energy efficiency of vessels and providing baseline information for issuing the International Energy Efficiency Certificate (IEEC) [3]. The index calculates the amount of CO₂ emitted in grams per ton of cargo transported over one nautical mile, thereby providing a standardized metric for comparing and improving vessel environmental performance [4]. The Required EEDI is determined based on the EEDI reference line and reduction factor X, which increases progressively in three phases, starting with 10% reduction from 2015, 20% from 2020, and 30% from 2025 onwards [2], with the intention of continuously improving the energy efficiency of the global fleet.

The implementation of EEDI has profound implications for ship design and construction, particularly for bulk carriers, which constitute a significant segment of the global merchant fleet. Bulk carriers typically feature relatively high block coefficients to maximize cargo capacity, low to medium service speeds with single-screw propulsion and are most commonly powered by slow-speed diesel engines. These design characteristics, while optimized for cargo capacity and operational efficiency, often present challenges in meeting increasingly stringent EEDI requirements. Analysis of 4,326 bulk carriers built between 2009 and 2014 shows a slow but steady improvement in EEDI values, particularly for newer vessels, with over 25% of vessels from 2013-

2014 already meeting the stricter Phase 1 targets prior to the set deadlines [5].

Remarkable progress in achieving EEDI compliance ahead of regulatory deadlines was demonstrated in the bulk carrier sector. For Phase 2 requirements (20% reduction by 2020), over half of new bulk carriers built during the initial EEDI period (2013-2015) already met this target, nearly five years before the set deadline [6]. By 2015-2016, approximately 50-55% of bulk carriers entering service had design efficiencies at least 20% better than the baseline, effectively complying with the 2020 Phase 2 standard early [7]. However, achieving the more stringent Phase 3 target (30% reduction by 2025) still presents challenges. While approximately 14% of bulk carriers delivered in 2016 achieved an attained EEDI roughly 30% below the reference line, meeting the 2025 Phase 3 target nearly a decade in advance, the vast majority still fall short of this benchmark [8]. Overall, less than 1% of bulk carriers built between 2013-2017 were efficient enough to satisfy the Phase 3 requirement, meaning that most bulk carriers will require substantial improvements or innovation to meet the 2025 standard [8].

Achieving EEDI compliance requires a comprehensive approach including various design optimization strategies and the implementation of innovative energy-efficient technologies. These technologies can be categorized based on their impact on the ship's energy system [9]: Category A technologies directly affect the ship's power-speed curve through hydrodynamic improvements; Category B technologies reduce propulsion power requirements at given speeds without generating electrical energy (such as air lubrication systems and wind-assisted propulsion); and Category C technologies enable onboard electrical energy generation (including waste heat recovery systems and photovoltaic cells). The selection and implementation of appropriate technologies depend on vessel type, operational profile, and economic considerations [9].

The maritime industry is in need of innovative solutions to address these environmental challenges and improve operational efficiency. Recent research has explored integrated propulsion systems combining alternative fuels with renewable energy technologies, particularly focusing on Flettner rotor assistance for LNG carriers to achieve significant reductions in fuel consumption and emissions [10]. Economic analysis reveals that transitioning to dual fuel diesel engine-Flettner rotor (DFE-FR) systems offers the most environmentally friendly option, with a 9.85% reduction in levelized energy cost compared to traditional diesel engine systems [10]. At the same time, the development of novel monitoring tools has become necessary for evaluating energy efficiency in merchant ships, particularly for shipping companies that lack resources for complex IT solutions [11]. These tools consolidate essential operational data to facilitate continuous monitoring of ship efficiency while considering both internal and external factors, providing practical frameworks for compliance with evolving climate regulations such as the Carbon Intensity Indicator (CII) [11]. Furthermore, the application of advanced machine learning techniques, including Random Forests and Extreme Gradient Boosting algorithms, has shown remarkable success in predicting fuel consumption of ship main engines, achieving high accuracy [12].

This paper presents a comprehensive analysis of EEDI compliance for a 38,400 DWT self-unloading bulk carrier designed at 3. Maj Shipyard, Rijeka [13]. The vessel, intended to operate in Sulphur Emission Control Areas (SECA) zones with the latest environmental standards, features a single-screw configuration powered by a 7 M 43 C main engine (7,000 kW MCR) manufactured by MAK (Caterpillar Motoren GmbH & Co. KG), auxiliary generators, and a shaft generator system [13]. The preliminary EEDI calculation, conducted according to MEPC.245(66) guidelines [14], revealed that the vessel's initial design yielded an attained EEDI of 5.866 g(CO₂)/t·nm, exceeding the required value of 5.63 g(CO₂)/t·nm for Phase 1 implementation. This non-compliance required the further research of optimization strategies, particularly focusing on the implementation of air lubrication technology [15] as a viable solution for achieving the required energy efficiency standards while maintaining operational performance and economic viability.

