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DIPLOMA THESIS

“CARBON INTENSITY INDICATOR (CII) MODELING”

Diploma Thesis

of

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Abstract

The primary concern in the shipping sector today is the decarbonization of shipping as part of a global campaign to prevent climate change. In this regard, the International Maritime Organization (IMO) recently established new regulations targeted at decreasing emissions per transport work, including the Carbon Intensity Indicator (CII) regulation. The purpose of this dissertation is mainly to present a decision support model that the decision makers can use to have a basis for their decisions of which decarbonization measures should be applied to the vessels, to meet the Carbon Intensity Indicator requirements. Firstly, it is considered essential to present the regulatory framework of all the decarbonization regulations in shipping, paying particular importance to CII regulation. Subsequently, as the essential regulatory basis of the study is set, the tool development is presented. The tool's development is divided into three parts, the first of which is the creation of required Carbon Intensity Indicator reduction factor scenarios since IMO has not yet established reduction factors after 2026[1]. The second one is the calculation of Carbon Intensity Index based on the IMO guidelines, and the third is the integration of decarbonization measures for the reduction of the attained CII. To determine the gain in fuel consumption-, and therefore the impact on CO2 emissions and CII- an assessment for the majority of decarbonization alternatives that are available in shipping industry is necessary. Finally, four vessel application cases are considered with real operational data, with the goal to highlight the importance of the strategy that IMO will follow when it comes to the reduction factors of required CII, and to determine the gain in the attained CII with the application of several decarbonization technologies.

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[1] The thesis work was from 10/2022 to 06/2023 and it doesn't account for MEPC 80 results of June 2023. However, the agreed now zero by 2050 is considered in this thesis.

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1. Introduction

1.1 Motivation

The climatic crisis and the harmful actions linked to human activity that cause it are without a doubt the most important challenges the world is facing today, as the consequences of air pollution are projected to intensify in the years to come and are more obvious than ever. The Paris Agreement, a binding worldwide agreement to prevent disastrous climate change by keeping global warming to well below 2°C and pursuing efforts to limit it to 1.5°C, was negotiated in 2015 at the twenty-first session of the Conference of the Parties (COP21) in Paris by 196 parties. The Intergovernmental Panel on Climate Change (IPCC), a United Nations group that evaluates climate change science, was asked to provide a report on how global warming may be kept to 1.5°C to help with agreement implementation [1]. The IPCC published a special report in 2018 that included carbon budgets and paths for reducing global emissions to keep global warming to 1.5°C [2]. Multiple modeling routes are described in the IPCC report, but they all have the same essential needs for global decarbonization:

- Global GHG emissions must peak between 2020 and 2025 at the latest.
- Global CO_2 emissions must be reduced by 45% by 2030 compared with 2010 levels and reach net zero by 2050.
- The transition must continue beyond 2050 and reach net negative CO2eq levels to compensate for historic emissions.

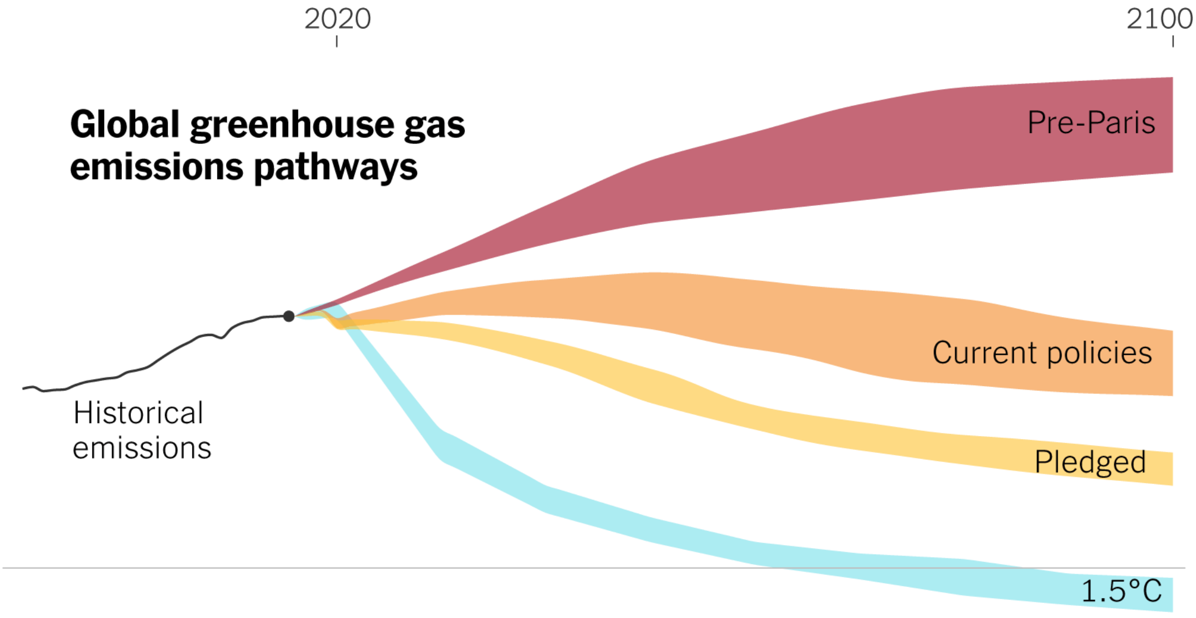


Figure 1: Pathways of greenhouse gas emissions.

