Evaluation of maritime industry compliance with existing environmental regulations – A benchmarking assessment from energy efficiency perspective

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Abstract. The present study provides an initial mapping process for the maritime industry from an energy and environmental perspective. The methodology follows a three-step evaluation process for assessing energy efficiency. At first, an initial categorization of all existing ship type and volume categories based the applied taxonomy within maritime transport sector is made. Secondly, two key energy performance indicators (EEXI & CII) are described and estimated for each individual vessel category. Lastly, an assessment between the examined KPIs values is performed in order to depict the compliance level of each vessel category with the existing environmental regulations set by the International Maritime Organization (IMO). The results of this paper aim to highlight the alignment of the existing vessel categories with the established environmental regulations and offer a starting point for decision-makers in maritime industry to adopt green shipping energy transition strategies, such as the usage of energy efficiency measures or green alternative fuels.

1 Introduction

The global maritime industry has made a firm commitment to achieving major decarbonisation actions (75% by 2050; compared to 2008) of international shipping and transportation by reducing greenhouse gas (GHG) emissions and establish a self-sustainable transportation ecosystem [1]. Over the past decade, the International Maritime Organization (IMO) has implemented various regulatory frameworks aimed at preventing environmental pollution, such as MARPOL Annexes [2, 3]. This study focuses on air pollution coming from operational ships, which is described in MARPOL Annex VI. Annex VI specifically addresses the prevention of air pollution from ships by applying crucial regulations and interventions in the maritime sector. Moreover, MARPOL Annex VI plays a crucial role in regulating and mitigating the impact of maritime activities on air quality and climate change, promoting a more environmentally sustainable shipping industry [4].

One of the initial major interventions of IMO on this path was the mandatory measurement of the Energy Efficiency Design Index (EEDI). The EEDI shows the minimum energy performance requirements that need to be met by a new-built vessel with specific technical characteristics [5]. Previous studies have indicated a relationship between EEDI and the amount of fuel burned, which in turn correlates with the quantity of air pollutants emitted. Continuing on this path, the 76th edition of the IMO's Marine Environment Protection Committee (MEPC 76) has recently approved technical and operational measures to decrease carbon emissions intensity in international maritime transport [6]. The latest mandatory measures include the implementation of the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII).

These two metrics quantify the carbon dioxide emissions per unit of transport work. Their main difference is that EEXI relies on the reference values of deadweight (DWT) and travelling speed (V_{ref}), which are vessel technical specifications; and CII relies on total annual voyage distance recorded. Both indices are quantified as carbon dioxide emissions per unit of transport work; grams of CO_2 per ton-knot for EEXI and grams of CO_2 per ton-mile for CII respectively. Plus, they show the minimum energy performance requirements that need to be met by an existing ship with specific technical characteristics [7, 8]. These environmental standards are effective from 1st January 2023 and is obligated in order to receive the International Energy Efficiency Certificate (IEEC) and/or the International Air Pollution Prevention Certificate (IAPPC) [8].

According to the latest report from DNV [9], 80% of the current global operational maritime fleet need to comply with the EEXI regulations and they will require to invest in immediate energy efficiency measures to reach the required level of environmental standards defined within the MARPOL Annex VI. Similarly, ABS report during 2020 created an initial global benchmarking of the current maritime industry status on an environmental perspective. In more detail, the results

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shown that approx. 20% of the tanker, 46% of the bulker and 25% of the container operational fleet are struggling to reach the required EEXI factor [10].

Based on the initial benchmarking efforts made recently, this paper contributes on establishing a preliminary benchmark tool that could provide valuable insights on the maritime transport's environmental impact in international level, highlight the compliance level of individual ship markets with the existing environmental regulations in effect by MARPOL Annex VI. Until recently (July 2023) and to the best of our knowledge, similar publications lack the holistic benchmarking approach of energy efficiency rates per ship type and category based on their capacity and operating fuel mix. Thus, the results of the present work make a first attempt to cover this gap by proposing an aggregated benchmarking evaluation for the maritime industry. Additionally, this comparative assessment will point out which ship markets require immediate green energy transition actions in order to reach the IMO's long-term carbon neutrality target for 2050.

