UNVEILING THE JOURNEY OF MARITIME ENERGY EFFICIENCY: A DEEP DIVE INTO EEDI, EEXI, CII, POTENTIAL CII REGULATION ENHANCEMENTS, AND PERSISTENT CHALLENGES

Reference NO. IJME 1309, DOI: 10.5750/ijme.v166iA2-A3.1309

N K Baijal*, Assoc, RINA, India

*Corresponding author. N K Baijal (Email): nalinbaijal@gmail.com

KEY DATES: Submission date: 30.11.2023; Final acceptance date: 18.07.2024; Published date: 05.06.2025

SUMMARY

The Energy Efficiency Design Index (EEDI) and the Energy Efficiency Existing Ship Index (EEXI), two crucial regulations in the maritime sector, are examined in detail in this paper. This study aims to understand the complexities of these restrictions and analyse how the Energy Efficiency Operational Indicator (EEOI) could be used to improve the way the maritime industry measures Carbon Intensity Indicator (CII).

This study offers insightful information on the regulatory environment governing energy efficiency in shipping by analysing the historical trajectory and transformation of the EEDI. It provides a thorough overview of the regulations now in effect, illuminating their tenets and guiding ideas.

Additionally, this study offers a path for prospective CII framework upgrades that goes beyond simple analysis. It investigates whether adding the EEOI is feasible and how it can improve the precision and applicability of emission measurement in the maritime industry.

In essence, this paper provides a comprehensive overview of the development of EEDI, the current regulatory landscape, and how creative modifications, such the inclusion of EEOI, could further improve existing methodologies to address the changing demands of sustainability in shipping.

KEYWORDS

EEXI, EEDI, Carbon intensity indicator, Statistics, Carbon emission

NOMENCLATURE

C_F	Conversion factor between fuel consumption and CO_2 emissions
V_{ref}	Ship speed
P	Power of main and auxiliary engines
P_{ME}	Power of main engines
P_{PTI}	Power of Shaft motor
P_{eff}	Innovative mechanical energy-efficient technology for main engine
P_{AEeff}	Innovative mechanical energy-efficient technology for auxiliary engine
P_{AE}	Power of auxiliary engines
SFC	Certified specific fuel consumption
f_j	Ship-specific design elements
f_w	Factor for speed reduction at sea
f_{eff}	Factor of each innovative energy efficiency technology
f_i	Capacity correction factor for different ship types
f_c	Cubic capacity correction factor
f_m	Factor for ice-classed ships having IA Super and IA
f_w	Non-dimensional coefficient indicating the decrease of speed in representative sea conditions of wave height, wave frequency and wind speed
$Capacity$	Deadweight or gross tonnes for each specific ship type
D_t	Total distance travelled in nautical miles
D_x	Distance travelled in nautical miles for voyage periods which may be deducted from CII calculation
$FC_{electrical,\,j}$	Mass (in grams) of fuel type j, consumed for production of electrical power
$FC_{boiler,\,j}$	The mass (in grams) of fuel type j, consumed by the boiler
$FC_{other,\,j}$	Mass (in grams) of fuel type j, consumed by other related fuel consumption devices
$TF_j = (1\text{-}AFTanker)$	
$*\ FC_{S,\,j}$	The quantity of fuel j removed for STS or shuttle tanker operation, where $FCS,j = FCj$ for shuttle tankers and FCS,j is the total quantity of fuel j used on STS voyages for STS ships.
$FC_{voyage,\,j}$	Mass (in grams) of fuel of type j, consumed in voyage periods during the calendar year
j	Fuel type
I	Voyage number

FC_{ij}	Mass of consumed fuel j at voyage i
CF_j	Fuel mass to CO_2 mass conversion factor for fuel j
m_{cargo}	Cargo carried (tonnes) or work done (number of TEU or passengers) or gross tonnes for passenger ships; and
D	Distance in nautical miles corresponding to the cargo carried or work done.
M	Mass of CO_2 and is computed as $-\sum_j FC_j \times C_{Fj}$
C	Ships capacity
$\delta^{(p)}$	Constant term
$\varepsilon^{(p)}$	Error term
p	Typical quantile, p = {.15, .35, .50, .65, .85}
y_i	consecutive numbering system starting at $y2023 = 0$, $y2024 = 1$, $y2025 = 2$
fi	Capacity correction factor for ice-classed ships as specified in the 2018 Guidelines on the method of calculation of the attained EEDI for new ships (resolution MEPC.308(73) as amended by resolutions MEPC.322(74) and MEPC.332(76), as may be further amended)
fm	Factor for ice-classed ships having IA Super and IA as specified in the 2018 Guidelines on the method of calculation of the attained EEDI for new ships (resolution MEPC.308(73) as amended by resolutions MEPC.322(74) and MEPC.332(76), as may be further amended)
fc	Cubic capacity correction factors for chemical tankers as specified in paragraph 2.2.12 of the 2018 Guidelines on the method of calculation of the attained EEDI for new ships (resolution MEPC.308(73) as amended by resolutions MEPC.322(74) and MEPC.332(76), as may be further amended)
fi,VSE	Correction factor for ship-specific voluntary structural enhancement as specified in paragraph 2.2.11.2 of the 2018 Guidelines on the method of calculation of the attained EEDI for new ships (resolution MEPC.308(73) as amended by resolutions MEPC.322(74) and MEPC.332(76), as may be further amended), to be applied only to self-unloading bulk carriers;

1. INTRODUCTION

The International Maritime Organization (IMO) and the Korea International Cooperation Agency (KOICA) collaborate together to launch the energy efficiency program in April 2011 (Baumler, et al, 2014). To enhance East Asian countries' ability to regulate ship-related greenhouse gas (GHG) emissions was the primary aim of this collaborative project This project was a crucial part of their "East Asia Climate Partnerships" climate change strategy. Additionally, it offers support to developing countries in the region (Baumler, et al, 2014).

During the 61st and 62nd sessions of the IMO's Marine Environment Protection Committee (MEPC) (IMO, 2011), there was a significant focus on developing a skilled workforce to tackle GHG emissions in the shipping industry. Mandatory GHG reduction measures were adopted at MEPC 62 (IMO, 2011), prompting the KOICA-IMO Project on GHG (Baumler, et al, 2014) to address this crucial need in the maritime sector. Resolution MEPC.203(62) (IMO, 2011) introduced regulations on energy efficiency for ships in MARPOL Annex VI, including measures such as the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP).

MARPOL Annex VI's Regulation 22 stipulates that each ship must maintain an onboard ship-specific energy efficiency management plan, which may be integrated into the ship's safety management system (SMS) (IMO, 2011).

Recognizing the challenges faced by developing countries in implementing IMO instruments, the IMO established the Integrated Technical Cooperation Programme (ITCP), aligning with its convention's provisions (Hattori, et al, 2022). This program focuses on enhancing human and institutional capabilities to ensure consistent adherence to IMO's regulatory framework. Research by (Hattori, et al, 2022) affirmed the program's effectiveness.

The ITCP significantly contributes to capacity-building in the maritime sector, assisting developing countries in successfully implementing IMO instruments. This, in turn, enhances environmental protection, safety in shipping, and smooth international maritime traffic facilitation. The program tailors its efforts to regions like Africa, Small Island Developing States (SIDS), and Least Developed Countries (LDCs), considering their unique compliance challenges. In 2012, the program incorporated the "Mitigation of climate change" initiative, transformed into the "Energy Efficiency Global Programme" due to the criticality of addressing global climate change.

2. IMO GHG STUDIES

In order to assess the contribution of ships to the worldwide emissions of CO_2 caused by human activity, the IMO carried out a number of studies on greenhouse gas emissions. The atmospheric discharge of several gases is shown in Figure 1.

2.1 INITIAL GHG STUDY

As per initial IMO GHG study (Marintek, et al, 2000) it is estimated that 1.8% of global anthropogenic CO_2 emissions in 1996 came from ships engaged in international trade, The United Nations Framework Convention on Climate Change (UNFCCC), the International Energy Agency

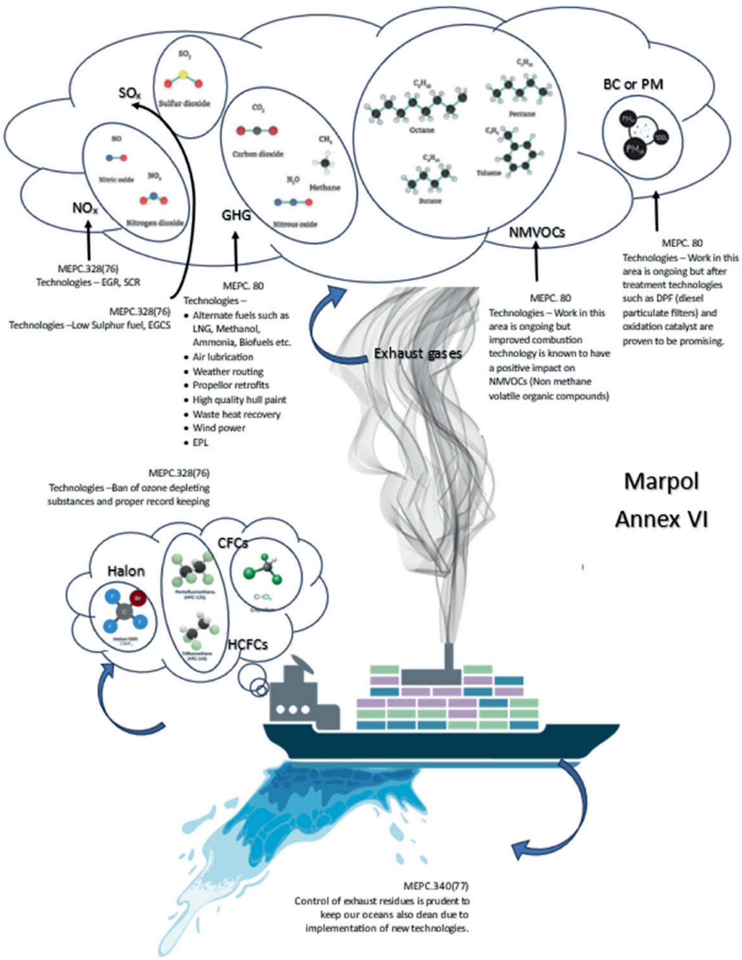

Figure 1. Summary of Maritime emissions and associated regulations

(IEA), and the Energy Information Administration (EIA) were among the organizations which participated in this study and conclusions were drawn from data on marine bunker supply in order to calculate these emissions.

2.2 SECOND GHG STUDY

According to the 2009 Second IMO GHG Study (Buhaug, et al, 2009), international shipping (apart from fisheries and military boats) contributed 870 million tons of CO_2 emissions in 2007, roughly 2.7% of total global anthropogenic CO_2 emissions. This study also showed that carbon dioxide emissions from international shipping might rise by a factor of two to three by 2050 compared to 2007 levels in the absence of effective controls, according to medium-range emission scenarios. This growth that is expected is a result of the growing shipping industry.

However, according to second GHG study it was concluded that there is substantial room for improvement in terms of lowering GHG emissions by applying operational and technical strategies. Effective implementation of these strategies holds the potential to improve overall efficiency which may result in emission rates that are 25% to 75% lower than current levels. This emphasizes how important it is to adopt proactive tactics and policies in order to lessen the shipping industry's negative environmental effects and support international efforts to combat climate change.