Regarding the maritime industry, CO_2 emissions from maritime transport represent 2.89% of total annual anthropogenic greenhouse gas (GHG) emissions, and these emissions are assumed to increase by 150–250% in 2050 in business-as-usual scenarios with a tripling of world trade [3]. Also, according to [4], even though maritime shipping is known for releasing the fewest grams of carbon dioxide (CO2) per tonne-kilometer of cargo transported, it is estimated that sea transportation emissions will reach the road transportation level by 2060. Therefore, the maritime industry must take immediate collective decarbonization action on an unprecedented scale to bring us closer to the Paris 1.5°C trajectory.

In this context, the International Maritime Organization (IMO) decided to adopt an initial strategy aimed at reducing 50% of total GHG emissions by 2050, as well as cutting CO2 emissions per transport work by 40%

until 2030 and 70% until 2050 compared to 2008. The IMO has been developing a regulatory toolbox for increasing technical and operational energy efficiency. There are now four key measures. The Energy Efficiency Design Index (EEDI), which was first implemented in 2013, is a technical measure that defines minimum energy efficiency levels for newly constructed ship designs according to their type and size. It aims to enhance the use of more effective tools and engines on new ships. The Energy Efficiency Existing Ship Index (EEXI), which comes into force in January 2023 and ships must reach EEXI compliance by the first periodical survey in 2023 at the latest, sets almost identical minimum energy efficiency standards for ship designs already in use. The Carbon Intensity Indicator (CII), which comes into effect from January 2023 with the first ratings and reports issued in 2024, uses carbon intensity (CO_2 emissions per transport work) as an operational metric and grading system to assess how effectively a ship delivers its cargo. The Ship Energy Efficiency Management Plan (SEEMP) Part III, which is in force beginning in January 2023 with the initial reports being released in 2024, is a component of the CII that gives ship management and operators a way to track and manage operations and fleet efficiency over time.

Regarding the Carbon Intensity Indicator, there is a cloud of uncertainty as there is no information about the regulations, thereby the required reductions to the factor, after 2026 and the amendments to be nominated and implemented. This means that the operational profile is unpredictable for the years after 2026, altering the trading routes and essentially the commercial setup of the shipping industry. This leads to the need of a calculation tool with adaptability and flexibility, for the creation of a variety of required CII reduction factor scenarios after 2026 and a plethora of different operational profiles. The same need still exists even if the trajectory is known, as with the implementation of decarbonization pathways -various technologies, innovative fuels, operational measures, etc.- the ship's CII can be reduced.

1.2 Scope

The goal of this thesis is to describe and subsequently model the Carbon Intensity Indicator and evaluate its impact on the shipping industry, providing an overview of the measures that are available in the shipping industry. The main target of this thesis is to develop a tool that calculates the CII of the ship dynamically by setting up different operational profiles, creates multiple required CII reduction factor scenarios until 2050 giving flexibility and creativity to the users to choose between lenient, moderate, or strict IMO strategy after 2026, regarding the CII reduction factors. Finally, another aim of the tool is to offer adaptability to ships by choosing between a wide variety of measures so that their CII decreases, improving their rating. One of the limitations of this study is that there are 6 different reduction factor scenarios in 5 different periods from 2026 to 2050 integrated in the tool. Moreover, the sailing operational modes and the speed - fuel consumption curves are restricted to a range of speeds between 8 and 23 knots, as it is assumed that most of the ships sail in this range of speeds. The step of the speed range is 1 knot allowing for the speed-power curve to be modelled appropriately in the tool. The tool is also restricted to only two drafts, laden and ballast, with separate speed-fuel consumption curves for each.

1.3 Organization of Thesis

The present study is structured as follows. The regulatory framework for lowering GHG emissions is addressed in Chapter 2. More explicitly, a rundown of IMO's measures regarding GHG emissions are mentioned, as well as their impact on the shipping industry. Also, CII regulation is described in depth, as it is the main segment of this thesis, and its influence is described. Consequently, Chapter 3 presents the methodology and tool development. The flowchart of the tool is illustrated, an overall tool preview is shown, and the calculations behind the tool are described. In Chapter 4, an overview of the decarbonization alternatives is provided. The tool is then used to demonstrate various application cases, the results of which are presented in Chapter 5. Chapter 6 presents the conclusions and suggestions for future work. Finally, in the Appendixes the input and results of each application case inside the tool are shown.

2. Regulatory framework

The regulatory framework for greenhouse gas emissions from shipping is examined in this chapter. The International Maritime Organization (IMO) is the source of the legislation that will be discussed. It is important to highlight that the regulatory framework only addresses greenhouse gases, leaving out rules for other pollutants including sulphur oxides (SOx) and nitrogen oxides (NOx). The IMO's energy efficiency metrics and its efforts to meet its short, medium, and long-term objectives are outlined. Special emphasis is given to the carbon intensity indicator (CII) and its calculation as they are an essential part of this effort.

2.1 General decarbonization regulations and their impact on shipping industry

2.1.1 Energy Efficiency Design Index (EEDI)

Changes to MARPOL Annex VI were approved at MEPC 62 (July 2011), making the Energy Efficiency Design Index (EEDI) a requirement for newly built ships that are either bulk carriers, combination carriers, container ships, cruise passenger ships, gas carriers, general cargo ships, LNG carriers, refrigerated cargo carriers, RO-RO cargo ships, RO-RO passenger ships, tankers, or vehicle carriers. Ships with a gross tonnage of 400 or more and engaged in international voyages are subject to EEDI regulation. The EEDI is determined for each new design and expresses the amount of CO2 produced (in grams) per ton-miles of carrying capacity. Therefore, the ship is more energy efficient the lower the value is. It expresses the impact on the environment to the benefit for society through freight transportation in its theoretical form.