2. Materials and methods

2.1. Vessel specifications and design parameters

The analysis was conducted on a self-unloading bulk carrier during the design phase at 3. Maj Shipyard, Rijeka, Croatia. The vessel specifications were obtained from the shipyard's technical documentation and preliminary design calculations, also presented in Table 1.

Table 1. Principal dimensions and specifications of the analyzed vessel [13]

Parameter	Value
Length overall (LOA)	190.00 m
Length between perpendiculars (LPP)	182.00 m
Beam	29.00 m
Depth	16.50 m
Summer draft	10.80 m
Deadweight (DWT)	38,400 t
Cargo hold capacity	28,000 m ³
Main engine type	MaK 7 M 43 C
MCR	7,000 kW @ 500-514 rpm
Number of cylinders	7
Cylinder bore	430 mm
Specific fuel consumption (75% MCR)	177 g/kWh
Shaft generator capacity	2,300 kW
Auxiliary generators	2 × 2,100 kW

The propulsion system configuration included a single-screw arrangement with controllable pitch propeller (CPP) driven through a single-stage reduction gearbox. The vessel features a typical bulk carrier configuration with seven cargo holds, a continuous main deck with watertight hatch covers, and accommodation superstructure positioned aft above the engine room, as illustrated in Figure 1.

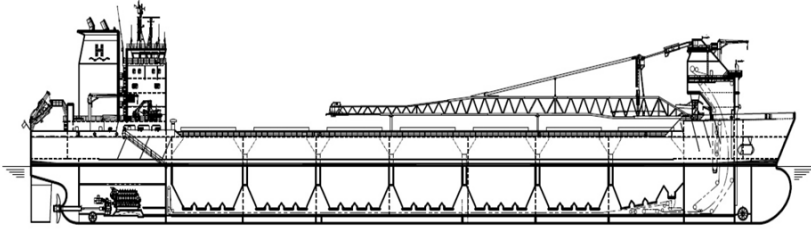


Figure 1. General arrangement profile of the analyzed vessel [13]

2.2. EEDI calculation methodology

The Energy Efficiency Design Index calculation followed the guidelines established in MEPC.245(66) [4,6], which superseded MEPC.212(63) with updated calculation procedures. The EEDI formula employed was [3]:

$$\begin{aligned}
 \text{EEDI} = & \frac{\left(\prod_{j=1}^M f_j\right) \left(\sum_{i=1}^{n_{\text{ME}}} C_{\text{FME}(i)} \cdot \text{SFC}_{\text{ME}(i)} \cdot P_{\text{ME}(i)}\right) + \left(P_{\text{AE}} \cdot C_{\text{FAE}} \cdot \text{SFC}_{\text{AE}}\right)}{f_i \cdot f_c \cdot f_j \cdot \text{capacity} \cdot V_{\text{ref}} \cdot f_w} \\
 & + \frac{\left(\left(\prod_{j=1}^M f_j \cdot \sum_{i=1}^{n_{\text{PTI}}} P_{\text{PTI}(i)} - \sum_{i=1}^{n_{\text{eff}}} f_{\text{eff}(i)} \cdot P_{\text{AEff}(i)}\right) \cdot C_{\text{FAE}} \cdot \text{SFC}_{\text{AE}}\right)}{f_i \cdot f_c \cdot f_j \cdot \text{capacity} \cdot V_{\text{ref}} \cdot f_w} \\
 & - \frac{\left(\sum_{i=1}^{n_{\text{eff}}} f_{\text{eff}(i)} \cdot P_{\text{eff}(i)} \cdot C_{\text{FME}} \cdot \text{SFC}_{\text{FME}}\right)}{f_i \cdot f_c \cdot f_j \cdot \text{capacity} \cdot V_{\text{ref}} \cdot f_w} \quad (1)
 \end{aligned}$$

The attained EEDI represents the ratio of total CO₂ emissions from main and auxiliary engines to the transport work, expressed as grams of CO₂ per ton-nautical mile. The calculation methodology accounts for all significant energy consumers onboard, including main propulsion, auxiliary power generation, and any energy-saving devices or innovative technologies that may be installed [16]. The calculation also includes multiple correction and adjustment factors such as the capacity factor (f_i) which accounts for any voluntary structural deadweight limitations; the cubic capacity correction factor (f_c) which adjusts for vessels where cargo is carried by volume rather than weight; weather factor (f_w) representing the decrease in speed attributable to representative sea conditions; and design features factor (f_j) which corrects for ship-specific structural or design constraints. For the present vessel, it is adopted $f_i = f_c = f_j$

= 1.0 and $f_w = 1.0$, as no special corrections were applicable.