2.3 THIRD GHG STUDY

The 2012 emissions from international shipping were evaluated for publication in the Third IMO GHG Study (Smith, et al, 2015), which was released in 2014. As per third GHG study (Smith, et al, 2015) it was found that the total amount of greenhouse gases emitted approximately 816 million tonnes of CO_2e, and 796 million tonnes of CO_2. These emissions from international shipping contributed to roughly 2.1% of global CO_2 emissions and 2.2% of all humans produced CO_2 emissions.

Moreover, estimates in the study suggested that by 2050, these emissions would rise by 50% to 250%. Along with these conclusions, the study also updated the CO_2 estimations for 2007. These revised estimates came out to be around 885 million tonnes, or 2.8% of the total anthropogenic CO_2 emissions worldwide.

2.4 FOURTH GHG STUDY

According to the 2020 Fourth IMO GHG Study (Faber, et al, 2020), shipping accounted for about 2.89% of all anthropogenic greenhouse gas emissions worldwide in 2018. Furthermore, according to the report, these emissions might vary from 90% to 130% of the 2008 emissions by 2050. These estimates show that if considerable steps are not taken to limit and reduce the environmental impact of the shipping industry, there could be a large increase in GHG emissions associated with shipping. As a result, addressing and reducing greenhouse gas emissions from the maritime industry remain an essential goal in the fight against climate change and to promote sustainability.

Notably, the predictions were revised during the 2020 Fourth GHG Study (Faber, et al, 2020). The total greenhouse gas (GHG) emissions from shipping between 2012 and 2018, measured in CO_2e (carbon dioxide, methane, and nitrous oxide), went up from 977 million tonnes to 1,076 million tonnes, which is a 9.6% rise. The amount of CO_2 emissions specifically contributed to these emissions was 962 million tonnes in 2012. By 2018, however, this number had increased by 9.3% to 1,056 million tonnes of emissions.

These figures show a considerable rise in shipping-related GHG emissions over the course of the six-year period, which calls for immediate steps to combat climate change on a worldwide scale. Furthermore, from 2.76% in 2012 to 2.89% in 2018, the proportion of shipping emissions in total anthropogenic emissions increased globally.

When examining international shipping separately using a voyage-based allocation method, CO_2 emissions increased from 701 million tonnes in 2012 to 740 million tonnes in 2018, representing a 5.6% increase. However, this growth rate was lower than the overall shipping emissions. Throughout this period, these international shipping emissions consistently accounted for approximately 2% of global CO_2 emissions. Conversely, when using the vessel-based allocation method from the Third IMO GHG Study (Smith, et al, 2015), international shipping CO_2 emissions grew from 848 million tonnes in 2012 to 919 million tonnes in 2018, marking an 8.4% increase.

For the first time, this 4th study managed to distinguish between domestic shipping emissions and international emissions on a voyage basis, aligning with the guidelines and definitions outlined by the Intergovernmental Panel on Climate Change (IPCC).

Based on projections, the fourth study estimates that international shipping GHG emissions in 2008, in terms of CO_2 equivalents (CO_2e), were 794 million tonnes using the new method, while the Third IMO GHG Study (Smith, et al, 2015) calculated them to be 940 million tonnes CO_2e. Through this fourth GHG study, a significant reduction in CO_2e emissions data has been observed compared to the first GHG study.

In summary, the following changes were observed between the first and fourth IMO GHG studies for total shipping emissions:

- The methodology for allocation, particularly in distinguishing between domestic and international shipping emissions, has evolved.
- When considering international shipping alone, different allocation methods yielded varying emission figures.
- Notably, there has been a substantial reduction in CO_2e emission data between the first and fourth GHG studies.
- The IMO has set a target to achieve a 50% reduction in GHG emissions from 794 million tonnes (as estimated in the Fourth GHG Study) to 397 million tonnes by 2050.

3. IMO GHG STRATEGIES

In 2018, the International Maritime Organization (IMO) unveiled an initial plan to reduce GHG emissions generated by ships (Joung, et al, 2020). This strategy presents a vision that reiterates the IMO 's strong commitment to reducing GHG emissions associated with international shipping and, ultimately, striving for their complete elimination as soon as possible. This pledge emphasises the organization 's proactive approach to addressing the environmental consequences of maritime operations and aligns with broader worldwide efforts to combat climate change.

The Initial Strategy establishes specific objectives for the international shipping sector, recognising that technological advancements and the global adoption of alternative fuels and energy sources will play a pivotal role in attaining these goals. The guiding aspirations of the strategy are described as follows:

- Reducing Carbon Intensity through EEDI Phases: The strategy seeks to lower the carbon intensity of ships by implementing successive phases of the Energy Efficiency Design Index (EEDI) for newly constructed vessels. The plan includes periodic assessments to enhance energy efficiency design requirements, with specific percentage improvement targets for each ship category determined as deemed appropriate.
- Decreasing Carbon Intensity in International Shipping: This strategy sets a target to reduce CO_2 emissions per unit of transport work across international shipping. The aim is to achieve, on average, at least a 40% reduction by 2030, with ongoing efforts towards a 70% reduction by 2050 compared to emissions in 2008.
- Peaking and Reducing GHG Emissions from International Shipping: This strategy strives for GHG emissions from international shipping to reach their highest point as soon as possible and subsequently decline. The overarching objective is to achieve a minimum reduction of 50% annual GHG emissions by 2050 compared with emissions in 2008. These efforts align with the broader goal of progressively phasing out these emissions, consistent with the Vision, which corresponds to a trajectory of reducing CO_2 emissions

in line with the temperature objectives outlined in the Paris Agreement.

This comprehensive framework charts a path towards a more environmentally friendly and sustainable future for international shipping. This underscores the industry 's dedication to aligning with worldwide climate objectives and decreasing its ecological impact.

The 2023 IMO GHG Strategy (IMO, 2023) adopted on 07 July 2023 vide resolution MEPC.377(80) (IMO, 2012) outlines different levels of ambition for the international shipping sector, emphasising the crucial role of technological advancements and the worldwide adoption of alternative fuels and energy sources to attain these aims. These objectives will undergo regular evaluations, considering updated emission assessments, options for emissions reduction, Intergovernmental Panel on Climate Change (IPCC) reports, and forthcoming IMO GHG assessments and studies. This ongoing assessment aims to track progress towards achieving net-zero GHG emissions from international shipping.

The specified levels of ambition outlined in the 2023 IMO GHG Strategy (IMO, 2023) encompass:

- Enhancing Energy Efficiency for New Vessels: With the objective of reinforcing energy efficiency design standards for ships, the aim is to reduce carbon intensity through further advancements in energy efficiency for newly constructed ships.
- Lowering the Carbon Intensity of Global Shipping: The goal is to achieve a minimum 40% reduction in CO_2 emissions per unit of transport work across international shipping by 2030, compared to the levels recorded in 2008.
- Increasing the Adoption of Green Technologies: The aspiration is to have zero or near-zero GHG emission technologies, fuels, and/or energy sources account for at least 5%, with the aim of reaching 10% of the energy used by international shipping by 2030.
- Attaining Net-Zero GHG Emissions from Shipping: This endeavour involves reaching the peak of GHG emissions from international shipping as soon as feasible and achieving net-zero emissions by or around 2050. This aligns with the Vision and the long-term temperature objective of the Paris Agreement.

The strategy additionally presents below milestones to direct the advancement towards achieving net-zero GHG emissions:

- Achieving a minimum reduction of 20%, with an aim of 30%, in total annual GHG emissions from international shipping by 2030, relative to the levels in 2008.
- Attaining a minimum reduction of 70%, with an aim of 80%, in total annual GHG emissions from international shipping by 2040, relative to the levels in 2008.

Note that while the Paris Agreement does not directly address international shipping, the International Maritime Organization (IMO), as the regulatory authority for the industry, is fully committed to mitigating GHG emissions from this sector. The strategy also emphasises the IMO's continuous efforts to implement the 2018 Initial IMO GHG Strategy immediate term GHG reduction measures.

These initiatives collectively underscore the maritime sector ‘s strong commitment to environmental sustainability and alignment with worldwide climate objectives. The Initial Strategy encompassed a series of short-term GHG reduction measures, which were slated for development and approval by the Committee within the timeframe from 2018 to 2023.

During the 76th session of the Marine Environment Protection Committee (MEPC) in June 2021, a significant short-term GHG reduction measure was adopted by amending MARPOL Annex VI. This measure comprises obligatory technical and operational requirements, constituting a combined approach. These amendments officially came into force in November 2022 and aim to achieve a minimum 40% reduction in the carbon intensity of international shipping by 2030, compared to the emission levels of 2008.

Additionally, a comprehensive review is planned for mandatory goal-based technical and operational measures designed to lower the carbon intensity of international shipping, commonly referred to as the "short-term GHG reduction measures." This review process is scheduled to be completed by January 1, 2026, ensuring that the measures remain effective and adaptable to changing circumstances and technological advancements. This enhances ongoing efforts to address GHG emissions within the shipping industry.

4. IMPACT OF SHIPPING EMISSION REDUCTION

Achieving a 10% reduction in emissions from shipping would have a relatively minimal impact on the overall global emission picture. In 2018, total shipping emissions contributed to 1,076 million tonnes of CO_2e. For example, if a rough estimate of 50,000 million tonnes of CO_2e is considered as the world 's total anthropogenic emissions for that year (a commonly used approximation), a 10% reduction in shipping emissions would translate to 107.6 million tonnes of CO_2e.

In order to calculate the percentage reduction relative to the world's total emissions, the reduction in shipping emissions

Table 1. EEDI and EEXI reduction factors and refernce lines

Ship Type	Size	EEDI Phase 01 Jan 2013 – 31 Dec 2014	EEDI Phase 1 1 Jan 2015 – 31 Dec 2019	EEDI Phase 2 1 Jan 2020 – 31 Dec 2024	EEDI Phase 3 1 Jan 2025 and onwards	EEDI Reduction factor EEXI	Reference line value (2013) a x b^{-c}
Bulk carrier	20,000 DWT and above	0	10%	20%	30%	15%	961.79* $DWT^{-0.477}$
	10,000 – 20,000 DWT	No required EEDI applies	0–10%	0–20%	0–30%	0–20%	
	20,000 and above but less than 20,000 DWT	0	0–10%	0–20%	0–30%	20%	
Gas carrier	10,000 DWT and above but less than 15,000 DWT	0	10%	20%	30%	20%	1120.00* $DWT^{-0.456}$
	2,000 – 10,000 DWT	n/a	0–10%	0–20%	0–30%	0–20%	
	15,000 DWT and above	0	0–10%	0–20%	0–30%	30%	
Tanker	20,000 DWT and above but less than 200,000 DWT	0	10%	20%	30%	20%	1218.80* $DWT^{-0.488}$
	4,000 – 20,000 DWT	n/a	0–10%	0–20%	0–30%	0–20%	
	200,000 DWT and above	0	10%	20%	30%	15%	
Container ship	15,000 DWT and above but less than 40,000 DWT	0	10%	20%	30%	20%	174.22* $DWT^{-0.201}$
	10,000 – 15,000 DWT	n/a	0–10%	0–20%	15–30%	0–20%	
	120,000 and above but less than 200,000 DWT	0	10%	20%	45%	45%	
	80,000 and above but less than 120,000 DWT	0	10%	20%	40%	35%	
	40,000 and above but less than 80,000 DWT	0	10%	20%	35%	30%	
	200,000 DWT and above	0	10%	20%	50%	50%	
General cargo ship	15,000 DWT and above	0	10%	15%	30%	30%	107.48* $DWT^{-0.216}$
	3,000 and above but less than 15,000 DWT	0	0–10%	0–15%	0–30%	0–30%	
Refrigerated cargo carrier	5,000 DWT and above DWT	0	10%	15%	30%	15%	227.01* $DWT^{-0.244}$
	3,000 and above but less than 5,000 DWT	0	0–10%	0–15%	0–30%	0–15%	
Combination carrier	20,000 DWT and above	0	10%	20%	30%	20%	1219.00* $DWT^{-0.488}$
	4,000 and above but less than 20,000 DWT	0	0–10%	0–20%	0–30%	0–20%	
LNG Carrier	10,000 DWT and above	n/a	10%	20%	30%	30%	2253.7* $DWT^{-0.474}$