The full EEDI formula is given by the below form and each parameter is described thoroughly in [5].

$$EEDI = \boxed{\frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE} *\right) + \left(\left(\prod_{j=1}^{n} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME} **\right)}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref}}} \quad (1)$$

The form below provides a succinct explanation of the attained EEDI formula.

$$attained\ EEDI = \frac{P \cdot SFOC \cdot C_f}{Capacity \cdot Speed} \quad (2)$$

Where:

- *P* is the power required from the Main Engine and Auxiliary Engines. The load of the Main Engine(s) is at 75% in most cases and for the Auxiliary Engines is at 50%.
- *SFOC* is the specific fuel consumption of the engines. The SFOC corresponds to 75% load of the Main Engine(s) in most cases and to 50% of the Auxiliary Engines load.
- C_f is the conversion factor of fuel to CO_2 depending on the fuel type.
- *Capacity* represents either 100% of the Deadweight at summer draught, 70% of the Deadweight at summer draught, or the Gross Tonnage depending on ship type.
- *Speed* represents the ship's speed correlating with the aforementioned power of main engine and the draught at which the capacity is represented.

To comply with the regulation, a ship must have an attained EEDI lower than the required EEDI.

$$attained\ EEDI \leq required\ EEDI$$

The regulation specifies the methodology for calculation of the Required EEDI and all relevant details. The Required EEDI is the regulatory limit for EEDI, and its calculation involves use of reference lines and reduction factors. By definition, a reference line is defined as a curve representing an average index value fitted on a set of individual index values for a defined group of ships [6]. The reference line is a function of ship size. Reduction factor, represented in the equation as X, is the percentage points for EEDI reduction relative to the reference line, as mandated by regulation for future years. This factor is used to tighten the EEDI regulations in phases over time by increasing its value. For new ships, the reduction factor X is figured out in stages based on the year of construction. The IMO has developed three phases, each needing progressively less energy (and thus less CO2) to complete the same amount of transport work. The following list of phases, as mentioned by [7], corresponds to the relevant time period:

- Phase 0 - ships built between 2013-2015 are required to have a design efficiency at least equal to the baseline.
- Phase 1 - ships built between 2015-2020 are required to have a design efficiency, at least 10% below the reference line.
- Phase 2 - ships built between 2021-2025 are required to have a design efficiency, at least 20% below the reference line.
- Phase 3 - ships built after 2025 are required to have a design efficiency, at least, 30% below the reference line.

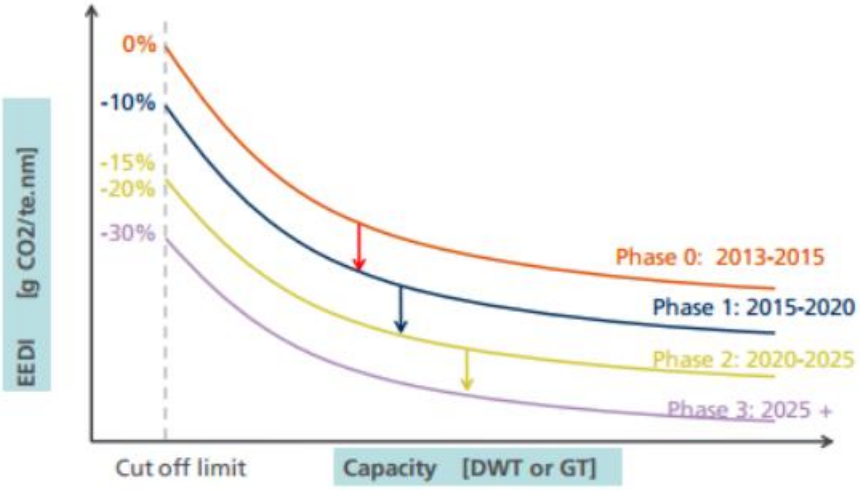


Figure 2: Concept of Required EEDI, reduction factor, and EEDI phases. [8]

Having established the reference lines and the reduction factors, the Required EEDI is calculated from the following equation:

$$required\ EEDI = \left(1 - \frac{X}{100}\right) \cdot reference\ line \qquad (3)$$

2.1.2 Energy Efficiency Existing Ship Index (EEXI)

The Energy Efficiency Existing Ship Index (EEXI) is a measure introduced by the IMO to reduce the greenhouse gas emissions of ships at the 76th Maritime Environment Protection Committee which took place in June 2021. The EEXI is a measure related to the technical design of a ship and almost identical to EEDI, with the distinction between the two being that the EEXI applies to existing vessels whereas EEDI to newly built ships. As is the case for EEDI, the requirements for EEXI must be fulfilled by all ships meeting a minimum size. The minimum size differs from ship type to ship type, varying between 250 and 10,000 DWT. EEXI also applies to the same ship categories as EEDI. To comply with the regulation, a ship must have an attained EEXI lower than the required EEDI.

$$attained\ EEXI \leq required\ EEXI$$

Just like EEDI, the Required EEXI is the regulatory limit for EEXI, and its calculation involves use of reference lines and reduction factors. Regarding the reduction factor, this regulation requires that most of the ships that fall under it need to reduce their attained EEXI to phase 2 EEDI level as defined in [9]. The exemptions are the container ships, cruise ships, LNG carriers, and gas carriers that need to meet phase 3 EEDI level. The reference value of EEXI and EEDI are identical and the guidelines for their calculation are presented in [10].