The remainder of this paper is structured as follows. Section 2 introduces a three-step evaluation process for assessing energy efficiency in global ship markets according to the established ship classifications. In more detail, a preliminary vessel categorization based on specific technical characteristics is made and a detailed description of EEXI & CII key energy performance indicators are provided. Section 3 presents the results of the comparative analysis and evaluates the current energy performance of each vessel category. Section 4 presents the outcomes and the conclusions of this study.

2 Proposed benchmarking methodology

This paper follows a three-step evaluation process for assessing energy efficiency. More specifically, the first step maps all individual vessel classifications operating in commercial maritime industry sector and categorizes them according to key technical attributes (ship type & capacity). Then, two key energy performance indicators (KPIs) are described and estimated for each individual vessel category as previously defined; EEXI and CII. During the last step, an assessment between the examined KPIs values is performed to depict the compliance level of each ship type classification with their respective energy efficiency target values. A comparative analysis is made between required (theoretical) values of the examined KPIs (according to the guidelines provided by MARPOL Annex VI amendments) and the attained values coming from secondary data available from open source data repositories, such as the IMO Data Collection System (IMO DCS) and the EU's Monitoring, Reporting, Verification (MRV) database. The respective results for each ship type and volume category are presented in a structured matrix format and figures.

2.1 Classification of maritime vessels

Firstly, a classification of the existing maritime vessels is initiated. This process is necessary to specify the different categories taking into account the shipping market trends, needs and utilization use cases. Accordingly, for each vessel type (i.e. containership, tankers, etc.), the categorization was performed based upon the vessel's capacity (deadweight; referred as DWT from now on) sharing similar technical and operational characteristics. The compilation of relevant open access data sources used in this study (IMO DCS & EU MRV database) created the list of categories illustrated in Table 1.

Table 1. Maritime vessel classifications included in the analysis according to ship type and deadweight (in tons).

Category Name	Ship Type	Deadweight Min.	Deadweight Max.
VLBC	Bulk carrier	279,000	500,000
Capesize		200,000	279,000
Supramax & Neopanamax		65,000	200,000
Handy & Handymax		20,000	65,000
Small bulk		10,000	20,000
Chinamax & Baltimax	Container Ship	200,000	2,000,000
Capesize		120,000	200,000
Neopanamax		80,000	120,000
Handymax & Panamax		40,000	80,000
Seawaymax & Handysize		15,000	40,000
Small Handysize		10,000	15,000
VLGC	Gas Carrier	65,000	500,000
Semi-Pressurized & Semi/Fully Refrigerated		50,000	65,000
Semi/Fully Pressurised Ships		15,000	50,000
Fully Pressurised Ships		10,000	15,000
MD, LRI, LRII	General Cargo	20,000	100,000
SRII		15,000	20,000
SR		3,000	15,000
VLNGC	LNG Carrier	100,000	500,000
Medium LNG carriers		65,000	100,000
Ethane carriers		10,000	65,000
VLCC & ULCC	Oil & Chemical Tanker	200,000	2,000,000
Aframax & Suezmax		20,000	200,000
Handysize		4,000	20,000

In this paper, the reference EEXI and CII will be examined independently for each ship category presented in Table 1 in order to easily distinguish and monitor the vessel's current energy efficiency operational profiles. However, vessel's capacity (DWT) is just one of the key variables that influence the operational profiles from an energy and environmental perspective. The other key criteria to determine the energy efficiency measures is the fuel type(s) used onboard in a yearly basis according to the ship operational profiles and installed engines. As this study relies on existing recorded data from IMO DCS & EU MRV databases; plus, key insights from DNV & ABS reports, the majority of ship categories used the same fuel mix (marine diesel oil together with very low Sulphur fuel oil; MDO & VLSFO). In this context, during this study all of the examined use cases already comply with the basic restrictions of SOx and NOx emission tiers enforced by MARPOL and fall under the same energy content scope. Similarly, all crucial parameters needed to calculate the two energy KPIs in this study are aligned according to the ship category (i.e. engines nominal power, reference speed, etc.) and analysis of secondary data used.