For the main engine power (P_{ME}), 75 % of the installed MCR was used after deducting shaft generator power, following the provision that the power reduction from shaft generators should not exceed the total auxiliary power (P_{AE}). The power calculation followed the formula [4]:

$$\sum_{i=1}^{nME} P_{ME(i)} = 0,75 \times \left(\sum MCR_{ME(i)} - \sum P_{PTO(i)} \right) \quad (2)$$

with the constraint:

$$0,75 \times \sum P_{PTO(i)} \leq P_{AE} \quad (3)$$

2.3. Fuel characteristics and emission factors

Specific fuel consumption (SFC) values were obtained from the engine manufacturer's technical specifications and verified against the NOx technical file requirements. For the main engine, the MaK 7 M 43 C demonstrated an SFCME of 177 g/kWh when operating at 75% MCR, which represents the standard EEDI calculation point as specified in MEPC.245(66). This value reflects optimization for the engine's typical operational profile in bulk carrier service, where engines rarely operate at maximum continuous rating during normal voyages. Both SFC values incorporate tolerance margins specified by the manufacturer and have been corrected to ISO 3046-1 reference conditions (ambient temperature 25°C, relative humidity 30%, and barometric pressure 100 kPa) [3,4].

The carbon conversion factor (C_F) for Heavy Fuel Oil was established as 3.114 t-CO₂/t-fuel, derived from the carbon content of 0.8493 specified in ISO 8217 for marine residual fuels grades RME through RMK. This value represents the stoichiometric conversion of fuel carbon to CO₂ during combustion, accounting for the typical elemental composition of heavy marine fuels including trace sulphur and nitrogen compounds. The same C_F value was applied for both main and auxiliary engines as both systems were designed to operate on the same fuel grade, though provisions for Marine Gas Oil (MGO) operation with C_F of 3.206 were included for SECA zone compliance. The values of the C_F factor, dependant on fuel type, are shown in Table 2.

The reference speed (V_{ref}) determination followed the methodology outlined in ISO 15016:2015, which provides standardized procedures for converting between trial and service conditions. Power-speed curves were initially derived from the shipyard's computational fluid dynamics (CFD) analysis using the proprietary "Ship Designer" software package, which incorporated hull form optimization algorithms and resistance prediction methods based on the Holtrop-Mennen regression analysis.

Table 2. Marine fuel types and their carbon conversion factors according to IMO guidelines [6]

Fuel Type	Reference Standard	Carbon Content	CF (t-CO ₂ /t-fuel)
Marine Diesel/Gas Oil	ISO 8217 Grades DMX to DMB	0.8744	3.206
Light Fuel Oil (LFO)	ISO 8217 Grades RMA to RMD	0.8594	3.151
Heavy Fuel Oil (HFO)	ISO 8217 Grades RME to RMK	0.8493	3.114
Liquefied Petroleum Gas (LPG) - Propane	Propane	0.8182	3.000
Liquefied Petroleum Gas (LPG) - Butane	Butane	0.8264	3.030
Liquefied Natural Gas (LNG)	Methane	0.7500	2.750

Note: Carbon conversion factors (CF) represent the stoichiometric conversion of fuel carbon content to CO₂ emissions during combustion, as specified in MEPC.245(66).

The preliminary analysis indicated a required brake power of 4,918 kW to achieve 13 knots at design draft, accounting for hull fouling margin, weather allowance, and engine degradation factors. The relationship between trial conditions (typically conducted in ballast condition) and design conditions (at full load draft) was established through the power ratio correction factor [6]:

$$\alpha_p = \frac{P_{\text{trial},P}}{P_{\text{trial},S}} \quad (4)$$

where $P_{\text{trial},P}$ represents the power predicted from basin model tests extrapolated to full scale, and $P_{\text{trial},S}$ notes the actual measured shaft power during sea trials. This correction methodology ensures that the reference speed used in EEDI calculations accurately reflects the vessel's performance capability at the design loading condition rather than the lighter trial condition.

2.4 Required EEDI determination

The required EEDI represents the maximum allowable value of CO₂ emissions per transport work for a specific vessel type and size category, serving as the regulatory benchmark against which the attained EEDI must be compared. This value

is determined through a systematic approach that combines a baseline reference value with progressive reduction factors designed to drive continuous improvement in fleet efficiency over time.