The formula of attained EEXI is very same with the EEDI one and it is described thoroughly in [11]. However, a point where EEXI does differ from EEDI is the amount of main engine power that goes into the calculation. If an existing ship needs to limit the power to its propeller in order to meet the EEXI by means of engine/shaft power limitation, it is 83% of this limited power that enters the EEXI calculation [12]. Therefore, the formula of the attained EEXI is as follows:

$$EEXI = \boxed{\frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE}*\right) + \left(\left(\prod_{j=1}^{n} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}**\right)}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref}}} \quad (4)$$

The main methods to abide by the regulation are Shaft Power Limitation (ShaPoLi) and Engine Power Limitation, as described in [13].

The following chart provides a detailed description of the EEXI application process.

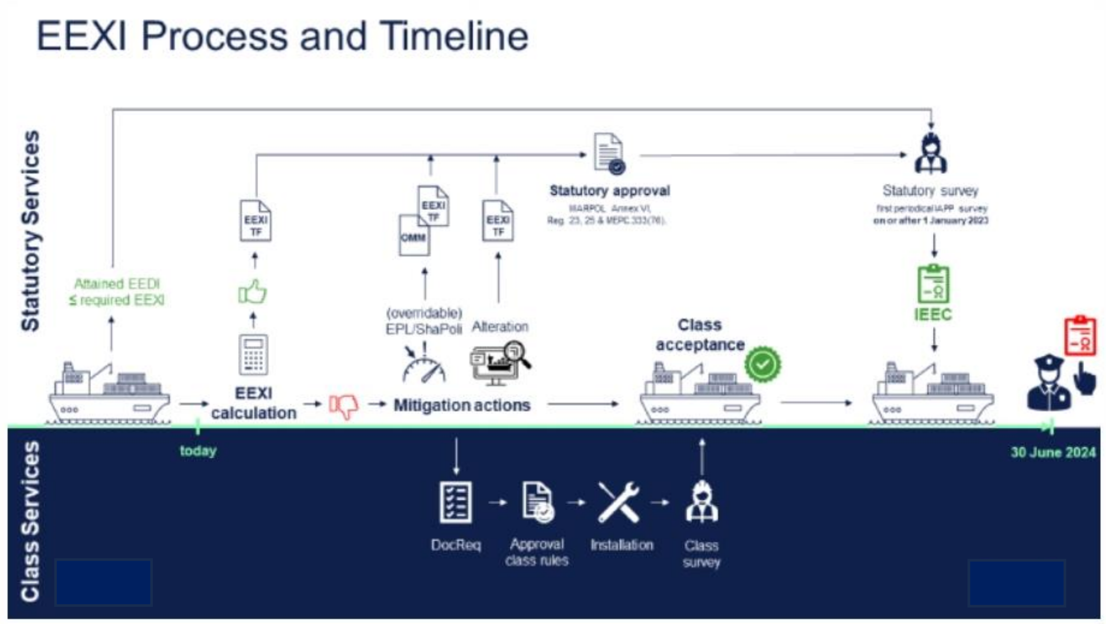


Figure 3: EEXI Process and Timeline. [14]

2.1.3 Ship Energy Efficiency Plan (SEEMP)

According to MARPOL Annex VI Regulation 22, starting on January 1, 2013, all ships over 400 GT operating internationally must have a Ship Energy Efficiency Management Plan (SEEMP) on board. The SEEMP, is an operational measure that creates a mechanism to increase a ship's energy efficiency in a practical way. A SEEMP has three parts.

A strategy for managing fleet efficiency performance over time and lowering the carbon intensity of ship operations is provided by SEEMP part I for shipping corporations. The SEEMP part I as a ship-specific plan should be created by the ship's owner, operator, or any other relevant party, such as the charterer. Planning, implementation, monitoring, self-evaluation, and improvement are the four processes that the SEEMP takes to increase a ship's energy efficiency [15].

The ship fuel oil data collecting plan is another name for the SEEMP Part II. The methods to be utilized to collect the data required to comply with MARPOL Annex VI regulation 27 are described in this section, as well as the steps the ship should take to report the data to its administration, or any other entity properly authorized by it. Any ship with 5,000 GT or more must comply with Part II of the SEEMP [15].

The SEEMP Part III is the most drastic part out of the three regarding GHG emissions. The ship operating carbon intensity plan is another name for SEEMP Part III. Further amendments to MARPOL Annex VI were approved at the IMO's MEPC's 76th meeting in 2021. On January 1, 2023, the CII rating, which is based on the annual fuel usage of each ship, will go into effect. The SEEMP Part III is made to make sure the ship operates effectively and reaches the necessary CII. According to Regulation 26.3.1 of MARPOL Annex VI, the SEEMP must include the following for certain kinds of ships of 5,000 GT and higher on or before 1 January 2023 [15]:

- The description of the methodology that will be used to calculate the ship's attained annual operational CII required by regulation 28 of MARPOL Annex VI and the processes that will be used to report this value to the ship's Administration.
- The required operational CIIs per year for the following three years.
- An implementation plan outlining how the required operational CIIs would be met annually over the following three years.
- A procedure for self-evaluation and improvement.