Once the ship categorization is completed, the estimation of the two energy KPIs is performed. These two values are calculated for each ship category independently and are presented accordingly. In more detail, the EEXI and CII calculations are applied to the following ship categories above 5000 gross tonnage (GT): (i) bulk carriers, (ii) containerships, (iii) gas carriers, (iv) general cargo ships, (v) liquefied natural gas-LNG carriers; and (vi) tankers (over 400 GT) engaged in international voyages.

2.2 EEXI

The Energy Efficiency Existing Ship Index (EEXI) is an overall energy efficiency index that measures CO_2 emissions per transport work, purely considering the ship's design parameters. EEXI is similar to EEDI however EEDI is applied on new built vessels and EEXI on existing ones. The EEXI determines the standard CO_2 emissions based on the installed engine power, transport capacity (DWT) and voyage speed (V_{ref}). It is applied to all ships over 400 gross tonnage (GT). The intended value that an individual ship should reach is the Attained EEXI and is calculated as shown in the Figure 1 below. Accordingly, this is compared with a reference value for each ship category (Required EEXI) based on the IMO guidelines [4-5, 8, 12-14].

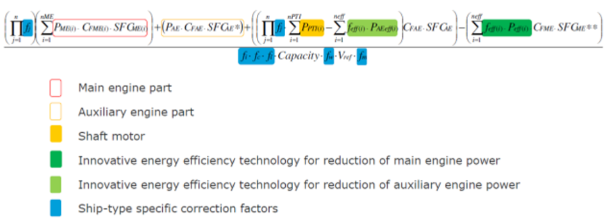

Fig. 1. EEXI mathematical formula [8, 13].

In the equation above (Figure 1), the following vessel design and emission parameters are included:

• P_{ME} &P_{AE} is the nominal power of main engine and auxiliary engine respectively (considered equal to 75% of nominal power during operational stages).

• P_{PTI} is 75% of installed power for each energy consuming device.

• P_{eff} is 75% of the reduction in engine power (kW) due to innovative energy efficiency engineering technologies.

• n_{ME} & n_{AE} is the number of main and auxiliary engines installed respectively.

• n_{eff} is the number of energy efficiency measures applied.

• V_{ref} is the speed (by design of the ship) in nautical miles per hour (knots) in the maximum loading condition, assuming deep water, calm sea and no wind.

• Capacity (in tons) is defined as the deadweight (DWT) for all ship categories examined in this study, except containerships which in that case equals to 70% of DWT.

• C_F is a non-dimensional emission conversion factor based on the carbon content of the fuel and gives the amount of CO_2 emitted from the combustion of a quantity of fuel (gram CO_2 per gram of fuel).

• SFC (Specific Fuel Consumption) (in g/kWh) is the Specific Fuel Consumption, i.e., the amount of fuel consumed by the engine per unit of energy delivered. It depends on the fuel type used and it is considered a constant value throughout a voyage.

Table 2. Reduction factors (in percentage) for the EEXI relative to the EEDI reference line [4-5, 8, 12-14].

Ship Type	Capacity (DWT)	Reduction factor (%)
Bulk carrier	200,000 DWT and above	15
	20,000-200,000 DWT	20
	10,000-20,000 DWT	0-20
Container Ship	200,000 DWT and above	50
	120,000-200,000 DWT	45
	80,000-120,000 DWT	35
	40,000-80,000 DWT	30
	15,000-40,000 DWT	20
	10,000-15,000 DWT	0-20
Gas Carrier	15,000 DWT and above	30
	10,000 - 15,000 DWT	20
	2,000 - 10,000 DWT	0-20
General Cargo	15,000 DWT and above	30
	3,000 - 15,000 DWT	0-30
LNG Carrier	10,000 DWT and above	30
Oil & Chemical Tanker	200,000 DWT and above	15
	20,000-200,000 DWT	20
	4,000-20,000 DWT	0-20

More specifically, the conditions that should be met based on the EEXI Technical File provided by IMO are described in the equations (1) and (2) below:

$$Attained\ EEXI \leq Required\ EEXI \quad (1)$$

$$Required\ EEXI = (1\text{-}Y/100) \times EEDI\ Reference\ value \quad (2)$$

Where Y is the reference reduction factor per ship type as shown in Table 2 below. The corresponding reference lines are provided in Table 3.