continued

Table 1. continued

Ship Type	Size	EEDI Phase 01 Jan 2013 – 31 Dec 2014	EEDI Phase 1 1 Jan 2015 – 31 Dec 2019	EEDI Phase 2 1 Jan 2020 – 31 Dec 2024	EEDI Phase 3 1 Jan 2025 and onwards	EEDI Reduction factor EEXI	Reference line value (2013) a x b^{-c}
Ro-ro cargo ship (vehicle carrier)	10,000 DWT and above	n/a	5%	15%	30%	15%	$(DWT/GT)^{-0.7}$ · 780.36 where $DWT/GT < 0.3$ 1,812.63 where $DWT/GT \geq 0.30$* $DWT^{-0.471}$
Ro-ro cargo ship	2,000 DWT and above	n/a	5%	20%	30%	5%	1686.17* $DWT^{-0.498}$
	1,000 and above but less than 2,000 DWT	n/a	0–5%	0–20%	0–30%	0–5%	
Ro-ro passenger ship	1,000 DWT and above	n/a	5%	20%	30%	5%	902.59* $DWT^{-0.381}$
	250 and above but less than 1,000 DWT	n/a	0–5%	0–20%	0–30%	0–5%	
Cruise passenger ship having nonconventional propulsion	85,000 GT and above	n/a	5%	20%	30%	30%	170.84* $DWT^{-0..214}$
	25,000 and above but less than 85,000 GT	n/a	0–5%	0–20%	0–30%	0–30%	

Table 2. Emissions values as per GHG studies

GHG Study	Year	CO_2 emissions (in million tonnes)	CO_2e emissions (in million tonnes)	CO_2 global emissions in %	CO_2e global emissions in %
1st IMO GHG study	1996			1.8	
2nd IMO SHG Study	2007	1046	1121		3.3
3rd IMO SHG Study	2012	938	961	2.2	2.1
4th IMO GHG Study	2018	1056	1076		2.89

Table 3. Changes in values as studies were backed by data

GHG Study	Year	CO_2 emissions (in million tonnes)	CO_2e emissions (in million tonnes)	CO_2 global emissions in %	CO_2e global emissions in %
1st IMO GHG study	-			-	
2nd IMO SHG Study	2008		794*		
3rd IMO SHG Study	2012	962**	977**		2.76**
4th IMO GHG Study	2018	1056	1076		2.89

* Value changed as depicted in GHG study 3
** Value changed as depicted in GHG study

(107.6 million tonnes) is divided by the estimated world 's total anthropogenic emissions (50,000 million tonnes) and then multiplied by 100:

(107.6 million tonnes / 50,000 million tonnes) * 100 ≈ 0.215%.

Basis these rough estimates, a 10% reduction in shipping emissions would mean less than a 0.2% reduction in the world 's total emissions.

Above example highlights the fact that while reducing emissions from shipping is important, broader efforts to reduce emissions from various other sectors is also crucial to effectively address climate change.

Tables 2 and 3 summarises how the IMO GHG studies have impacted the projected GHG/CO2 emissions in a short span of time. The data presented in the tables clearly demonstrate that, with the implementation of the International Maritime Organization 's Data Collection System (IMO DCS) introduced through MEPC.278(70) (IMO, 2016) in October 2016, significant improvements have been made in terms of both emissions projections and the accuracy of emissions data. IMO DCS has played a crucial role in enhancing our understanding of GHG emissions from the maritime sector.

It has provided more reliable and up-to-date information, enabling better informed data backed decisions.

5. EEDI

5.1 DEFINING EEDI

In accordance with regulation 20 of MARPOL Annex VI, the Attained Energy Efficiency Design Index (EEDI) must be computed for every new vessel, or any new vessel that has undergone significant modification, or any new or existing vessel that has undergone a substantial major alteration as determined by the administration, which deems this alteration as equivalent to a new vessel. In addition, applicable vessels are required to maintain an EEDI technical file for the verification of the Attained EEDI, complete with the necessary information for calculating it, and to provide an illustration of the calculation process.

Likewise, under regulation 21 of MARPOL Annex VI, it became obligatory to calculate the Required EEDI for each new ship, any new ship that has undergone significant modification, or any new or existing ship that has undergone a substantial major alteration as deemed by the administration. Consequently, it can be asserted that the Required EEDI sets the benchmark for the Attained EEDI and varies based on the type and size of the vessel. The initial EEDI limit was established with a reference line value in 2013, and this limit will progressively decrease in three phases from 2013 to 2025, as outlined in Table 1. This signifies that ships must continuously meet more stringent energy efficiency standards as time advances.

The required EEDI is computed as per the following equation:

$$\text{Required EEDI} = \left(1 - \frac{x}{100}\right) * \textit{EEDI Reference Line} \quad (1)$$

where x is the reduction factor, as indicated in Table 1, and EEDI reference line is computed using equation (2) and the values indicated in Table 1.

5.2 EVOLUTION OF EEDI

On January 1, 2013, resolution MEPC.203(62) (IMO, 2011) came into effect, along with regulation 20, which required ships affected by the new regulations to calculate the Attained Energy Efficiency Design Index (EEDI). It is important to note that in 2012, resolution MEPC.212(63) (IMO, 2012), which replaced the interim guidelines outlined in MEPC.1/Circ.681 (IMO, 2009) issued on August 17, 2009, was adopted on March 2, 2012. Subsequently, amendments to these guidelines were made through resolution MEPC.224(64) (IMO, 2012), which was adopted on October 5, 2012. MEPC.212(63) (IMO, 2012) provided a definition of EEDI, simplifying it as a measure of a ship 's energy efficiency. It's worth noting that MEPC.1/Circ.681 (IMO, 2009) initially defined EEDI as a measure of CO_2 efficiency. EEDI is quantified in units of g/t*nm or grams of CO_2 per tonne nautical mile. In simpler terms, EEDI can be viewed as a measure of the environmental impact divided by the societal benefit, which translates to CO_2 emissions divided by transport work.

On April 4, 2014, further guidelines for calculating EEDI were adopted through MEPC.245(66) (IMO, 2014), and subsequent amendments were introduced via resolutions MEPC.263(68) (IMO, 2015) on May 15, 2015, and MEPC.281(70) (IMO, 2016) on October 28, 2016. On October 26, 2018, resolution MEPC.308(73) (IMO, 2018) was adopted, superseding MEPC.245(66) (IMO, 2014), as amended by resolutions MEPC.263(68) (IMO, 2015) and MEPC.281(70) (IMO, 2016), as well as MEPC.1/Circ.866 (IMO, 2017) issued on January 30, 2017. Resolution MEPC.308(73) (IMO, 2018) itself was amended by

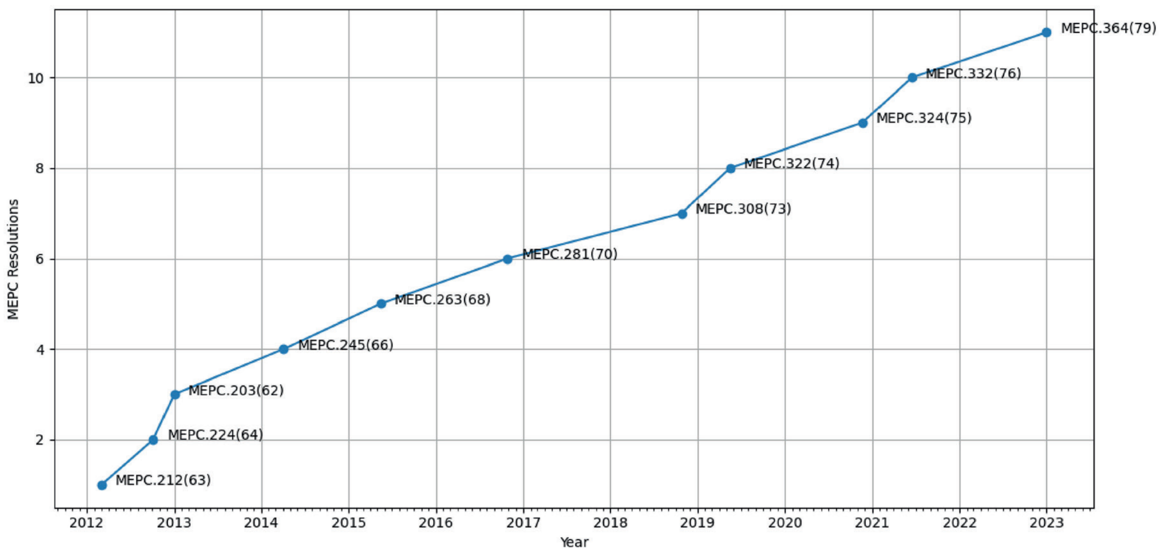

Figure 2. Timeline depicting changes in EEDI

resolution MEPC.322(74) (IMO, 2019) on May 17, 2019, and MEPC.332(76) (IMO, 2021) on June 17, 2021.

During MEPC 75, another set of amendments were made to MARPOL Annex VI through MEPC.324(75) (IMO, 2020), which was adopted on November 20, 2020. Finally, during MEPC 79, the 2022 guidelines on the method of calculating the Attained EEDI were adopted via resolution MEPC.364(79) (IMO, 2022). See Figure 2 representing the timeline of MEPC resolution in terms of EEDI. there has been a significant evolution in the guidelines for calculating the Energy Efficiency Design Index (EEDI) over the span of 10 years, with 11 different sets of guidelines issued. This evolution reflects the ongoing efforts within the maritime industry to improve and refine the measurement of a ship 's energy efficiency and its impact on the environment. These changes in guidelines have contributed to a better understanding of how to quantify and assess a vessel 's environmental performance, particularly in terms of CO_2 emissions per unit of transport work.

5.3 DETERMING THE EEDI REFERNCE LINE

The reference line for the required energy efficiency design index (EEDI) is established through equation 1, as outlined in MEPC.215(63) (IMO, 2012). It is important to note that MEPC.215(63) (IMO, 2012) was replaced by MEPC.231(65) (IMO, 2013), which was adopted on May 17, 2013. In this formula, 'a' and 'c' represent parameters determined through a regression curve fit, while 'b' corresponds to the 100% deadweight of the ship. The reference line serves as a critical benchmark for setting limits and ensuring a continuous enhancement in the energy efficiency of newly constructed ships. See Table 1.

$$\text{EEDI reference line} = (a \times b^{-c}) \tag{2}$$

5.4 COMPLEX EEDI EQUATION

The Energy Efficiency Design Index (EEDI) formula was introduced to the world through MEPC.1/Circ.681 (IMO, 2009). This circular provides the initial guidelines and information regarding the calculation and implementation of the EEDI.