2.1.4 IMO Data Collection System (DCS)

The International Maritime Organization (IMO) adopted a required Fuel Oil Data Collection System (DCS) for international shipping, mandating ships of 5,000 gross tons or greater to start gathering and reporting data to an IMO database from 2019.According to the approach described in Part II of the SEEMP, ships of 5000 GT and above are expected to submit annual reports to their administration on fuel usage, distance traveled, and hours underway. After the monitoring period has ended, every ship 5000 GT or greater is required to prepare a fuel oil data report using an IMO-provided standardized data reporting format. As noted in [16], the fuel oil data report must contain the following components:

- IMO number.
- Period of calendar year for which the data is submitted (start date and end date).
- Technical characteristics of the ship: Ship type, GT, NT, DWT, Power output of main and auxiliary engines, EEDI (if applicable), Ice class (if applicable).
- Fuel oil consumption, by fuel oil type in metric tonnes and methods used for collecting fuel oil consumption data.
- Distance travelled.
- Hours underway.

2.1.5 Energy Efficiency Operational Indicator (EEOI)

For existing ships, the Energy Efficiency Operational Indicator (EEOI), introduced by the IMO in 2010, is used as a voluntary means of monitoring and managing ship emissions. The objective of EEOI, according to IMO regulations, is to develop a uniform methodology for figuring out a ship's energy efficiency for each journey or over a certain period of time. It is hoped that the EEOI will assist ship owners and operators in evaluating the operational effectiveness of their fleet. In fact, the SEEMP suggests using the EEOI as a monitoring tool. EEOI estimates the CO2 emissions from a ship per ton-mile of cargo transported, much like EEDI and EEXI do. The EEOI, as opposed to the EEDI and EEXI, which are defined for one operating point of a ship, represents the actual CO2 emissions from combustion of all fuel types on board a ship during each voyage. It is calculated by multiplying the total fuel consumption for each fuel type by the appropriate carbon factor for each fuel. Multiplying the actual cargo weight (in tonnes, TEUs, automobiles, or passengers) by the actual distance traveled by the vessel yields the computed amount of transport work.

EEOI for a voyage's basic expression is defined as follows [17]:

$$EEOI = \frac{\sum_j FC_j \cdot C_{f_j}}{m_{cargo} \cdot D}$$

The regulations permit averaging EEOI over several voyages. The EEOI is calculated as follows when the indicator's average is achieved over time (for example, over a year) or over a number of voyages:

$$EEOI = \frac{\sum_i \sum_j \left(FC_{i,j} \cdot C_{f_j}\right)}{\sum_i m_{cargo_i} \cdot D_i} \quad (5)$$

Where:

- *j* is the fuel.
- *i* is the voyage number.
- $FC_{i,j}$ is the mass of consumed fuel *j* at voyage *i*.
- $C_{f,j}$ is the fuel mass to CO_2 mass conversion factor for fuel *j*.
- m_{cargo} is cargo carried (tonnes) or work done (number of TEUs or passengers) or gross tonnes for passenger ships.
- *D* is the distance in nautical miles corresponding to the cargo carried or work done.

2.1.6 Poseidon Principles

Poseidon Principles offer a yardstick by which leading ship-financing institutions can demonstrate their commitment to reduce the greenhouse gas impact of the fleets they finance. Poseidon Principles, that were introduced in 2019, create awareness of the GHG impact of the lending decisions taken, provide a common target for the intended annual improvement, and underline the commitment of the ship finance community to global GHG reduction targets [18]. Making access to finance, conditional upon the level of compliance with environmental measures, seeks to encourage ‘greener’ ships in the industry. The Poseidon Principles are applicable to lenders, lessors, and financial guarantors globally, who are termed as Signatories.

There are four principles per [19]:

- Assessment of climate alignment. Signatories will, on an annual basis, measure the carbon intensity and assess climate alignment (carbon intensity relative to established decarbonization trajectories) of their shipping portfolios.
- Accountability. For each step in the assessment of climate alignment, Signatories will rely exclusively on the data types, data sources, and service providers identified by the IMO’s Fuel Data Collection System (DCS).
- Enforcement. Signatories will agree to work with clients and partners to covenant the provision of necessary information to calculate carbon intensity and climate alignment.
- Transparency. Upon becoming a Signatory, the Signatory will publicly acknowledge that it is a Signatory of the Poseidon Principles. On an annual basis, each Signatory will report the overall climate alignment of its shipping portfolio and supporting information. Also on an annual basis, each Signatory will publish the overall climate alignment of its shipping portfolio in relevant institutional reports.

Needs to be noted that the carbon intensity assessment of a ship is completed by calculating its Annual Efficiency Ratio (AER) which is interchangeable with Carbon Intensity Index (CII).

2.1.7 Sea Cargo Charter (SCC)

Inspired by the launch of Poseidon Principles, initiative action was taken for the creation of Sea Cargo Charter in 2020 from cargo and ship owners. The Sea Cargo Charter (“the Charter”) provides a global transparent framework and baseline for assessing and disclosing the climate alignment of chartering activities against the IMO’s absolute target. The principal aim of the signatories to the SCC is to support and to work towards the decarbonization of international shipping. Other adverse impacts of shipping may also be identified over time for inclusion in the SCC according to [20]. All charterers are eligible signatories, those with interest in the cargo on board, those who simply charter out the vessels they charter in, disponent owners, and in a charterparty chain. The Sea Cargo Charter must be applied in the following bulk chartering activities per [21]:

- On time or voyage charters, including contracts of affreightment and parceling, with a mechanism to allocate emissions from ballast voyages.
- For voyages carried out by dry bulk carriers, chemical tankers, oil tankers and liquefied gas carriers.
- Where a vessel or vessels are engaged in international trade.