Table 3. EEDI reference line [5, 15].

Ship Type	Capacity (DWT)	Reference Line
Bulk carrier	>279,000 DWT	$961.79 \times DWT^{-0.477}$
	≤279,000 DWT	$961.79 \times 279{,}000^{-0.477}$
Container Ship	-	$174.22 \times DWT^{-0.201}$
Gas Carrier	-	$1120.00 \times DWT^{-0.456}$
General Cargo	-	$107.48 \times DWT^{-0.216}$
LNG Carrier	-	$2253.7 \times DWT^{-0.474}$
Oil & Chemical Tanker	-	$1218.80 \times DWT^{-0.488}$

2.3 CII

The Carbon Intensity Indicator, known and referred to by the acronym CII, is enforced to all cargo ships over 5000 gross tonnage (GT) and involved in international trades. CII is a measure of energy operational efficiency according to the actual annual fuel consumption recorded by the ship operator. The calculation of CII is performed annually, starting in 2023, based on the reported IMO Data Collection System [8] and its formulas (3) and (4) shown below:

$$Attained\ CII = \frac{\sum c_{ME} \cdot P_f \cdot SFC_{ME} + \sum c_{AE} \cdot P_f \cdot SFC_{AE} - \sum c_{Ess} \cdot P_{Ess} \cdot SFC_{Ess}}{Capacity \cdot D} \quad (3)$$

$$CII_{Ref} = a \times Capacity^{-c} \quad (4)$$

The units of score are the same as that for the EEXI, which is the annual CO_2 mass per unit of cargo carried certain distance; grams CO_2 per ton-nautical mile (gCO_2/t. Nm). Once the CII score is calculated, a rating label is given to the vessel between A (best case) to E (worst case). The rating levels are defined and calculated based on the CII guidelines provided by IMO as illustrated in Figure 2 below, according to which the lower assessment thresholds will become increasingly strict towards 2030 (20% reduction of required CII score by 2030). Each ship needs to achieve rating C or better and if a ship gets rated D or E for three consecutive years will be required to submit a corrective action plan to show how the required index (C or higher) will be achieved. This could be achieved with different short-term measures (i.e. engine power limitation, energy saving devices), medium-term (i.e. installation/retrofit of scrubbers) and long-term measures (i.e. alternative zero-carbon fuel usage, ship replacement) [4, 8].

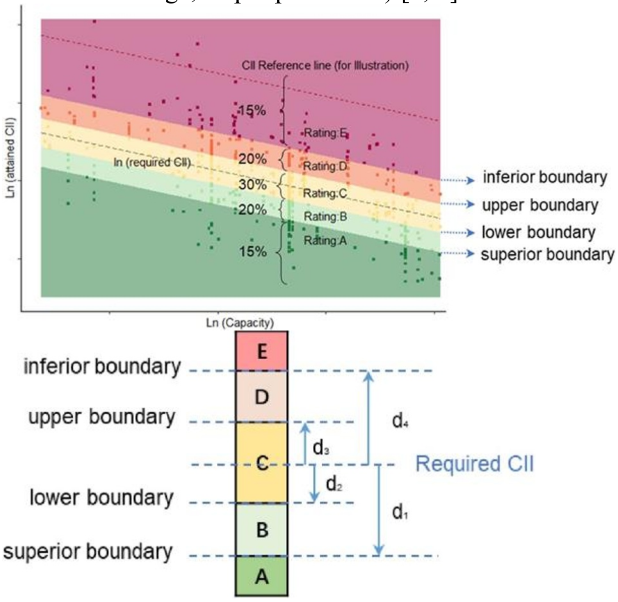

Fig. 2. CII energy efficiency performance rating scale [8]

So, the difference between EEXI and CII is a difference between theoretical amount of CO_2 a vessel might produces based on design versus the actual amount based on the fuel it has consumed. However, in both cases the same context is preserved, which is the Attained CII should be lower than the Required CII as stated in the equations (5) and (6) below, where z is the annual reduction factor of reference CII value.