EEDI was first represented by the following equation:

$$\frac{\begin{gathered}\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} * C_{FME(i)} * SFC_{ME(i)}\right) + \left(P_{AE} * C_{FAE} * SFC_{AE}\right) \\ + \left(\left(\prod_{j=1}^{M} f_j * \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} * P_{AEeff(i)}\right) C_{FAE} * SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} * P_{eff(i)} * C_{FME} * SFC_{ME}\right)\end{gathered}}{f_i * Capacity * V_{ref} * f_w} \tag{3}$$

When equation (2) was introduced, it constituted to 5 major divisions that covered all attributes of emission contributing sources. These 5 major divisions are as follows:

$$\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} * C_{FME(i)} * SFC_{ME(i)}\right) : \textit{Main engine emission} \tag{4}$$

$$(P_{AE} * C_{FAE} * SFC_{AE}): \textit{Auxilary engine emissions} \tag{4}$$

$$\left(\left(\prod_{j=1}^{M} f_j * \sum_{i=1}^{nPTi} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} * P_{AEeff(i)}\right) C_{FAE} * SFC_{AE}\right) : \textit{Shaft generator or motor emssions} \tag{5}$$

$$\left(\left(\prod_{j=1}^{M} f_j * \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} * p_{AEeff(i)}\right) C_{FAE} * SFC_{AE}\right) : \textit{Efficienciy technologies} \tag{6}$$

$$f_i * Capacity * V_{ref} * f_w : \textit{Transport work} \tag{7}$$

Vide resolution MEPC.364(79)[24] last EEDI equation (3) was revised as Equation (8):

$$\frac{\begin{gathered}\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} * C_{FME(i)} * SFC_{ME(i)}\right) + \left(P_{AE} * C_{FAE} * SFC_{AE}\right) \\ + \left(\left(\prod_{j=1}^{M} f_j * \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} * P_{AEeff(i)}\right) C_{FAE} * SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} * P_{eff(i)} * C_{FME} * SFC_{ME}\right)\end{gathered}}{f_i * f_c * f_i * Capacity * V_{ref} * f_w * f_m} \tag{8}$$

It is worth highlighting the significance of the conversion factor (C_F). C_F is a dimensionless factor employed to convert fuel consumption, measured in grams (g), into CO_2 emissions, also measured in grams (g). This conversion is based on the carbon content of the fuel. C_F plays a crucial role in establishing a connection between the quantity of fuel used and the resulting CO_2 emissions generated from the combustion of that fuel. It recognizes the carbon content as the primary determinant influencing the production of CO_2. The initial C_F factor table was introduced through circular MEPC.1 Circ. 684 (IMO, 2009). See Table 4.

It should be noted that the parameter C_F (conversion factor) plays a pivotal role in the EEDI equation, as it is the most influential factor within the formula. Reducing C_F, which can be achieved by using the correct and more efficient fuel, has the potential to significantly lower the EEDI of a ship. This emphasises the importance of selecting the right type of fuel to enhance a ship ‘s energy efficiency and reduce its environmental impact.

Furthermore, the introduction and adoption of alternative fuels, along with their respective lower calorific values

Table 4. Calorific and C_F Values of future fuels.

Type of fuel	Reference	Lower calorific value (KG/Kg)	Carbon content	C_F (t-CO_2/t-Fuel)
Diesel/Gas Oil	ISO 8217 Grades DMX through DMC	42,700	0.875	3.206000
Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	41,200	0.86	3.151040
Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	40,200	0.85	3.114400
Liquified Petroleum Gas (LPG)	Propane Butane	46,300 45,700	0.819 0.827	3.000000 3.030000
Liquified Natural Gas (LNG)		48,000	0.75	2.750000
Ethane		46,400	0.799	2.927000
Methanol		19,900	0.375	1.375000
Ethanol		26,800	0.522	1.913000

(KJ/Kg), through MEPC.364(79) (IMO, 2022) represent an important development. See Table 4.

Methanol appears to be a promising winner in terms of the C_F (correction factor) parameter, as it plays a crucial role in reducing the Energy Efficiency Design Index (EEDI) and subsequently improving the energy efficiency of vessels. Its low C_F value signifies its potential to contribute to lower EEDI scores, which align with efforts to enhance the environmental performance of ships.

However, work on other zero C_F fuels, such as ammonia, is still ongoing. While these alternative fuels hold promise for reducing emissions and improving energy efficiency, guidelines and regulations defined by the International Maritime Organization (IMO) are yet to be introduced for their widespread adoption in the maritime industry. The development and implementation of such guidelines are crucial steps in ensuring the safe and effective use of these innovative fuels to further reduce the environmental impact of shipping.

6. EEOI

The initial measurement of ship energy efficiency was introduced through circular MEPC.1 Circ. 684 (IMO, 2009), released on August 17, 2009. This measure was entirely voluntary and still is when it was first introduced and was referred to as the EEOI indicator, which stands for Energy Efficiency Operational Indicator.

$$EEOI = \frac{\sum_j FC_j \times C_{Fj}}{m_{cargo} \times D} \quad (9)$$

$$Average\ EEOI = \frac{\sum_i \sum_j \left(FC_{ij} \times C_{Fj}\right)}{\sum_i \left(m_{cargo,i} \times D_i\right)} \quad (10)$$

Unit of EEOI is tonnes of CO_2 released/distance travelled in nautical miles, which depending on cargo can be interpreted as tonnes CO_2/ (TEU* nautical miles) for container ships and tonnes CO_2/ (person* nautical miles) for passenger ships, etc.

6.1 COMPARING EEDI AND EEOI

The Energy Efficiency Operational Indicator (EEOI) and Energy Efficiency Design Index (EEDI) are significant metrics for assessing and enhancing the energy efficiency of vessels. Although closely connected, they fulfil distinct roles and are employed at various points in a ship ‘s life cycle.

EEDI: As explained above, the EEDI is a mandatory metric used to measure the energy efficiency of a new ship ‘s design. It is calculated on the basis of ship ‘s technical specifications and design characteristics, such as its size, speed, and engine efficiency. The purpose of the EEDI is to design and build ships that are more energy-efficient and produce fewer GHG emissions during their operation.

Ships must meet specific EEDI reduction targets over time. The baseline (initial) EEDI level is determined on the basis of ship type and size. New ships are expected to have an EEDI lower than this baseline. The targets become stricter with time, driving the industry to adopt more energy-efficient designs. See Table 1.

EEOI: The EEOI, is a voluntary metric used to assess the actual energy efficiency of a ship during its operational phase. It is calculated on the basis of the amount of fuel consumed in relation to the cargo carried and the distance travelled. The purpose of the EEOI is to provide real-time data on vessel’s energy efficiency and to help identify opportunities for operational improvements that can lead to fuel savings and emission reductions.

The EEOI is often used as a performance benchmark for individual ships and for fleets. It allows the comparison of the energy efficiency of different vessels and the monitoring of the impact of operational practises and maintenance on fuel consumption and emissions.

In summary, EEDI focuses on the energy efficiency of a ship ‘s design and construction, aiming to set higher efficiency standards for new ships. EEOI, on the other hand, assesses a ship ‘s energy efficiency during its operational life, helping to optimise its operations and reduce fuel consumption and emissions.

7. EEXI

7.1 DEFINING EEXI

The Attained Energy Efficiency Existing Ship Index (EEXI) is a metric that quantifies a ship ‘s energy efficiency and is expressed in grams per tonne per nautical mile (g/t*nm).

The Energy Efficiency Existing Ship Index (EEXI) is a metric that evaluates a ship ‘s carbon dioxide (CO_2) emissions per unit of transport work, solely based on the vessel ‘s design characteristics. It does not necessitate the measurement or reporting of actual CO_2 emissions while the ship is in operation. EEXI is essentially the counterpart to the Energy Efficiency Design Index (EEDI), which has been in effect since 2013.

7.2 DETERMINING THE EEXI REFERENCE LINE

EEXI uses the same reference line as EEDI as per Equation (2).

7.3 THE COMPLEX EEXI EQUATION

The EEXI formula was introduced vide resolution MEPC.350(78) (IMO, 2022) adopted on 10 June 2022 and was represented by the following equation:

$$\frac{\begin{array}{c}\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} * C_{FME(i)} * SFC_{ME(i)}\right) \\ + \left(P_{AE} * C_{FAE} * SFC_{AE}\right) \\ + \left(\left(\prod_{j=1}^{M} f_j * \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} * P_{AEeff(i)}\right) C_{FAE} * SFC_{AE}\right) \\ - \left(\sum_{i=1}^{neff} f_{eff(i)} * P_{eff(i)} * C_{FME} * SFC_{ME}\right)\end{array}}{f_i * f_c * f_i * Capacity * V_{ref} * f_w * f_m} \tag{11}$$

It should be noted here that EEDI equation (8) is the same as EEXI equation (9).

In simple terms, it can also be said that EEXI is simply the attained EEDI while the ship is in operation, and it should ideally be either equal to or less than the required EEDI or EEXI (this is based on the required EEDI reference line). Since the ship is in operation and may have been built before 2013 and has not undergone any major conversions, in such a scenario, the required EEXI may be calculated as per the following equation:

$$\text{Required EEXI} \le \left(1 - \frac{y}{100}\right) * EEDI\ Reference\ line \tag{12}$$

where y is the reduction factor, and the EEDI reference line value is the same as that in Table 1.

7.4 COMPARING EEDI AND EEXI

Both EEXI and EEDI serve the same purpose in practise, which is to assess and promote the energy efficiency of ships. However, there is a distinction in their application: EEDI: This index is applicable to new ships during the design and construction phase. It sets energy efficiency standards for new vessels, encouraging the incorporation of efficient design features and technologies into their construction.

EEXI: This index is applied to existing ships. It assesses the energy efficiency of ships that are already in operation on the basis of their design parameters. This allows for the evaluation and potential improvement of the energy efficiency of the existing global fleet.

The primary distinction between the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Existing Ship Index (EEXI) lies in the “reduction factor” applied to each.

EEDI primarily focuses on new ship designs and, establishes reduction factors that become progressively more demanding with each phase. These phases are designed to encourage the incorporation of more energy-efficient technologies and features into new vessels.

On the other hand, EEXI assesses existing ships that, are not built to meet the latest EEDI requirements because they were constructed before those standards were in place. As a result, the reduction factors for EEXI are generally less stringent than those for EEDI. However, some ship types such as container ships, cruise ships, LNG carriers, and gas carriers may face more stringent requirements and need to meet the same level as the accelerated Phase 3 EEDI reduction factors, which became effective from April 1, 2022.

This differentiation recognises the practical challenges and costs associated with retrofitting existing vessels to meet the latest energy efficiency standards while still aiming to improve the overall energy efficiency of the global shipping fleet.

It is also be noted that for existing ships seeking to meet EEXI requirements, the calculation involves using 83% of the limited power to the propeller if engine/shaft power limitation is employed.

Nevertheless, it is essential to highlight that if this 83% value is less than 75% of the main engine’s installed power or maximum continuous rating (MCR) — the same calculation as EEDI — then the lower percentage is used. In essence, this means that for many existing ships, the power value used in the EEXI calculation is lower than that of new ships, resulting in a lower EEXI value. This adjustment makes it relatively easier for existing vessels to meet the EEXI requirements, considering the technical and operational limitations they may face when retrofitting for improved energy efficiency.

In summary, EEXI and EEDI are complementary tools aimed at enhancing the energy efficiency of ships, with EEDI focussed on new ship designs and EEXI addressing existing vessels.

7.5 IMPROVING EEXI

IMO has defined/proposed multiple means to improve the EEXI for existing ships. It should be noted that such means can also be utilised by newer ships and hence ultimately attain a lower EEDI from the beginning.

7.5.1 EPL/SHAPOLI

EPL/ShaPoLi was defined vide resolution MEPC.335(76) (IMO, 2021) adopted on 17 June 2021.