The required EEDI calculation follows the formula established in MEPC.203(62):

$$\text{Required EEDI} = \left(1 - \frac{X}{100}\right) \times \text{EEDI Reference Line Value} \quad (5)$$

where X represents the reduction factor that increases progressively across implementation phases, and the reference line value is calculated using ship-type-specific regression parameters derived from the existing fleet's performance data collected during the IMO's comprehensive study of global shipping emissions.

For bulk carriers, the reference line value is determined by:

$$\text{EEDI Reference Line} = 961.79 \times \text{DWT}^{-0.477} \quad (6)$$

These parameters ($a = 961.79$, $c = 0.477$) were established through statistical analysis of the existing bulk carrier fleet, representing the average efficiency of vessels built between 1999 and 2009. The negative exponent reflects the economy of scale inherent in ship design, where larger vessels typically demonstrate better efficiency per ton-mile of cargo transported [7].

The IMO established a phased implementation approach with progressively stringent reduction factors to allow the industry adequate time for technological development and fleet renewal. For bulk carriers $\geq 20,000$ DWT, the reduction schedule specified in Table 3 applies, with Phase 0 (2013-2014) serving as the baseline period with no required reduction, followed by 10% reduction in Phase 1 (2015-2019), 20% in Phase 2 (2020-2024), and 30% in Phase 3 (from 2025 onwards). For bulk carriers between 10,000-20,000 DWT, the regulation provides flexibility with reduction ranges (0-10%, 0-20%, 0-30%) to account for technical constraints in smaller vessel designs [7,17].

Table 3. EEDI reduction factors for bulk carriers by size category and implementation phase [17]

Ship Type	Size (DWT)	Phase 0	Phase 1	Phase 2	Phase 3
Bulk Carrier	20,000 and above	0%	10%	20%	30%
Bulk Carrier	10,000-20,000	N/A	0-10%*	0-20%*	0-30%*

2.5. Air lubrication system parameters

Among available innovative energy efficiency technologies, air lubrication was selected for optimization analysis due to its proven effectiveness on vessels with high block coefficients and friction-dominated resistance profiles. The technology operates on a simple principle: injecting compressed air beneath the hull creates a thin boundary layer that fundamentally alters the fluid dynamics at the hull-water interface, replacing liquid-solid friction with substantially lower gas-solid friction. For the optimization analysis, the air lubrication parameters shown in Table 4 were applied based on empirical data. Several empirical approaches exist for estimating air lubrication drag reduction, including flat plate boundary layer models, CFD-based two-phase flow simulations, and regression models derived from full-scale trials. The formulation from [15] was adopted here because it explicitly accounts for the main parameters which control the system performance, namely the air-covered surface ratio, local drag reduction efficiency, and compressor power penalty while remaining compliant for preliminary design-stage analysis.

Table 4. Air lubrication system parameters [15]

Parameter	Symbol	Value	Basis
Air-covered/wetted surface ratio	AAC/Awet	0.4	Hull form analysis
Drag reduction on air-lubricated areas	%DR	80%	Model test data
Compressor power	P_{comp}	280 kW	4% of MCR
Propulsion efficiency	η_{prop}	0.75	Design value
Generator efficiency	η_{gen}	0.90	Manufacturer data
Availability factor	f_{eff}	1.0	Continuous operation

The theoretical framework for quantifying air lubrication benefits derives from the Great Lakes Maritime Research Institute studies [15], which established the relationship between power savings and system parameters:

$$\frac{\%E}{100} \approx f_{FD} \frac{A_{AC}}{A_{wet}} \left(\frac{\%D_R}{100} \right) - \frac{P_{comp}}{P_E} \cdot \frac{\eta_{prop}}{\eta_{gen}} \quad (7)$$

where $\frac{\%E}{100}$ is the the percentage reduction in required propulsion power achieved through the air lubrication system and f_{FD} is the proportion of frictional resistance to total hull resistance. The relationship $\frac{A_{AC}}{A_{wet}}$ is the ratio between hull surface area covered by the air layer and total wetted surface area, while $\left(\frac{\%D_R}{100} \right)$ notes the drag reduction

percentage on air-lubricated surfaces. The compressor power requirement is noted by P_{comp} , and it is typically estimated as 3-4% of main engine power based on full-scale trials [18]. The effective propulsion power is noted by P_E , the propulsive efficiency by η_{prop} and the generator efficiency for compressor supply by η_{gen} .

The friction resistance contribution (f_{FD}) depends on the vessel's speed-length relationship, expressed through the Froude number:

$$F_R = \frac{v}{\sqrt{g \cdot L}} \quad (8)$$

where v is the vessel speed of 6.72 m/s at service conditions, g represents the gravitational acceleration constant of 9.81 m/s², L denotes the waterline length of 186 m, yielding a Froude number F_R of 0.157.