$$Attained\ CII \leq CIIRef \quad (5)$$

$$Required\ CII = (1\text{-}Z/100) \times CIIRef \quad (6)$$

2.4 Parameters specification

As mentioned previously, the energy efficiency rates in operational level depend on several key parameters and variables, such as fuel types used, engine configurations, etc. Therefore, at this stage the specific values and assumptions for the key parameters introduced in this chapter (Chapter 2) need to be defined in order to have a clear path on the energy KPIs calculations and interpretation of results. In this paper, the below assumptions are made:

- C_F is equal to 3.114 for most diesel engines (using heavy fuel oil, low Sulphur fuel oil combinations or marine diesel oil).
- The optimal performance in main engines (P_{ME}) is operating at 75% of nominal power setting. Only for LNG carriers this value is set in 83%.

• The nominal power of main and aux. engines is altered for each ship category based upon the average values from the maritime vessel databases used in this study.
• As common standard in diesel engines that have insufficient performance testing reports, the specific fuel consumption (SFC) for main and aux. engines respectively are defined as SFC_{ME} =190 g/kWh and SFC_{AE} =220 g/kWh.
• Correction factors f are all equal to 1, as all ship categories are examined without taking into account any technological, regulatory and capacity limitations.
• Reference travelling speed (V_{ref}) is altered for each ship category based upon the average values from the maritime vessel databases used in this study.
• In the LNG Carriers ship type, the usage of primary fuel is MDO and secondary fuel is LNG (25% usage rate). The respective parameters that change, together with their corresponding values, are: C_F=2.75, P_{ME}=83%.

3 Assessment Results

In this chapter, the above-mentioned methodology is applied for a specific scenario and have been performed for all the ship types and categories as presented in Table 1. The results of these calculations are compared with energy efficiency operational data coming from (i) outsource open access databases (over 9,000 vessels) plus (ii) analysis results from other relevant studies performed on approx. 30,000 ships [3, 9-10]. In this context, the results provide an initial benchmarking of the operational global fleet per ship type from an environmental perspective, plus offer a key insight on the future actions that may be needed per ship category in order to comply with the environmental regulations defined by MARPOL Annex VI. Nevertheless, several parameters specifications are defined and presented in section 2.4, which formulate the scenario examined in this study. The investigated scenario considered the following assumptions:
• Due to the data sources and accessibility on primary data sources, the deviation between the attained and required values for both EEXI and CII are significant.
• All ship types used the same fuel mix (MDO & VLSFO). This fuel mix has been selected as the majority of ship types in the available data used the specific fuel mix; plus, this fuel mix satisfies the established NOx and Sox concentration environmental regulations when sailing inside emission control area (ECA) zones. However, in reality several ship categories (i.e. LNG carriers) use alternate fuel such as LNG, ethanol, etc. in operational level, which highly affects the energy efficiency values.
• Additional technical characteristics such as ship age and equipment degradation shall be considered in future studies as they could rearrange in several use cases the energy efficiency measures onboard (i.e. replacing engine or retrofit scrubber).
• No additional short-term energy efficiency techniques such engine power limitation or speed optimization have been examined in order to evaluate all ship types under the same context and provide lower uncertainty levels in the calculation method.
• Ship reference speed (V_{ref}) and distance travelled (in nautical miles) for each ship category is estimated via considering the average values of the respective categories from available data analysis.
• EEXI reference values have been set according to the latest guidelines provided by IMO. However, these are subject to change by IMO during 2027 [4-5, 8-9, 15]. In the same principle, CII annual reduction factor is set to 2.5% (starting 5% in 2023 with maximum of 20% by 2030).

According to these aspects, the respective Required EEXI and Required CII values for the baseline year 2023 have been estimated and presented in Table 4. These values are aggregated per ship type and analyzed in the following chapter (Chapter 4) in comparison with the available data used.