One of the cheapest and simplest means to improve EEXI is the installation of EPL i.e., Engine power limitation which will limit the engine power within the engine optimum setting. As a result, this will have a direct impact on the engine speed which in turn reduces the EEXI.

The engine power limiter (EPL) is a straightforward device that can effectively restrict the maximum engine power by adjusting the fuel index limiter on the engine control system. Importantly, it achieves this without requiring the installation of a complex and extensive system within the existing regulatory framework.

One notable advantage of the EPL is its ease of installation, which can be completed quickly while a ship is in port. Importantly, this installation process does not necessitate updates to the Engine International Air Pollution Prevention (EIAPP) certificate or the NOx technical file. This simplicity and flexibility make EPL a practical and efficient solution for optimising engine power control and ensuring compliance with regulatory requirements.

In contrast, shaft power limitation (ShaPoLi) is a comprehensive system to monitor and control power transmission from a ship ‘s engine to its propeller(s). It includes sensors for measuring torque and rotational speed at the propeller shaft, a data recording and processing device for continuous monitoring and calculation of key data points (such as shaft rotational speed, torque, and power), and a control unit for regulating and optimising the power transmitted by the shaft to the propellers. See Figure 3.

7.5.2 ESD OR INNOVATIVE ENERGY EFFICIENCY TECHNOLOGIES

Energy-saving devices (ESDs), or Innovative energy efficiency technologies are outlined in MEPC.1/Circ.896 (IMO, 2021).

Innovative energy efficiency technologies in the context of the EEDI are categorized into three main groups: Category (A), Category (B), and Category (C). The allocation to these categories is based on the specific characteristics and the impact of these technologies on the EEDI formula.

Furthermore, within Categories (B) and (C), there are subcategories:

- Category (B) is subdivided into two subcategories: (B-1) and (B-2).

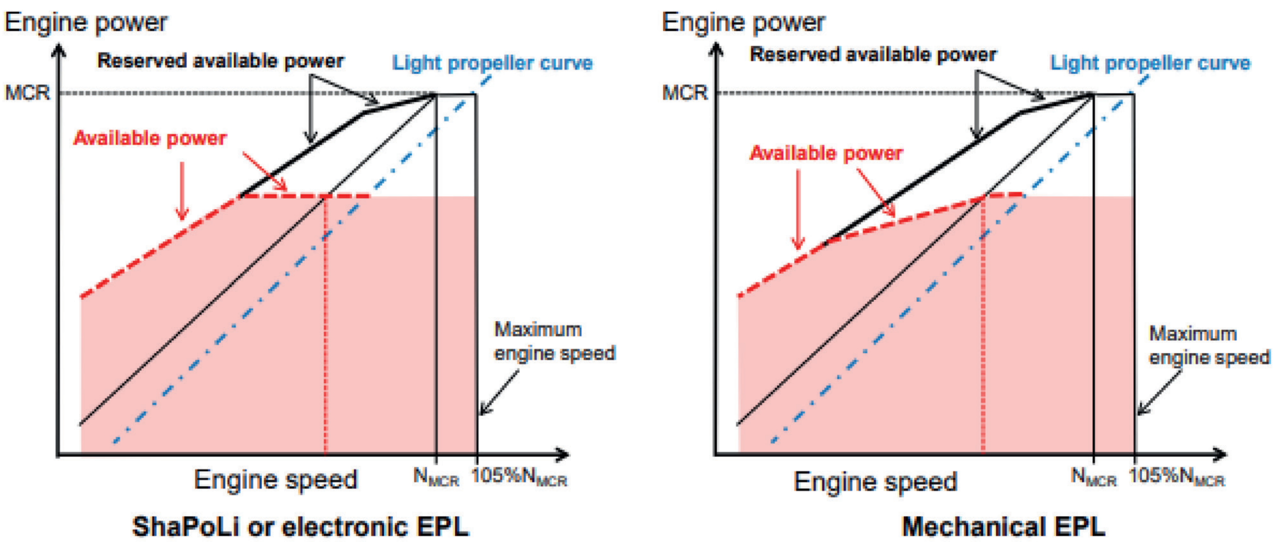

Figure 3. Significance of ShaPoli and EPL. Figure source –MEPC.335(76)[22]

- Category (C) is also subdivided into two subcategories: (C-1) and (C-2).

These subcategories likely represent different degrees of innovation, effectiveness, or applicability of the energy efficiency technologies within the broader categories (B) and (C). This categorisation system helps to classify and evaluate various energy efficiency technologies in the context of ship design and construction, particularly regarding their influence on the EEDI.

The categorisation of innovative energy efficiency technologies within the EEDI framework is as follows:

Category (A): These technologies alter the power curve, resulting in changes to the combination of propulsive power (PP) and reference speed (Vref). For instance, when Vref remains constant, PP decreases, and vice versa.

Category (B): These technologies reduce the propulsion power (PP) at the reference speed (Vref) but do not generate electricity. The saved energy is accounted for as Peff.

- Category (B-1): Technologies in this sub-category can be used at any time during operation, and their availability factor (feff) (8) is treated as 1.00 (full availability).
- Category (B-2): Technologies in this sub-category can only operate at their maximum output under limited conditions, and the availability factor (feff) (8) is set at less than 1.00 (partial availability).

Category (C): These technologies generate electricity, and the saved energy is counted as PAEeff.

- Category (C-1): Technologies in this subcategory can be used at any time during operation, with their availability factor (feff) (8) treated as 1.00 (full availability).
- Category (C-2): Technologies in this sub-category can only operate at their full output under specific conditions, and the availability factor (feff) (8) is set at less than 1.00 (partial availability).

This categorisation system helps assess and classify energy efficiency technologies based on their impact on ship design and operation within the EEDI framework. It distinguishes between technologies that alter the power curve, those that reduce propulsion power, and those that generate electricity, while further differentiating technologies based on their availability and operational characteristics. Figure 4 depicts different types of such technologies.

However, it should be noted that ESDs impact a ship 's operation by typically lowering the necessary engine power by approximately 3-7% during voyages. It is worth noting that when considering the Energy Efficiency Existing Ship Index (EEXI) calculation, ESD primarily influences the ship's speed. Consequently, the resulting improvement in the attained EEXI score is generally in the range of 1-3%.

7.5.3 INCREASING THE DEADWEIGHT

Enhancing the attained EEXI can also be achieved by increasing the ship 's deadweight. However, it is important to note that as deadweight is increased, the required EEXI also becomes more stringent.

Specifically, if the deadweight is increased by 5%, the actual improvement in the EEXI is approximately 1.4%. Nevertheless, it is essential to consider that augmenting the deadweight may not always represent a cost-effective solution for enhancing the ship's attained EEXI.

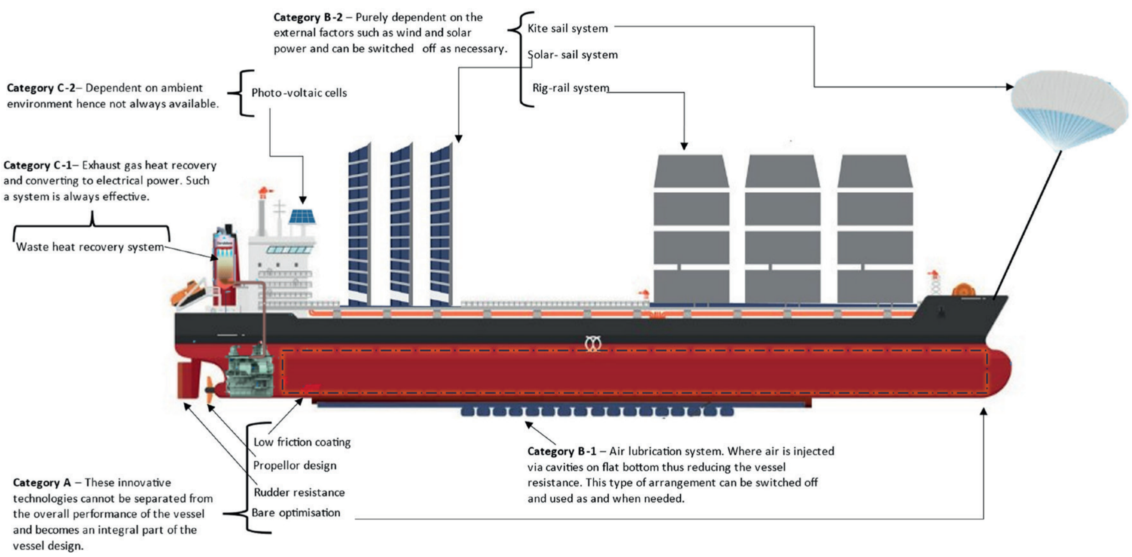

Figure 4. ESD categories

8. CARBON INTENSITY INDICATOR (CII)

8.1 DEFINING CII

The carbon intensity indicator (CII) is a metric used to gauge the efficiency of a ship in transporting goods or passengers. It is expressed in grams of carbon dioxide (CO_2) emissions per unit of cargo-carrying capacity and nautical mile. Ships are assigned an annual rating on a scale from A to E, with rating criteria becoming progressively stricter up to 2030.

The CII applies to all cargo, RoPax (Roll-on/Roll-off passenger), and cruise ships with a gross tonnage (GT) exceeding 5,000. The yearly CII rating is determined on the basis of reported data from the International Maritime Organisation ‘s Data Collection System (IMO DCS). Ships are then classified into one of five rating categories: A to E.

If ships consistently achieve a D rating for three consecutive years or an E rating in a single year, it is necessary to develop and integrate a remedial plan within the Ship Energy Efficiency Management Plan (SEEMP). This plan must be approved to address and rectify the ship ‘s energy efficiency performance.

The fundamental CII is presently computed as the amount of CO_2 emitted per unit of cargo-carrying capacity and nautical mile. There are plans to enhance the CII calculation by introducing correction factors in a separate guideline that will be developed in the upcoming year/s.

At present, the use of actual cargo carried (referred to as the Energy Efficiency Operational Indicator or EEOI as explained above) instead of capacity can only be reported voluntarily and is not used for determining the CII rating.

To streamline the assignment of ratings, a five-grade rating mechanism is established for each year spanning from 2023 to 2030. This mechanism incorporates four boundaries: superior, lower, upper, and inferior. By comparing a ship’s annual operational Carbon Intensity Indicator (CII) with these boundary values, a rating can be determined.

Specific boundaries are established based on the distribution of CIIs among individual ships in 2019. The aim is to achieve the following outcomes:

- The middle 30% of ships within each fleet segment, as measured by their annual operational CIIs, will receive a rating of C.
- The upper 20% and an additional upper 15% of ships will be rated D and E, respectively.
- The lower 20% and an additional lower 15% of ships will be assigned ratings of B and A, respectively.

This rating system is designed to categorise ships on the basis of their carbon intensity performance, aiming to incentivize improvements in environmental efficiency within the maritime industry. See Figure 5.

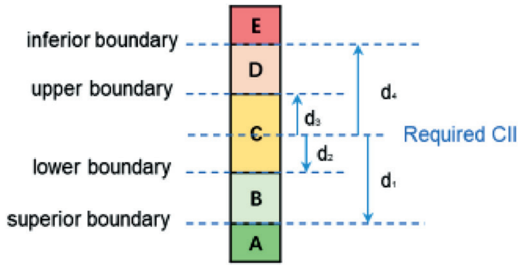

Figure 5. *dd* vector distribution
(Source – MEPC.354(78)) [29]

The boundaries for rating assignments can be established by considering the required annual operational CII in conjunction with vectors. These vectors represent both the direction and the extent to which individual ships deviate from the required value denoted as *dd*. This approach helps determine the specific rating boundaries for ships based on their operational CII performance. Statistically, the directional and distance (*dd*) vectors rely on the distribution of the achieved annual operational CII for ships of the relevant type. This distribution can be estimated through a quantile regression method, using data collected from the Data Collection System (DCS) in 2019 as the sample dataset. See Figure 5. This statistical approach allows for a more precise determination of the vectors and, subsequently, the rating boundaries for different ship types.