2.6. Validation and verification process

The EEDI verification methodology followed the two-phase process described in in [4] as amended by MEPC.261(68), ensuring compliance with international standards for energy efficiency certification. This comprehensive approach included both design-stage documentation review and performance validation procedures, with clearly defined requirements for each phase. The common practice of the complete verification process is shown in Figure 2.

The preliminary verification phase, conducted during the design stage, requires the compilation of an EEDI Technical File containing all calculation parameters and supporting documentation. This file includes detailed specifications of the ship's propulsion, auxiliary systems, and energy-saving devices.

Power-speed relationship validation also forms a component of the verification process. The methodology requires correlation between multiple data sources: computational fluid dynamics predictions from the design phase, towing tank test results extrapolated to full scale using ITTC 1978 correlation methods, and manufacturer's performance guarantees. These predictions are then subject to correction procedures accounting for the difference between calm water trial conditions and the weather conditions represented by f_w in the EEDI equation [4,15].

The final verification phase requirements include sea trial protocols following ITTC Recommended Procedure 7.5-04-01-01.2 for speed and power measurements. Trial conditions monitoring includes continuous recording of wind speed and direction, wave height and period, current velocity, and water depth to ensure compliance with acceptable trial conditions. The ship's loading condition, trim, and draft are always documented before and after trials in order to verify consistency.

For uncertainty quantification, the verification process incorporates sensitivity analyses on key parameters affecting EEDI calculations. Reference speed variations of

± 0.1 knots were evaluated to account for measurement uncertainty and environmental corrections. Specific fuel consumption tolerances of $\pm 2\%$ reflected manufacturer's definite margins and measurement accuracy limits [8].

The calculation framework in this paper used standardized computation templates aligned with IMO guidelines, with checks for parameter consistency and range validation. All correction factors, such as the weather factor (f_w), the capacity factor (f_i), cubic capacity correction (f_c), and special design features factor (f_j), were systematically evaluated against regulatory criteria.

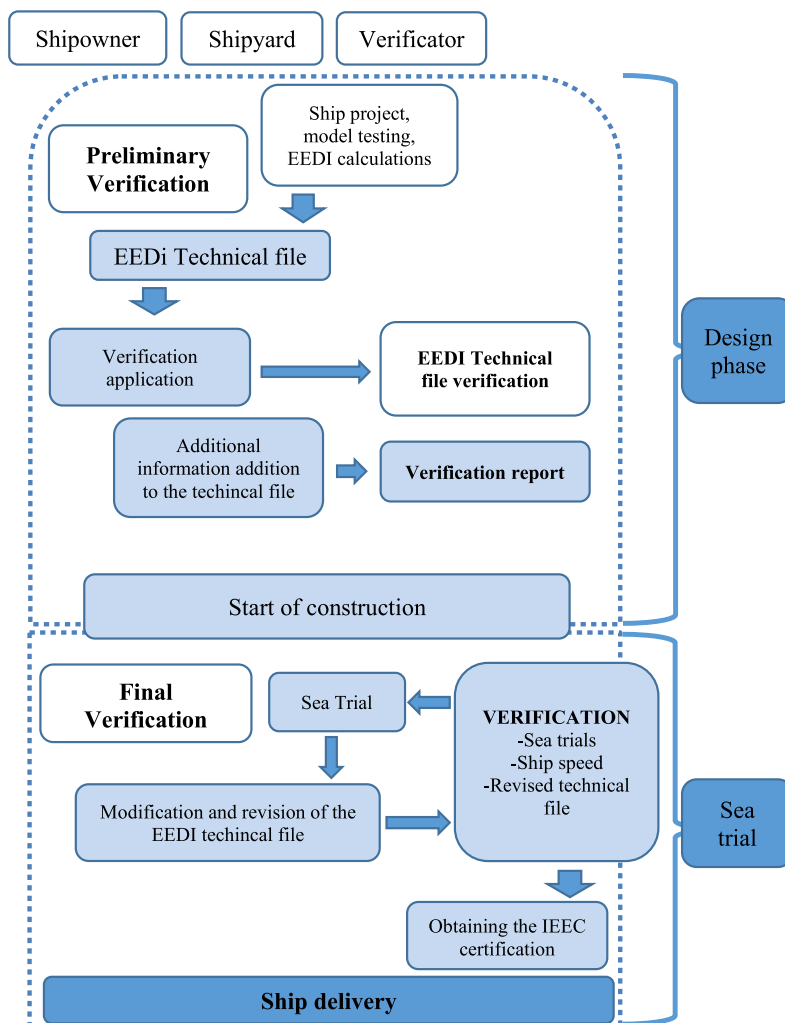


Figure 2. The schematic illustration of the complete verification process

The validation methodology extends beyond regulatory compliance to comprehend operational performance prediction. This includes establishing correlations between EEDI calculation conditions (75% MCR at design draft) and expected service performance across the operational range, enabling realistic assessment of the ship's environmental performance throughout its exploitation rather than solely at the regulatory checkpoint [7].