Table 4. Required EEXI & CII values per ship category

Category Name	Ship Type	DWT range	Req. EEXI	Req. CII
VLBC	Bulk carrier	279,000 - 500,000	2.062	1.844
Capesize		200,000 - 279,000	2.421 - 2.062	2.274 – 1.844
Supramax & Neopanamax		65,000 - 200,000	3.894 - 2.421	4.574 - 2.274
Handy & Handymax		20,000 - 65,000	7.687 - 3.894	9.522 - 4.574
Small bulk		10,000 - 20,000	10.698 - 7.687	12.495 - 9.522
Chinamax & Baltimax	Container Ship	200,000 - 2,000,000	1.736 – 0.513	4.820 – 1.563
Capesize		120,000 - 200,000	2.632 - 1.736	5.276 - 4.820
Neopanamax		80,000 - 120,000	3.455 - 2.632	6.433 - 5.276
Handymax & Panamax		40,000 - 80,000	5.537 - 3.455	9.029- 6.433
Seawaymax & Handysize		15,000 - 40,000	10.053 - 5.537	14.585 - 9.029
Small Handysize		10,000 - 15,000	12.253 -10.053	17.784 - 14.585
VLGC	Gas Carrier	65,000 - 500,000	5.008 - 1.975	6.471 – 0.218
Semi-Pressurized & Semi/Fully Refrigerated		50,000 - 65,000	5.644 - 5.008	7.652 - 6.471
Semi/Fully Pressurised Ships		15,000 - 50,000	11.169 -5.644	16.516 -7.652
Fully Pressurised Ships		10,000 - 15,000	13.437 -11.169	21.4 - 16.516
MD, LRI, LRII	General Cargo	20,000 - 100,000	8.859 - 6.258	11.917 – 3.328
SRII		15,000 - 20,000	11.448 -8.859	13.326 -

				11.917
SR		3,000 - 15,000	16.206 -11.448	24.902 - 13.326
VLGC	LNG Carrier	100,000 - 500,000	6.730 - 3.138	9.336
Medium LNG carriers		65,000 - 100,000	8.254 - 6.730	9.336
Ethane carriers		10,000 - 65,000	20.044 -8.254	5.061
VLCC & ULCC	Oil & Chemical Tanker	200,000 - 2,000,000	2.524 – 0.872	2.911 – 0.715
Aframax & Suezmax		20,000 - 200,000	8.735 - 2.524	11.858 - 2.911
Handysize		4,000 - 20,000	19.159 -8.735	31.65 - 11.858

3.1 EEXI results

The EEXI determines the standard CO_2 emissions based on the installed engine power, transport capacity (DWT) and voyage speed (V_{ref}). As mentioned previously, voyage speed is automatically aligned based on the ship category average value from the available maritime database used (IMO DCS & EU MRV). Similarly, the vessel capacity (DWT) is calculated with an incremental step of 5,000 tonnes for all ship categories. This creates a significant dataset range of values in which the afore-mentioned benchmarking analysis methodology is performed. Having this in mind, the results for each ship type have been recorded and the average value per ship type is estimated (average Required EEXI). This value is compared with the typical emission ranges from the ABS & DNV reports [9-10] as shown in Figure 3, which contain energy efficiency information based on over 30,000 vessels examined.

The highlighted grey area in the chart (Figure 3) illustrates the Attained EEXI range from all operational vessels contained in the analysed datasets. This area should be aligned with range of Required (Req.) EEXI or the average Req. EEXI value estimated via the proposed methodology. For our scenario, the average Req. EEXI value for each ship type is shown as a black dot in the following graph. In case the black dot is below the "shaded" area, indicates that the specific ship category needs further energy efficiency actions to secure the compliance with the new environmental standard set by MARPOL. On the other hand, if the highlighted area contains or is below the average Req. EEXI value, then no further energy efficiency actions are required for the baseline year (in this case is 2023).

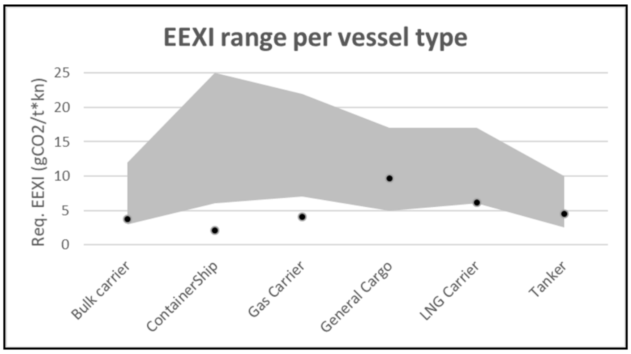

Fig. 3. Benchmark of maritime vessel categories according to average Required EEXI.