CII calculation techniques are illustrated under the following 5 MEPC resolutions:

- MEPC.352(78) 2022 Guidelines on Operational Carbon Intensity Indicators and the Calculation Methods (CII Guidelines, G1) (IMO, 2022)
- MEPC.353(78) 2022 Guidelines on the Reference Lines for Use with Operational Carbon Intensity Indicators (CII Reference Lines Guidelines, G2) (IMO, 2022)
- MEPC.338(76) 2021 Guidelines on the Operational Carbon Intensity Reduction Factors Relative to Reference Lines (CII Reduction Factors Guidelines, G3) (IMO, 2021)
- MEPC.354(78) 2022 Guidelines on the Operational Carbon Intensity Rating of Ships (CII Rating Guidelines, G4) (IMO, 2022)
- MEPC.355(78) 2022 Interim Guidelines on Correction Factors and Voyage Adjustments for CII Calculations (CII Guidelines, G5) (IMO, 2022)

The required annual operational CII for a ship can be calculated using the formula:

$$\text{Required annual operational CII} = \left(1 - \frac{z}{100}\right) * CII_R \quad (13)$$

where Z is the reduction factor, as indicated in Table 5, and CII_R is computed as per equation (14) and the values

Table 5. CII_{ref}, CII reduction factors and *dd* vectors value

Ship Type	**Size**	**CII ref = a * Capacity^{-c}**	**Reduction factor year (Z)**				***dd* vectors (after exponential transformation)**			
			2023	2024	2025	2026	exp(d1)	exp(d2)	exp(d3)	exp(d4)
Bulk carrier	279,000 DWT and above	$4745 * 279{,}000^{-0.622}$					0.86	0.94	1.06	1.18
	Less than 279,000 DWT	$4745*DWT^{-0.622}$								
Gas carrier	65,000 and above	$14405E7*DWT^{-2.071}$					0.81	0.91	1.12	1.44
	Less than 65,000 DWT	$8104*DWT^{-0.639}$					0.85	0.95	1.06	1.25
Tanker	–	$5247*DWT^{-0.610}$					0.82	0.93	1.08	1.28
Container ship	–	$1984*DWT^{-0.489}$					0.83	0.94	1.07	1.19
General cargo ship	20,000 DWT and above	$31948*DWT^{-0.792}$					0.83	0.94	1.06	1.19
	Less than 20,000 DWT	$588*DWT^{-0.3885}$								
Refrigerated cargo carrier	–	$4600*DWT^{-0.557}$					0.78	0.91	1.07	1.20
Combination carrier	–	$5119*DWT^{-0.622}$					0.87	0.96	1.06	1014
LNG Carrier	100,000 DWT and above	$9.827*DWT^{-0.000}$					0.89	0.98	1.06	1.13
	65,000 DWT and above, but less than 100,000 DWT	$14479E10*DWT^{-2.673}$	5%	7%	9%	11%	0.78	0.92	1.10	1.37
	Less than 65,000 DWT	$14479E10*65000^{-2.673}$								
Ro-ro cargo ship (Vehicle carrier)	57,700 GT and above	$3627*57700^{-0.590}$					0.86	0.94	1.06	1.16
	30,000 GT and above but less than 57,700 GT	$3627*GT^{-0.590}$								
	Less than 30,000 GT	$330*GT^{-0.329}$								
Ro-ro cargo ship	–	$1967*GT^{-0.485}$					0.76	0.89	1.08	1.27
Ro-ro passenger ship	Ro-ro passen-ger ship	$2023*GT^{-0.460}$					0.76	0.92	1.14	1.30
	High-speed craft designed to SOLAS chapter X	$4196*GT^{-0.460}$								
Cruise passen-ger ship	–	$930*GT^{-0.383}$					0.87	0.95	1.06	1.16

indicated in Table 5. It is to be noted that CII_R would vary YOY, and values indicated in Table 5 are for the year 2019. At present, the Z value is defined only until the year 2030 as more work needs to be done by the IMO in relation to the same.

8.2 DETEMINING CII REFERNCE LINE (CII_R)

Similar to EEDI and EEXI methodologies, the CII reference line is also determined by the same methodology and uses of the following equation:

$CII_R = (a \times capacity^{-c})$ (14)

8.3 COMPLEX CII EQUATION

Actual interim formula for attained CII as per MEPC.355(78) (IMO, 2022) adopted on 10 June 2022, CII guidelines, G5 is:

Attained CII_{Ship} =

$$\frac{FC_{voyage\,j} + \sum_j C_{Fj}\left\{FC_j - \left(TF_j + (0.75 - 0.03y_i)(FC_{electrival,j} + FC_{boiler,j} + FC_{others,j})\right)\right\}}{f_i * f_m * f_c * f_{iVSE} * capacity * (D_t - D_x)} \quad (15)$$

By incorporating voyage adjustments and correction factors into the formula, the calculated CII_{Ship} provides a more accurate reflection of a ship 's carbon intensity while accounting for various operational conditions and variables that can influence emissions. This modification helps ensure that the CII rating system provides a fair and comprehensive assessment of a ship 's environmental performance.

In simple terms:

CII_{Ship} = [(Total CO_2 Emissions in a Year) - (Voyage Adjustments + Correction Factors)] / (Transport Work in a Year)

In this modified formula:

- Total CO_2 Emissions in a Year represents the sum of all CO_2 emissions produced by the ship during its operations for that year.
- Transport Work in a Year still denotes the amount of work the ship performed in terms of cargo or passengers transported over nautical miles.
- Voyage adjustments are factors that may be applied to account for specific conditions or operational characteristics of certain voyages. These adjustments can either increase or decrease the reported CO_2 emissions for a particular voyage, depending on factors such as route distance, operational practises, or fuel types used.
- Correction Factors are additional adjustments that are made to ensure accuracy and fairness in calculating the CII. These may include factors related to fuel type, measurement methods, or other variables that affect emission calculations.

The attained annual operational CII for international shipping as a whole is calculated by considering the ratio of two aggregated values:

- Aggregated Mass (in grams) of CO_2 Emitted (aggregated M): This represents the total amount of CO_2 emissions from all individual ships of representative ship types during a specific calendar year.
- Aggregated Mass (in tonne·nmiles) of Transport Work Undertaken (aggregated W): This represents the total amount of transport work carried out by all individual ships of representative ship types during the same calendar year.

The formula for calculating the attained CII for international shipping is as follows:

Attained $CII_{shipping}$ = Aggregated M / Aggregated W (16)

This formula provides a comprehensive measure of the carbon intensity of international shipping, considering the emissions relative to the transport work carried out by various representative ship types.

For individual ships, the methodology remains the same, where the attained CII is represented by the following simplified equation:

$$Attained\ CII_{ship} = M / W \quad (17)$$

The total mass of CO_2 emissions from a ship can be calculated as the sum of CO_2 emissions (in grams) resulting from all the fuel oil consumed on board the ship during a specific calendar year. This calculation is expressed as:

$$M = FCj \times CFj \quad (18)$$

Where:

- *M*: This is the total mass (in grams) of CO_2 emissions from the ship for the given calendar year.
- *FCj*: This signifies the total mass (in grams) of fuel oil type *j* consumed by the ship during the calendar year. These data are reported under the International Maritime Organization Data Collection System (IMO DCS).
- *CFj*: Represents the fuel oil mass to CO_2 mass conversion factor for the specific fuel oil type *j*. These factors are in accordance with those outlined in the 2018 Guidelines on the method of calculation of the attained EEDI for new ships (resolution MEPC.308(73) (IMO, 2018)) and may be subject to further amendments. In cases where the fuel oil type is not covered by these guidelines, the conversion factor should be obtained from the fuel oil supplier, supported by appropriate documentary evidence.

This formula allows for the calculation of the total CO_2 emissions from a ship based on its fuel oil consumption and the conversion factors applicable to the specific fuel types used.

When data on the actual transport work is unavailable, a proxy measure called supply-based transport work (*Ws*) can be used. This proxy is calculated as the product of a ship's capacity (*C*) and the distance travelled (*Dt*) during a specific calendar year (IMO, 2022). The formula for *Ws* is as follows:

$$Ws = C \times Dt \tag{19}$$

Here's what the variables signify:

- *Ws*: This is the supply-based transport work, which serves as a proxy for the ship 's actual transport work. It is calculated on the basis of the ship 's capacity and the distance travelled during the calendar year.
- *C*: represents the ship's capacity, which depends on the type of ship:
  - For bulk carriers, tankers, container ships, gas carriers, LNG carriers, general cargo ships, refrigerated cargo carriers, and combination carriers, the appropriate measure for capacity should be deadweight tonnage (DWT).
  - For cruise passenger ships, ro-ro cargo ships (vehicle carriers), ro-ro cargo ships, and ro-ro passenger ships, gross tonnage (GT) should be used as the capacity measure.
- *Dt*: Signifies the total distance travelled by the ship during the calendar year, measured in nautical miles. This distance is reported under the International Maritime Organization Data Collection System (IMO DCS).

This formula provides a way to estimate the transport work of a ship when direct data on actual transport work is not available, using capacity and distance travelled as proxies.

8.3 COMPARING CII, EEDI AND EEXI

The unit of measurement for CII (Carbon Intensity Indicator) is grams of CO_2 emitted per cargo-carrying capacity nautical mile, whereas the unit for EEDI (Energy Efficiency Design Index) or EEXI (Energy Efficiency Existing Ship Index) is also grams of CO_2 emitted per cargo carrying capacity nautical mile. In addition, it is important to note that EEXI considers the vessel 's speed, while CII does not and rely on the distance travelled.

EEDI is determined during a vessel 's initial stages, such as construction or significant modification, and applies to vessels built or modified after 2013. It is also applicable to vessels with a gross tonnage (GT) exceeding 400.

EEXI is assigned to all vessels with a gross tonnage (GT) above 400, regardless of their delivery date.

CII, on the other hand, is relevant for all vessels with a gross tonnage (GT) exceeding 5000, regardless of their construction date.

8.4 ANALYSING THE CII EQUATION

The CII methodology describes the capture of CO_2 for the vessel under operation however, this capture is purely dependent on the DWT of the vessel. It is to be noted here that the equation of the CII involves the usage of ship 's capacity and not the cargo carried, or the tonnes of work performed by the vessel while carrying a certain amount of cargo.

This methodology does not fit well with the definition since the definition makes uses the term "operational" and hence the amount of cargo carried should be considered instead of the full DWT of the vessel.

Furthermore, the CII rating system, which is based on emissions per transport work, provides a strong incentive for shipping companies to optimise the time their ships spend at anchorage or in ports. When a ship is not in motion, its transport work is essentially zero; however, it may still emit CO_2 if auxiliary engines and boilers are running for various shipboard operations.

This means that extended periods of inactivity, such as prolonged anchorage or time spent at berth, can have a significant negative impact on a ship's CII rating (Since the distance travelled reduces and CII is being measured annually). To improve their CII ratings, shipping companies are encouraged to minimise the time their ships spend idle in ports or at anchor.