3. Results

Based on comprehensive data obtained from the shipyard and engine manufacturer specifications, the vessel's attained EEDI was calculated following IMO guidelines [3,4,9,17]. The vessel's specifications, shown in Table 1, were used for the analysis. Operating at 75% MCR, the effective power was estimated to be 4,987.5 kW after accounting for the shaft generator load. The auxiliary power requirement was determined to be 350 kW, calculated according to IMO regulations for vessels with total propulsion power below 10,000 kW [17]. Due to regulatory constraints in MARPOL Annex VI requiring that the power reduction from the shaft generator cannot exceed the total auxiliary power, the actual 2,300 kW shaft generator capacity was limited to 350 kW for calculation purposes. This limitation significantly impacts the EEDI calculation methodology, as the full benefit of the installed shaft generator cannot be recognized [19].

The propulsion system utilizes Heavy Fuel Oil (HFO) conforming to ISO 8217 specifications, with a carbon content of 0.8493 and a carbon conversion factor of 3.114 t-CO₂/t-fuel [17,19]. The main engine operates at a specific fuel consumption of 177 g/kWh at 75% MCR, while the auxiliary engines consume 182 g/kWh at 50% load. Through power-speed curve analysis derived from computational fluid dynamics simulations, a reference speed of 13.06 knots was established for the specified power output. With the vessel's capacity defined as 100% of its deadweight tonnage per bulk carrier regulations, the attained EEDI was calculated using Eq. (1) to be 5.866 g(CO₂)/t·nm.

The required EEDI for this vessel class is established at 5.63 g(CO₂)/t·nm, incorporating a 10% reduction factor applicable to Phase 1 vessels constructed between 2015 and 2019. The baseline EEDI of 6.2568 g(CO₂)/t·nm was calculated using the standard formula for bulk carriers with parameters $a=961.79$, $b=DWT$, and $c=0.477$. Figure 3 presents the comparison between the vessel's attained EEDI and the required threshold, revealing that the attained value exceeded requirements by approximately 4.2%, necessitating design optimization to achieve regulatory compliance.

The vessel's initial non-compliance comes from several design constraints inherent to self-unloading bulk carriers. The full-form hull, characterized by a high block coefficient essential for maximizing cargo capacity, creates substantial hydrodynamic resistance requiring significant propulsion power. Additionally, the absence of energy-saving technologies and the regulatory calculation methodology that limits recognition

of the shaft generator’s full capacity compound the challenge of achieving EEDI compliance.

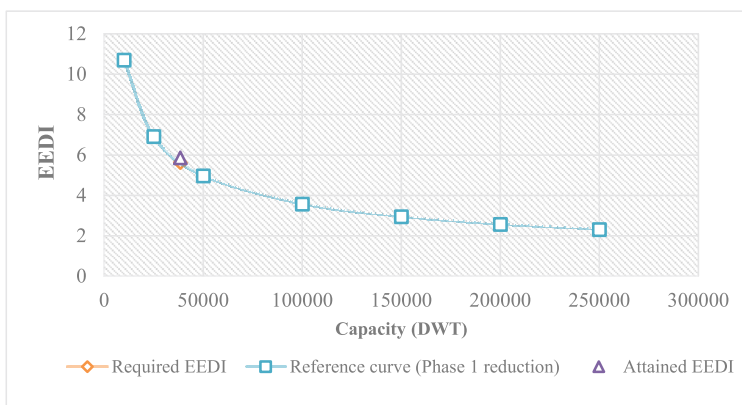


Figure 3. Bar chart comparing Attained EEDI (5.866) vs Required EEDI (5.63) with clear indication of non-compliance.

A comprehensive evaluation of available energy efficiency technologies was conducted, categorizing options according to IMO’s framework for innovative technologies (Figure 4).