Signatories to the SCC commit to the same principles four Poseidon Principles, Assessing of climate alignment, Accountability, Enforcement, Transparency. The differences between Poseidon Principles and Sea Cargo Charter regarding their principles are in the data types, sources and service providers, and the carbon intensity assessment of each ship. In SCC the signatories can only use the data types, sources and service providers identified in chapter 3.3 of Sea Cargo Charter Technical Guidance [21]. Also, the carbon intensity assessment of a ship is completed by calculating its Energy Efficiency Operational Indicator (EEOI).

2.1.8 Impact in shipping industry

The impact in the shipping industry of the aforementioned regulations is undeniable. To begin with, the EEDI promotes the use of more energy efficient (less polluting) design features, equipment, and engines on new ships and on ships undergoing a major conversion. This regulation allows ship designers and builders to choose the technologies needed to ensure ships meet set energy efficiency levels, which increase incrementally every five years. The incremental adjustment of the EEDI encourages continued innovation and technical development to improve the efficiency of ships from the design phase.

EEXI will leave its footprint in the shipping industry starting in 2023. The non-compliant ships of the regulation will have to limit their main engine output either with EPL or ShaPoLi. Therefore, the ships’ speed will be reduced, and this alters their previous operational profile, which could also mean changes in the trading routes and thus the interests of the operator. Last but not least, slower vessels are unattractive to charterers.

Despite being a voluntary index, EEOI is significant in the shipping industry. EEOI is a very helpful tool for tracking a ship's efficiency, which is why Sea Cargo Charter decided to utilize it as the index to measure a ship's carbon intensity. Therefore, the choice of whether to charter a ship or not is greatly influenced by EEOI.

2.2 Detailed description of Carbon Intensity Indicator regulations

2.2.1 Reference Lines

An operational carbon intensity indicator (CII) reference line is defined as a curve representing the median attained operational carbon intensity performance, as a function of Capacity, of a defined group of ships in the year 2019. Due to the scant amount of data for the year 2008, the operational carbon intensity performance of different ship types in the year 2019 is used as the reference. The reference line is formulated as follows per [22]:

$$CII_{ref} = a \cdot Capacity^{-c} \quad (6)$$

Where:

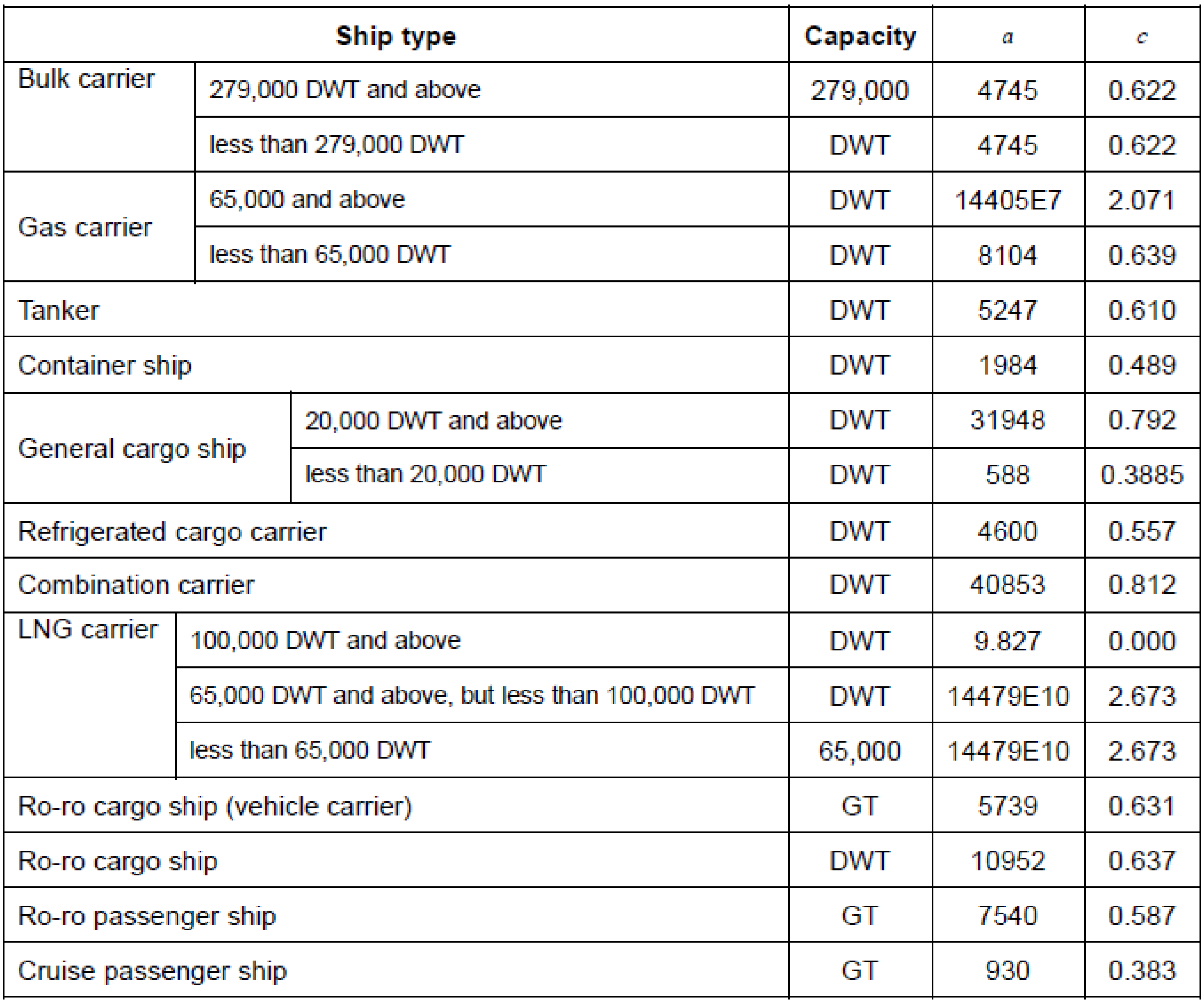
CII_{ref} is the reference value of year 2019 as mentioned.