One strategy to achieve this optimisation is adopting just-in-time (JIT) arrivals. JIT arrivals involve carefully coordinating a ship 's arrival at a port so that it arrives precisely when it is scheduled to berth and unload/load cargo. This reduces the need for the ship to linger at anchorage, waiting for a berth to become available. JIT arrivals not only improve the efficiency of port operations but also contribute to lower emissions and better CII ratings.

In summary, the CII rating system incentivizes shipping companies to reduce idle time at anchorages and in ports, which can be achieved through practises like Just-In-Time arrivals, ultimately leading to lower emissions and improved environmental performance.

The design of the CII formula does pose a challenge for vessels that may spend longer periods in port due to factors such as the extent of cargo discharge or the efficiency of port cargo handling. Vessels that have longer port stays and thus less transport work during those periods may face year-over-year penalties in their CII ratings. This can make it more challenging for them to achieve CII targets compared with vessels that trade between ports with more efficient operations.

The omission of correction factors for certain fuel-consuming activities such as cargo heating, cargo discharge, electrical consumption for refrigerated containers, cargo cooling/reliquification systems on gas tankers, extra fuel consumption by standalone engine-driven cargo pumps, and fuel consumption during STS operations, the calculation of the Carbon Intensity Indicator (CII) attained can indeed present a limitation in accurately assessing a ship 's environmental performance.

These activities, which involve significant fuel consumption and emissions, should ideally be factored into the CII calculation to provide a more comprehensive and representative measure of a ship 's carbon intensity. Ignoring them could lead to underestimating a ship 's true emissions during specific operational phases.

To improve the accuracy of CII assessments, it's essential not to consider incorporating correction factors that account for these additional fuel-consuming activities. This adjustment would provide a more holistic picture of a ship 's emissions profile, especially during critical operational stages when emissions can be higher. This way, the CII system can better incentivize environmentally friendly practises and provide shipping companies with a more accurate basis for improving their environmental performance.

Recognizing and addressing these limitations in the CII calculation is crucial for achieving the environmental goals set by international regulations and promoting sustainability in the shipping industry.

9. THE TRUE MEASURE EEOI WITH CII

Vide MEPC.352(78) (IMO, 2022) adopted on 10 June 2022, CII guidelines G1, para 5, other metrics that may be used for trial purposes are defined.

Among these metrics, the one that is of the greatest interest is EEPI i.e., energy efficiency performance indicator.

EEPI is calculated by the following equation:

$$EEPI = \frac{M}{C \times Dt} \tag{20}$$

Note – EEPI is identical to CII.

Recalling the EEOI equation:

$$EEOI = \frac{\sum_j FC_j \times C_{Fj}}{m_{cargo} \times D} \tag{9}$$

It should be noted that EEPI and EEOI are identical except for the capacity/cargo element in the equations.

EEOI reveals a more realistic approach since it considers the actual cargo being carried on board compared to the EEPI or CII equation, where the total cargo carrying capacity is considered.

EEOI:

- Basis of Calculation: EEOI is calculated as the ratio of the total CO_2 emissions from a ship 's operations (including auxiliary engines) to the actual cargo carried and the total nautical miles travelled.
- Actual cargo carried: EEOI considers the ship 's actual cargo on board when calculating the denominator, which may be less than its full DWT capacity if the ship is not fully loaded.

CII:

- Basis of Calculation: CII is calculated as the ratio of CO_2 emissions to the cargo-carrying capacity and nautical miles travelled,
- Cargo-Carrying Capacity: CII. uses the ship's full deadweight tonnage (DWT) as the denominator, which represents the ship's maximum cargo-carrying capacity.

For maintaining a baseline, if the required CII is calculated using the developed existing methodology with changes to how the CII reference is being measured and EEOI is used instead for attained CII, the actual emissions can be easily compared since a clear emission value while the ship was loaded can be calculated.

In simple terms –

$$\text{Required CII} = 1 - \left(\frac{z}{100}\right) \times CII_R \tag{13}$$

$$\text{Attained CII} = \text{EEOI} = \frac{\sum_j FC_j \times CF_j}{\sum m_{cargo} \times D} \tag{9}$$

The use of the weight of the cargo, rather than the deadweight tonnage (DWT), can provide a more accurate and precise measure of emissions in relation to the ship 's operational conditions. This approach reflects the ship 's actual performance during specific voyages when carrying a certain amount of cargo and emitting a corresponding amount of CO_2. Furthermore, the actual fuel consumed onboard is considered for this calculation and there are no adjustments being made. This means that no voyage adjustments nor any other correction factor is applied.

As per the original methodology, CII reference lines are calculated based on the ship's DWT, which represents its theoretical maximum cargo carrying capacity. In this study, adjustments have been made to the CII reference values to ensure a comprehensive view and precise reference lines. Rather than relying on the deadweight tonnage (DWT) of the ship, which is the usual approach, this study incorporates cargo data to calculate the attained CII. To establish the CII reference lines, the average cargo volume carried by each vessel class throughout the year is considered. The resulting formula for the new CII reference value is given as follows:

$$CII_R = a \times \mu m_{cargo}^{-c} \tag{21}$$

Here, *a* and *c* are coefficients that play a role in defining the reference lines, and *µmcargo* represents the mean cargo volume carried throughout the year for a specific vessel. Values of a and c is calculated using median regression curve fit technique using the attained CII (9) and new cargo data. This adjusted approach provides a more precise representation of a vessel 's performance by considering cargo values in the calculation of the CII reference value.

Using the actual cargo weight as the denominator in the attained CII calculation aligns the indicator more closely with the ship 's real-world emissions, providing a clearer picture of its environmental performance during specific voyages. This approach is valuable for assessing and improving the ship efficiency under practical operational conditions.

To calculate the rating, the Attained CII is divided by the Required CII, and the value is compared with the *dd* directional and distance vectors, and the necessary rating assigned.

Calculating the *dd* vectors, as defined, requires the utilisation of operational CII data collected throughout the previous year. This means that the values used for setting the *dd* vectors in a specific year should be based on the operational CII data collected from the preceding year. Here is how this process works:

- Data Collection (e.g., 2019): Operational CII data for various ships is collected for a specific reference year (e.g., 2019), and the reference line is computed basis average of cargo carried by each vessel type.
- Setting *dd* Vectors: Using the operational CII data collected for the reference year (2019), *dd* vectors are calculated on the basis of distribution of the attained annual operational CIIs of the ships within specific segments or categories.
- Application to Subsequent Years: Once *dd* vectors are set for a reference year (e.g., 2019), they can be applied to calculate CII ratings for subsequent years (e.g., 2020 and beyond). These *dd* vectors serve as reference values for comparing the operational CII of individual ships in subsequent years.
- Rating Assignment: By evaluating the yearly operational CII of a particular vessel in relation to the *dd* vectors, a rating can be designated for the ship within that specific year.

In summary, the *dd* vectors are established on the basis of distribution of operational CIIs from a reference year (e.g., 2019). These vectors are then used in subsequent years to assess and assign CII ratings to individual ships, considering their carbon intensity relative to the reference values. This approach ensures that the CII rating system remains dynamic and adaptable to changing emissions performance over time as not only the reference line is being changed YOY but also the rating thresholds.

The vectors mentioned in the context of calculating the CII ratings depend on the distribution of the attained annual operational CIIs of ships of a specific type. These vectors can be estimated statistically using a method called quantile regression, which uses data collected through the Data Collection System (DCS) in the year 2019 as the sample

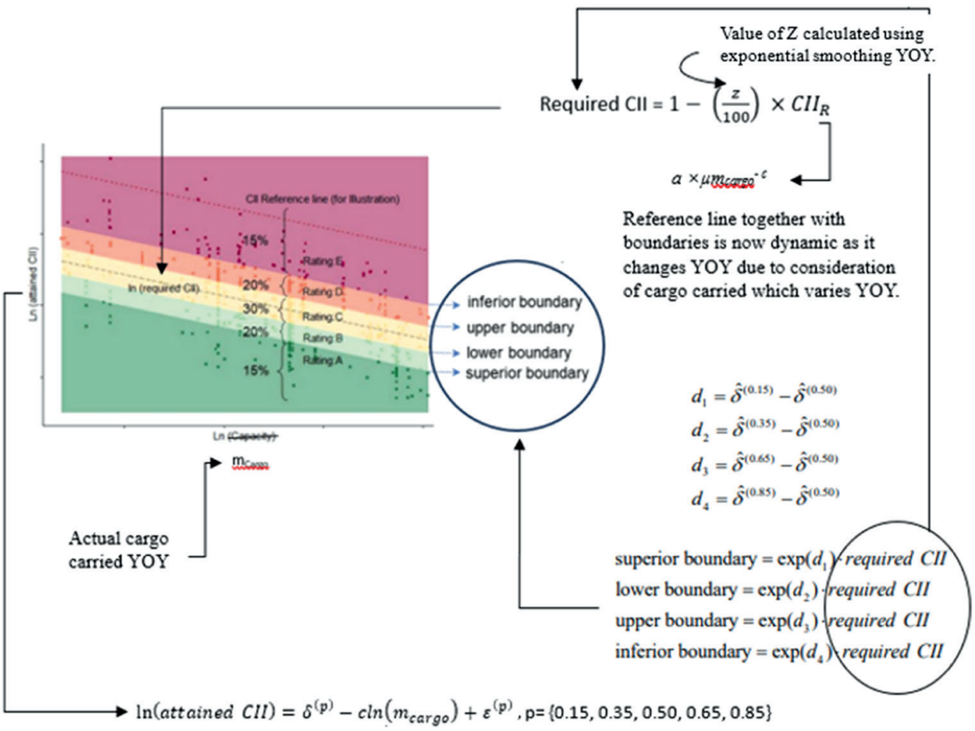

Figure 6. Potential CII accurate ratings measure

and used under MEPC.354(78) (IMO, 2022) adopted on 10 June 2022, CII rating guidelines G4.

Quantile regression is a statistical technique used to model and analyse relationships between variables, specifically focussing on different percentiles of the data distribution. In this case, it's used to estimate the vectors that indicate how much individual ships deviate from the required CII values based on their type.

By examining the data collected in 2019, quantile regression helps determine how various factors affect the CIIs of different ships of the same type, allowing for the establishment of appropriate rating boundaries and the assignment of CII ratings based on ship-specific characteristics and performance. This statistical approach ensures that the rating system accurately reflects the distribution of CIIs across the fleet for a given ship type.

As per the new methodology, again since it is operational CII, which is being used to determine *dd* vectors, here again EEOI is used instead of Attained CII using the DWT. Figure 6 depicts how the reference lines and vectors be calculated as per proposed new methodology.

The quantile regression for specific ship type as represented in MEPC.354(78) (IMO, 2022). is as follows:

$$\text{In (attained } CII) = \delta^{(p)} - cln\ (capacity) + \varepsilon^{(p)} \quad (22)$$

As per proposed new methodology for the scope of this study, capacity may be replaced by m_{cargo}. It is to be noted that value of *c* in equation 22 is derived from MEPC.353(78) (IMO, 2022), however it is not explicitly defined by IMO in MEPC.354(78) (IMO, 2022) regarding the true origins of value of *c*.

In view of the reduction factor, "Z", since the reference line calculation is dynamic, by what percentage the reduction factor be applied in the subsequent year entirely depends on the amount of cargo carried and actual performance of the vessels. Such approach gives a realistic goal setting and provides an opportunity to the ship owners and maritime industry to achieve targets. Use of statistical techniques such as exponential smoothing may provide a feasible methodology to set the Z values.