As shown in figure 3, almost all Attained EEXI values are placed above the respective average Required values, except for the general cargo and oil & chemical tankers ship types. At first glance, this indicates the necessity for immediate energy efficiency actions. Specifically, EEXI is a ship design index thus it confirms the need for medium or long-term actions. However, several Req. EEXI values are in close proximity to the lower bound of the shaded area. In these cases, short-term energy efficiency measures could satisfy the environmental standards and thus new calculations for EEXI values are necessary in order to re-evaluate the impact of the applied energy efficiency techniques. The interpretation of the results is discussed in the next chapter (Chapter 4).

3.2 CII results

CII is a measure of energy operational efficiency according to the actual annual fuel consumption recorded by the ship operator. The Req. CII values are determined by the installed engine power, transport capacity (DWT) and distance travelled (nautical miles). As mentioned previously, annual travelling distance is automatically aligned based on the ship category average value from the available maritime database used (IMO DCS & EU MRV). Similarly, the vessel capacity (DWT) is calculated with an incremental step of 5,000 tonnes for all ship categories. This creates a significant dataset range of values in which the afore-mentioned benchmarking analysis methodology is performed. Having this in mind, the results for each ship type have been recorded and the average value per ship type is estimated (average Required CII) for the baseline year (2023) and near future (2030). This value is compared with the typical emission ranges from the ABS & DNV reports [9-10] as shown in Figure 3, which contain energy efficiency information based on over 30,000 vessels examined.

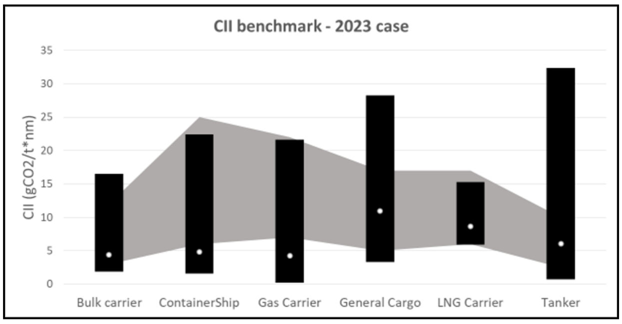

Fig. 4. Benchmark of maritime vessel categories according to average Required CII on baseline year 2023.

Similarly, as in the EEXI section, the highlighted grey area in the following charts (Figures 4&5) illustrates the Attained CII range from all operational vessels contained in the analysed datasets. This area should be aligned with the range of Req. CII (black chart columns) and average Req. CII value (white dots) estimated. The average Req. CII value for each ship type is shown as a white dot inside the corresponding black column; which is the Req. CII range for a specific ship type. In case the Req. CII section is below the "shaded" area, it indicates that the specific ship category needs to differentiate the annual operational voyage plan or operational profiles (i.e., fuel mix, voyage speed, increase total cargo transported, etc.) in order to secure the compliance with the new environmental standard set by MARPOL. On the other hand, if the highlighted area contains or is below the average Req. CII value, then no further energy efficiency actions are required for the meantime. During this study, a benchmarking analysis is made for the current operational profiles assumed in the global maritime fleet for two different timestamps. The first (Figure 4) is made on the baseline year (2023) which illustrates the short-term energy efficiency measures that may be needed. Similarly, in Figure 5 the same process is executed considering the CII reduction by 2030.

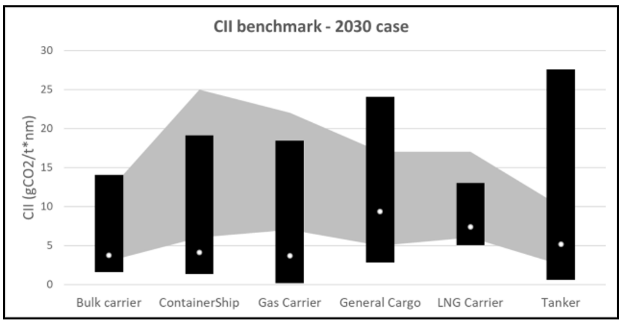

Fig. 5. Benchmark of maritime vessel categories according to average Required CII on year 2030.