Capacity represents the ship's capacity:

- For bulk carriers, tanker, container ships, gas carriers, LNG carriers, ro-ro cargos ships, general cargo ships, refrigerated cargo carrier and combination carriers, deadweight tonnage (DWT) should be used as Capacity.
- For cruise passenger ships, ro-ro cargo ships (vehicle carriers and ro-ro passenger ships, gross tonnage (GT) should be used as Capacity.

a and *c* are parameters determined through median regression fits on the achieved CII and Capacity of individual ships from the IMO DCS in 2019. The parameters for determining the ship type specific reference line are specified as follows:

Table 1: Parameters for determining the 2019 ship type specific reference lines. [22]



Ship type		**Capacity**	*a*	*c*
Bulk carrier	279,000 DWT and above	279,000	4745	0.622
	less than 279,000 DWT	DWT	4745	0.622
Gas carrier	65,000 and above	DWT	14405E7	2.071
	less than 65,000 DWT	DWT	8104	0.639
Tanker		DWT	5247	0.610
Container ship		DWT	1984	0.489
General cargo ship	20,000 DWT and above	DWT	31948	0.792
	less than 20,000 DWT	DWT	588	0.3885
Refrigerated cargo carrier		DWT	4600	0.557
Combination carrier		DWT	40853	0.812
LNG carrier	100,000 DWT and above	DWT	9.827	0.000
	65,000 DWT and above, but less than 100,000 DWT	DWT	14479E10	2.673
	less than 65,000 DWT	65,000	14479E10	2.673
Ro-ro cargo ship (vehicle carrier)		GT	5739	0.631
Ro-ro cargo ship		DWT	10952	0.637
Ro-ro passenger ship		GT	7540	0.587
Cruise passenger ship		GT	930	0.383

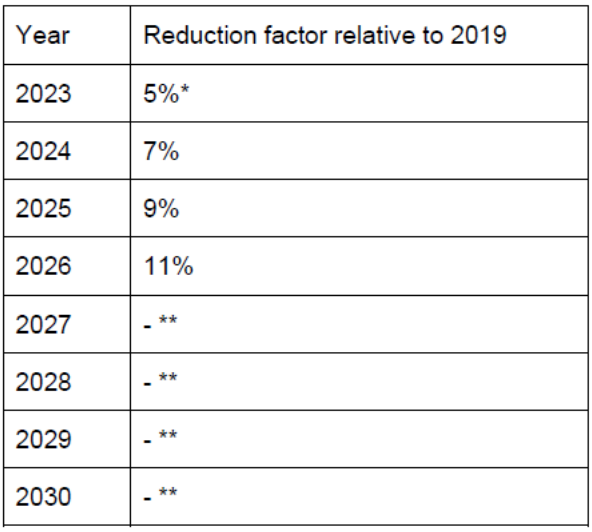
2.2.2 Required CII - Annual reduction of reference value

The required yearly operational CII for a ship is determined using the formula below, as stated in MARPOL Annex VI Regulation 28:

$$Required\ annual\ operational\ CII = \left(1 - \frac{Z}{100}\right) \cdot CII_{ref} \qquad (7)$$

CII_{ref} is the reference value in year 2019 as defined in *2.2.1 Reference Lines*. Factor Z is a general reference to the reduction factors for the required annual operational CII of ship types from year 2023 to 2030 per [23]. Z factors 1%, 2%, 2% are set for the years 2020, 2021, 2022 respectively. Therefore, Z will be starting from 5% in 2023 and 2% will be deducted yearly. Z factors for the years of 2027 to 2030 will be considered and developed taking into account the review of the short-term measure.

Table 2: Reduction factor (Z%) for the CII relative to the 2019 reference line. [23]



Year	Reduction factor relative to 2019
2023	5%*
2024	7%
2025	9%
2026	11%
2027	- **
2028	- **
2029	- **
2030	- **

2.2.3 Attained CII

In its most simple form, the attained annual operational CII of individual ships is calculated as the ratio of the total mass of CO_2 (*M*) emitted to the total transport work (*W*) undertaken in a given calendar year, as follows [24]:

$$attained\ CII_{ship} = {}^{M}/_{W}$$

The total mass of CO_2 is the sum of CO_2 emissions (in grams) from all fuel oil consumed on board a ship during a given calendar year, calculated as follows:

$$M = FC_j \cdot C_{F_j}$$

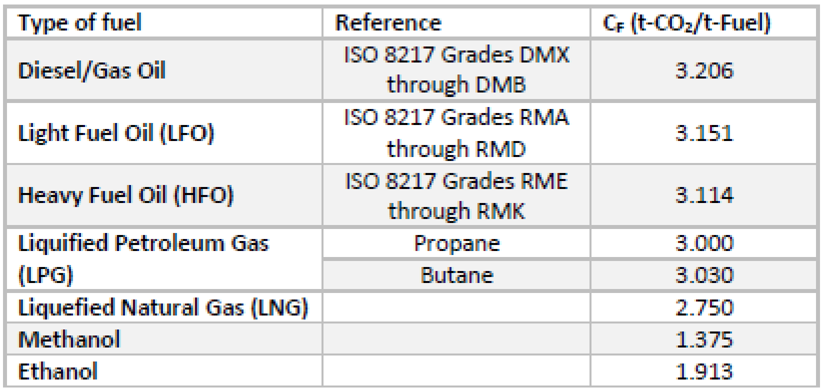
Where:

j is the fuel oil type;