10. CHALLENGES

Developing such a methodology may pose a big challenge to the IMO because not all shipowners are willing to share their cargo data.

The reluctance of shipowners to share cargo data can be attributed to several factors:

- Competitive Advantage: Shipowners often view cargo data as a competitive advantage. Sharing detailed information about the type, quantity, or destination of cargo may provide insights to competitors, potentially leading to disadvantages in negotiations, pricing, or market positioning.
- Confidentiality: Cargo data may contain sensitive and confidential information, especially when dealing with specific clients or industries. Sharing such data may breach confidentiality agreements and harm business relationships.
- Security Concerns: Cargo data can have security implications, particularly when transporting sensitive or hazardous materials. Revealing this information may pose security risks or regulatory compliance challenges.
- Data Privacy Regulations: In some cases, cargo data may include personal or private information. Compliance with data privacy regulations, such as the General Data Protection Regulation (GDPR) in the European Union, may restrict the sharing of such data without explicit consent.
- Operational Considerations: Shipowners may have concerns about the operational implications of sharing cargo data. Managing and securing data can be resource-intensive, and shipowners may prefer to focus on core shipping operations.
- Market Dynamics: Cargo data can be a valuable commodity in the shipping industry. Some shipowners or charterers may be willing to pay a premium for access to these data, which can serve as an additional revenue stream.
- Lack of Standardization: Standardization and data-sharing protocols in the shipping industry are still evolving. Shipowners may be hesitant to share data without clear industry standards and frameworks in place.

11. CONCLUSION

On the basis of this study, it can be inferred that challenges are attributed not only to the methods of gathering data but also to fostering industry cooperation in pursuit of a shared objective for a sustainable future. Proposed methodology for CII calculation also needs to be further tested with the real-world data to draw concrete conclusions.

Ensuring the accuracy and dependability of CII ratings is contingent upon the precision and trustworthiness of the data utilized to compute emissions concerning cargo capacity and nautical miles. Dubious or erroneous data can yield inaccurate ratings, ultimately subverting the intended purpose of the CII. The voluntary nature of the EEOI poses a challenge in gathering comprehensive and precise data, indicating that mandating EEOI reporting could enhance data availability for CII calculations. Gathering cargo data, especially for diverse ship and cargo types, presents a significant challenge. Streamlining data collection processes and enhancing their accessibility and efficiency could promote broader adoption. The use of statistical methodologies to establish benchmarking thresholds represents a positive step towards establishing equitable and representative rating parameters. Continuous improvement of these techniques, coupled with industry collaboration, has the potential to augment the credibility of CII ratings. Assessing the viability of metrics such as EEOI in real-world scenarios is crucial, encompassing considerations regarding the practicability of data collection methods and their implications for ship operations. Collaborative efforts among various industry stakeholders, such as shipowners, charterers, regulators, and technology providers, are essential to effectively address these challenges. Industry associations and forums can play a pivotal role in the formulation and promotion of best practises. Embracing a regulatory framework that mandates reporting and rating systems, coupled with providing regulatory incentives for emission reduction, can bolster compliance and enhance data accuracy. Moreover, leveraging advancements in digital technologies, including Internet of Things (IoT) sensors and data analytics, can streamline data collection, rendering it more efficient and precise, while also enabling real-time monitoring and reporting.

In summary, while there are challenges in implementing CII and improving the measurement of operational efficiency in the shipping industry, there is also potential for progress. This progress will likely involve a combination of regulatory changes, industry collaboration, improved data collection methods, and the use of advanced technologies. The goal is to create a more transparent and environmentally sustainable shipping sector.

12. ACKNOWLEDGEMENTS

The author would like to extend special thanks to Dr. Lakshmi Subramani from SP Jain School of Global Management for her invaluable guidance, and support throughout this study.

13. REFERNCES

1. BAUMLER, R., ÖLÇER, A.I., PAZAVER, A., NAKAZAWA, T., BALDAUF, M., MOON, D. AND COLE, C., (2014). *Train-the-trainer course on energy efficient operation of ships*. American Journal of Climate Change, 3(04), p.404.
2. BUHAUG, Ø., CORBETT, J., ENDRESEN, Ø., EYRING, V., FABER, J., HANAYAMA, S., LEE, D.S., LEE, D., LINDSTAD, H., MARKOWSKA, A.Z. AND MJELDE, A., (2009). *Second IMO GHG study*.
3. FABER, J., HANAYAMA, S., ZHANG, S., PEREDA, P., COMER, B., HAUERHOF, E., VAN DER LOEFF, W.S., SMITH, T., ZHANG, Y., KOSAKA, H. AND ADACHI, M., (2020). *Fourth IMO GHG Study*.
4. HATTORI, T., NAM, H. AND CHAPMAN, A., (2022). Multilateral energy technology cooperation: *Improving collaboration effectiveness through evidence from International Energy Agency Technology Collaboration Programmes*. Energy Strategy Reviews, 43, p.100920.
5. IMO (2009). *Interim guidelines on the method of calculation of the energy efficiency design index for new ships*, Marine environment protection committee of the organisation by circular MEPC.1/Circ.681, International maritime organisation, London, UK.
6. IMO (2009). *Guidelines for voluntary use of the ship energy efficiency operational indicator (EEOI)*, Marine environment protection committee of the organisation by circular MEPC.1/Circ.684, International maritime organisation, London, UK.
7. IMO (2011). *Report of the Marine Environment Protection Committee on Its Sixty-Second Session*, MEPC 62/24, Agenda item 24, International Maritime Organisation, London UK.
8. IMO (2011). *Amendments to the Annex of the Protocol of 1997 to amend the International Convention for the prevention of pollution from ships, 1973, as modified by the protocol of 1978 relating thereto*, Marine environment protection committee of the organisation by resolution MEPC. 203(62), International Maritime Organisation London UK.
9. IMO (2012). *Guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships, (2012)*, Marine environment protection committee of the organisation by resolution MEPC.212(63), International Maritime Organisation, London, UK
10. IMO (2012). *Amendments to the 2012 guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships*. Marine environment protection committee of the organisation by resolution MEPC.224(64), International Maritime Organisation, London, UK
11. IMO (2012). *Guidelines for Calculation of Reference Lines for use with the Energy Efficiency Design Index (EEDI)*, Marine environment protection committee of the organisation by resolution MEPC 215(63), International Maritime Organisation, London, UK
12. IMO (2013). *2013 Guidelines for Calculation of Reference Lines for Use with the Energy Efficiency Design Index (EEDI)*, Marine environment protection committee of the organisation by resolution MEPC.231(65), International Maritime Organisation, London, UK
13. IMO (2014). *Guidelines on the method of calculation of the attained Energy Efficiency Design Index (EEDI) for new ships*, Marine environment protection committee of the organisation by resolution MEPC.245(66),

International Maritime Organisation, London, UK
14. IMO (2015). *Amendments to the 2014 guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships (resolution MEPC.245(66))*, Marine environment protection committee of the organisation by resolution, MEPC.263(68), International Maritime Organisation, London, UK
15. IMO (2016). *Amendments to the annex of the protocol of 1997 to amend the international convention of pollution from ships, 1973, as modified by the protocol of 1978 relating thereto*, Marine environment protection committee of the organisation by resolution MEPC.278(70), International Maritime Organisation, London, UK.
16. IMO (2016). *Amendments to the 2014 guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships (resolution MEPC.245(66), as amended by resolution MEPC.263(68))*, Marine environment protection committee of the organisation by resolution MEPC.281(70), International Maritime Organisation, London, UK
17. IMO (2017). *2014 Guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships, as amended (resolution MEPC.245(66), as amended by resolutions MEPC.263(68) and MEPC.281(70))*, Marine environment protection committee of the organisation by circular MEPC.1/Circ.866, International Maritime Organisation, London, UK
18. IMO (2018). *2018 Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for New Ships*, Marine environment protection committee of the organisation by resolution MEPC.308(73), International Maritime Organisation, London, UK
19. IMO (2019). *Amendments to the 2018 guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships (resolution MEPC.308(73))*, Marine environment protection committee of the organisation by resolution MEPC.322(74), International Maritime Organisation, London, UK
20. IMO (2020). *Amendments to the annex of the protocol of 1997 to amend the international convention for the prevention of pollution from ships, 1973, as modified by the protocol of 1978 relating thereto*. Marine environment protection committee of the organisation by resolution MEPC.324(75), International Maritime Organisation, London, UK
21. IMO (2021). *Amendments to the 2018 guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships (resolution MEPC.308(73), as amended by resolution MEPC.322(74))*, Marine environment protection committee of the organisation by resolution MEPC.332(76), International Maritime Organisation, London, UK
22. IMO (2021). *2021 guidelines on the shaft / engine power limitation system to comply with the EEXI requirements and use of a power reserve*, Marine environment protection committee of the organisation by resolution MEPC.335(76), International Maritime Organisation, London, UK
23. IMO (2021). *2021 guidance on treatment of innovative energy efficiency technologies for calculation and verification of the attained EEDI and EEXI*. Marine environment protection committee of the organisation by circular MEPC.1/Circ.896, International Maritime Organisation, London, UK
24. IMO (2022). *2022 guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships*. Marine environment protection committee of the organisation by resolution MEPC.364(79), International Maritime Organisation, London, UK
25. IMO (2022). *2022 guidelines on the method of calculation of the attained energy efficiency existing ship index (EEXI)*, Marine environment protection committee of the organisation by resolution MEPC.350(78), International Maritime Organisation, London, UK
26. IMO (2022). *2022 Guidelines on operational carbon intensity indicators and the calculation methods (CII guidelines, G1)*, Marine environment protection committee of the organisation by resolution MEPC.352(78), International Maritime Organisation, London, UK
27. IMO (2022). *2022 Guidelines on the Reference Lines for Use with Operational Carbon Intensity Indicators (CII Reference Lines Guidelines, G2)*, Marine environment protection committee of the organisation by resolution MEPC. 353(78), International Maritime Organisation, London, UK
28. IMO (2021). *2021 guidelines on the operational carbon intensity reduction factors relative to reference lines (CII reduction factors guidelines, G3)*, Marine environment protection committee of the organisation by resolution MEPC.338(76), International Maritime Organisation, London, UK.
29. IMO (2022). *2022 guidelines on the operational carbon intensity rating of ships (CII rating guidelines, G4)*, Marine environment protection committee of the organisation by resolution MEPC.354(78), International Maritime Organisation, London, UK.

30. IMO (2022). *2022 Interim guidelines on correction factors and voyage adjustments for CII calculations (CII guidelines, G5)*, Marine environment protection committee of the organisation by resolution MEPC.355(78), International Maritime Organisation, London, UK
31. JOUNG, T.H., KANG, S.G., LEE, J.K. AND AHN, J., (2020). *The IMO initial strategy for reducing Greenhouse Gas (GHG) emissions, and its follow-up actions towards 2050*. Journal of International Maritime Safety, Environmental Affairs, and Shipping, 4(1), pp.1–7.
32. MARINTEK, T. AND CM, D., (2000). *Study of greenhouse gas emissions from ships*. Final report to the International Maritime Organization.
33. SMITH, T.W.P., JALKANEN, J.P., ANDERSON, B.A., CORBETT, J.J., FABER, J., HANAYAMA, S., O'KEEFFE, E., PARKER, S., JOHANASSON, L., ALDOUS, L. AND RAUCCI, C., 2015. *Third IMO GHG study*.
34. 2023 IMO Strategy on Reduction of GHG Emissions from Ships. https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx. (Last accessed – 15 Sep 2023).