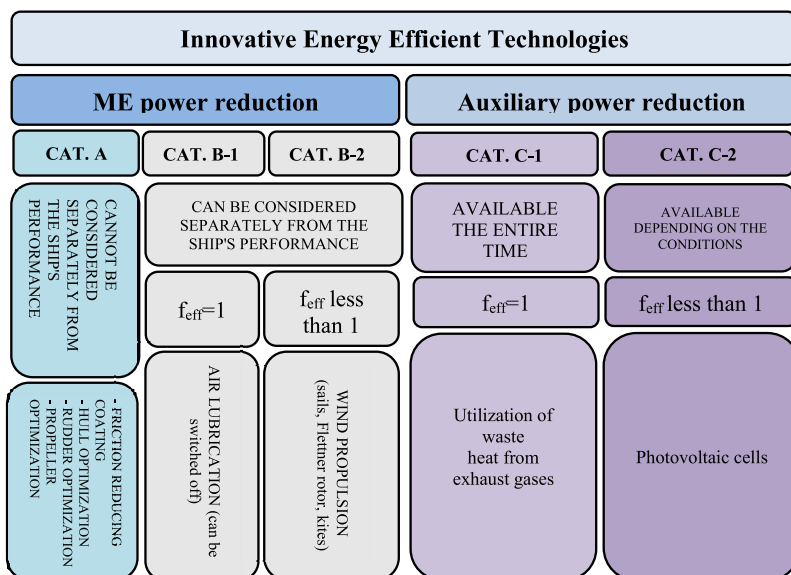


Figure 4. Flowchart showing categorization of innovative energy efficiency technologies (Categories A, B1, B2, C1, C2) [9]

Category A technologies, which directly influence the ship's power-speed curve through hydrodynamic improvements, were considered but ultimately excluded.

Based on the technology assessment, air lubrication emerged as the optimal solution for achieving EEDI compliance. This system operates by injecting compressed air through outlets in the vessel's flat bottom, creating a stable air layer that reduces frictional resistance between the hull and water. This technology is particularly suitable for vessels with low Froude numbers ($Fr < 0.3$) and large flat bottom areas, characteristics that align well with the chosen bulk carrier design.

The air lubrication system analysis drew upon empirical data [18] vessels of similar configuration. The vessel's Froude number of 0.157, calculated at the design speed of 13.06 knots, indicates operation in a regime where frictional resistance dominates. Analysis of the resistance components revealed that friction accounts for approximately 60% of total resistance, providing substantial potential for improvement through friction reduction technologies. Examination of the vessel's general arrangement revealed that approximately 40% of the wetted surface area (roughly 2,800 m²) consists of flat or near-flat bottom surfaces suitable for air cavity formation. This assessment considered the need to maintain clear water flow to the propeller and bow thrusters, excluding these regions from the air coverage area. Based on model test data and full-scale trials on comparable vessels, an 80% local friction reduction was assumed for air-lubricated surfaces, consistent with published results for well-designed systems operating at similar speeds.

At the design draft of 10.8 meters, the system must overcome approximately 1.1 bar gauge pressure, requiring an estimated 280 kW of compressor power (4% of main engine MCR). This power requirement accounts for pressure losses in the air distribution system, inefficiencies in the compressor train, and the need to maintain adequate air flow rates across varying operational conditions.

The net benefit calculation incorporated the complex interaction between power reduction and consumption. With a propulsion efficiency (η_{prop}) of 0.75 accounting for hull-propeller interaction and a generator efficiency (η_{gen}) of 0.90 for the electrical supply to the compressors, the analysis yielded a net power reduction of 13.1%. This translates to an effective power reduction of 365.46 kW after deducting the compressor power requirements, following IMO's prescribed methodology for calculating innovative technology contributions. The implementation requires installation of air injection chambers along the flat bottom, connected via a manifold system to redundant air compressors. Flow deflectors at the stern prevent air ingestion into the propeller, maintaining propulsive efficiency. The system's continuous availability ($f_{eff}=1$) ensures consistent EEDI benefits regardless of environmental conditions.

The main engine power reduction (P_{eff}) of 365.46 kW was applied according to IMO guidelines, while the auxiliary power increase (PAE_{eff}) of 287.9 kW accounted for the compressor electrical load. All correction factors (f_i, f_c, f_j, f_w) remained the same. The revised EEDI calculation yielded an attained value of 5.46 g(CO₂)/t-nm, representing a 6.9% reduction from the baseline configuration. Figure 5 illustrates

the comparison between the optimized attained EEDI and the required threshold, demonstrating successful compliance with a 3.0% margin. This improvement confirms that targeted application of a single, well-suited technology can achieve regulatory compliance without compromising operational capability or requiring extensive design modifications.