Observing both figures (Figures 4&5) it can be identified that the CII reduction of 15% between years 2023 and 2030 bring insignificant changes to the overall benchmark results. Furthermore, it can be observed that bulk carriers, general cargo, LNG carriers and oil &chemical tankers are in compliance with the environmental regulations set by IMO. On the other hand, containerships and gas carriers could fulfil the necessary requirements during 2023 with several short-term energy efficiency techniques. However, in 2030 these short-term measures might be insufficient. In this case, additional investments on long-term energy strategies may bring the solution.

4 Conclusion

This paper proposes a three-step methodology attempts to identify the level of compliance of the operational global maritime fleet with the new environmental standards set by MARPOL Annex VI. A specific scenario is examined with the usage of available data from previous initial mapping attempts (ABS &DNV reports) plus available open access datasets (IMO DCS & EU MRV) in order to evaluate the current status per maritime vessel type from an energy efficiency perspective. The present work contributes on establishing a preliminary benchmark tool that could provide valuable insights to the maritime key stakeholders and fleet operators. The level of energy efficiency techniques or strategies that could be applied (short, medium, long-term) should be selected accordingly.

The calculations of the EEXI and CII values (required value per ship category) and the corresponding results presented in Figures 3-5 shown that the initial remarks made within the DNV and ABS reports [9, 10] are merely true. Noticing the annual operational energy results (CII results), the majority of ship categories seems to be roughly aligned with the newly introduced environmental regulations until 2030. Nevertheless, it must be taken into account that several ship types may have a flexible treatment towards environmental regulations. This can be noticed in oil & chemical tankers and general cargo vessels, in which due to their unique design characteristics the range of KPI values is broader; thus more flexible to short-term changes. Similarly, from the opposite perspective, a stricter regulatory framework is observed in containerships and gas/LNG carriers. For these ship categories long-term energy transition investments seem necessary in the near future.

In the same principle and focusing on the design-related index (EEXI), the results assured that, in overall, the maritime transportation sector needs immediate actions to retrofit most of the ship types in order to implement innovative technologies and use low or zero carbon alternative fuels, such as ammonia, hydrogen, methanol and many more. A variety of long-term energy efficiency strategies should be applied in order to test these technologies in the constantly demanding shipping market and in parallel achieve IMO's maritime decarbonization ambitions by 2050.

The results reflect the implication of operational benchmarks for different ship types during the second phase of a vessel's life cycle. At the same time differentiations in other operational activities such as cargo handling processes, cargo residues and waste treatment could affect a similar ship type's performance.

In this context, the present study could expand by investing the effects of these side-operational activities for specific ship categories where field data will be available. Additionally, future research on the potential effect of either alternative fuels utilization or short-term energy efficiency techniques (i.e., voyage parameters optimization, engine power limitation) would comprehend on the valuable insights provided from the present work.

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Acronyms

Acronym	Definition
ABS	American Bureau of Shipping
CII	Carbon Intensity Indicator
CO_2	Carbon dioxide
DNV	Det Norske Veritas
DWT	Deadweight (in tonnes)
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EU MRV	EU's Monitoring, Reporting, Verification (MRV) database
g CO_2	Grams of carbon dioxide
GHG	Greenhouse Gas(es)
GT	Gross Tonnage
H_2	Hydrogen
IMO	International Maritime Organization
IMO DCS	IMO Data Collection System
LNG	Liquefied Natural Gas
KPI	Key Performance Indicator
Kw, kWh	kilowatt, kilowatt per hour
MARPOL	International Convention for the Prevention of Pollution from Ships
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
NH_3	Ammonia
NO_X	Nitrogen oxide
SFC	Specific Fuel Consumption
SO_X	Sulphur oxide
t	Metric tonne
VLSFO	Very Low Sulphur Fuel Oil

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