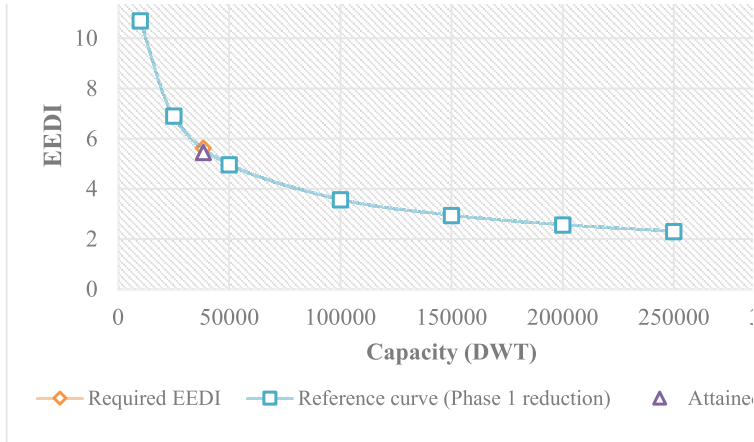


Figure 5. Bar chart comparing Original Attained EEDI (5.866), Optimized Attained EEDI (5.46), and Required EEDI (5.63).

Sensitivity analysis indicates that the compliance margin provides adequate tolerance for uncertainties in the preliminary estimates. Even if the air lubrication system achieves only 75% of the predicted effectiveness, the vessel would still marginally comply with Phase 1 requirements. However, looking ahead to Phase 2 (20% reduction) and Phase 3 (30% reduction) requirements, additional technologies will likely be necessary. It should be emphasized that these calculations rely on empirical correlations from similar vessels rather than model tests of the specific hull form under consideration. The actual air lubrication effectiveness depends on numerous factors including boundary layer characteristics, air injection rates, and operational profiles that can only be accurately determined through dedicated model testing and computational fluid dynamics analysis.

4. Discussion

The findings of this study highlight the well-known challenge facing the maritime industry between traditional vessel design practices optimized for cargo capacity and operational efficiency, and increasingly rigorous environmental regulations. The narrow margin by which the analysed bulk carrier failed initial EEDI compliance (4.2% exceedance) demonstrates that conventional design approaches, even when

incorporating standard energy-saving features like shaft generators, are no longer sufficient for meeting current environmental standards.

The successful application of air lubrication technology to achieve compliance reveals both opportunities and limitations in the current regulatory framework. While the 6.9% EEDI reduction achieved through this single technology proved adequate for Phase 1 compliance, the analysis exposes a fundamental issue: the regulatory calculation methodology often fails to recognize the full benefit of installed energy-saving equipment. The restriction limiting shaft generator credit to auxiliary power demand, despite the installation of a 2,300 kW unit, exemplifies how current regulations may inadvertently discourage certain efficiency investments. This suggests a need for regulatory refinement to better the comprehensive energy efficiency strategies rather than narrowly defined solutions.

The technology evaluation process undertaken here has broader implications for naval architecture practice as well. The systematic exclusion of multiple innovative technologies due to operational constraints specific to self-unloading bulk carriers underscores that EEDI compliance cannot be achieved through a one-size-fits-all approach. Technologies that might be optimal for other vessel types often prove impractical when cargo handling equipment and operational profiles are considered. This emphasizes the necessity of integrating EEDI considerations from the earliest design stages rather than treating compliance as an add-on requirement. With Phase 2 and Phase 3 compliance mandating 20% and 30% reductions respectively, single-technology solutions will likely prove insufficient. This progression suggests that the industry must move beyond incremental improvements toward more fundamental reconsiderations of vessel design. The traditional approach of maximizing cargo capacity through full hull forms may need to adhere to designs that balance transport efficiency with environmental performance from the outset.

5. Conclusions

This study demonstrated that a 38,400 DWT self-unloading bulk carrier initially failing EEDI Phase 1 requirements by 4.2% could achieve compliance through implementation of air lubrication technology, reducing the attained EEDI from 5.866 to 5.46 g(CO₂)/t·nm. While Phase 1 compliance has been met, achieving the more stringent Phase 2 and Phase 3 requirements will necessitate an additional 10-20% reduction in EEDI, presenting a substantial ongoing challenge for this vessel type. The analysis revealed that operational constraints specific to vessel types significantly limit technology options, while regulatory calculation methodologies may not fully credit installed efficiency measures, necessitating early integration of EEDI considerations in the design process.

However, the focus on CO₂ emissions through EEDI represents only one dimension of maritime environmental impact. The selection of air lubrication over alternative technologies was driven primarily by EEDI mathematics rather than holistic

environmental assessment. As regulations evolve to include methane slip, underwater noise, and other environmental concerns, the optimal technology mix may shift, potentially stranding investments in single-purpose solutions. This further emphasizes the apparent need for integrated environmental design approaches that consider multiple impact pathways simultaneously rather than optimizing for a single metric, ensuring that today's compliance solutions remain viable throughout the vessel's operational lifetime.

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