FC_j is the total mass (in grams) of consumed fuel oil type j in the calendar year, as reported under IMO DCS; and

C_{F_j} represents the fuel oil mass to CO_2 mass conversion factor for fuel oil type j, in line with those specified in the 2018 Guidelines on the methods of calculation of the attained Energy Efficiency Design Index (EEDI) for new ships [5], as may be further amended. In case the type of the fuel oil is not covered by the guidelines, the conversion factor should be obtained from the fuel oil supplier supported by documentary evidence.

Table 3: Carbon factors. [5]



Type of fuel	Reference	C_F (t-CO_2/t-Fuel)
Diesel/Gas Oil	ISO 8217 Grades DMX through DMB	3.206
Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	3.151
Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	3.114
Liquified Petroleum Gas (LPG)	Propane	3.000
	Butane	3.030
Liquefied Natural Gas (LNG)		2.750
Methanol		1.375
Ethanol		1.913

In the absence of the data on actual transport work, the supply-based transport work (W_s) can be taken as a proxy, which is defined as the product of a ship's capacity and the distance travelled in a given calendar year, as follows:

$$W_s = Capacity \cdot D_t$$

Where:

Capacity is identical with the one defined in *2.2.1 Reference Lines*.

D_t represents the total distance travelled (in nautical miles), as reported under IMO DCS.

Therefore, the attained annual operational CII in a more developed form would be:

$$attained\ CII_{ship} = \frac{FC_j \cdot C_{F_j}}{Capacity \cdot D_t} \qquad (8)$$

At the 78th MEPC, adopted in June of 2022, CII correction factors for certain ship types, operational profiles and/or voyages were introduced before entry into force of the aforementioned guidelines of MEPC 76. Use of voyage adjustments and correction factors require changes to be made to the overall attained annual operational CII (CII_{Ship}) formula as follows [25]:

$$attained\ CII_{ship} = \frac{\Sigma_j C_{F_j} \cdot \left\{FC_j - \left(FC_{voyage,j} + TF_j + (0.75 - 0.03y_i) \cdot \left(FC_{electrical,j} + FC_{boiler,j} + FC_{other,j}\right)\right)\right\}}{f_i \cdot f_m \cdot f_c \cdot f_{iVSE} \cdot Capacity \cdot \left(D_t - D_\chi\right)} \quad (9)$$

Where:

j is the fuel type.

C_{F_j} as defined above.

FC_j as defined above.

$FC_{voyage,j}$ is the mass (in grams) of fuel type j, consumed in voyage periods during the calendar year which may be deducted from the calculation of the attained CII in case the ship encounters 1 of the following situations:

- scenarios specified in regulation 3.1 of MARPOL Annex VI, which may endanger safe navigation of a ship.
- sailing in ice conditions, which means sailing of an ice-classed ship in a sea area within the ice edge.

In cases where $FC_{voyage,j}$ is used, any associated distance travelled must also be deducted using Dx otherwise ships will benefit from distance travelled without any associated CO_2 emission.

$TF_j = (1 - AF_{tanker}) \cdot FC_{S,j}$ (9.1) represents the quantity of fuel j removed for STS or shuttle tanker operation, where $FC_{S,j}$ for shuttle tankers and $FC_{S,j}$ is the total quantity of fuel *j* used on STS voyages for STS vessels. If $TF_j > 0$ then $FC_{electrical,j} = FC_{boiler,j} = FC_{others,j} = 0$. Moreover regarding AF_{tanker}:

- Tankers engaged in STS voyages may apply the correction factor $AF_{tanker,STS}$ to all fuel consumption relating to STS voyages, including cargo transfer at offshore location, voyage, cargo discharge and waiting periods at anchor or drifting during which the ship reports being part of an STS operation and voyage. The STS operation includes fuel consumption in port where the transferred cargo is discharged after such a voyage. The correction is calculated from the following formula:

  $$AF_{tanker,STS} = 6.1742 \cdot DWT^{-0.246} \quad (9.1.1)$$

  Where $AF_{tanker,STS}$ is applied, $FC_{electrical,j}, FC_{boiler,j}, FC_{others,j}$ should not be used.

  Shuttle tankers equipped with Dynamic Positioning may apply the correction factor $AF_{tanker,Shuttle}$ to total fuel consumption. The correction factor is calculated as:

  $$AF_{tanker,Shuttle} = 5.6805 \cdot DWT^{-0.208} \quad (9.1.2)$$

  Where $AF_{tanker,Shuttle}$ is applied, $FC_{electrical,j}, FC_{boiler,j}, FC_{others,j}$ should not be used.

$FC_{electrical,j}$ is the mass (in grams) of fuel of type j, consumed for production of electrical power during the calendar year which may be deducted from the calculation of the attained CII for the following purposes:

1. For ships carrying refrigerated containers. The correction $FC_{electrical}$ may be applied as follows:
   a. For ships that have the ability to monitor reefer electrical consumption, the ship may calculate reefer container kWh consumption as follows:

      $$FC_{electrical\_reefer,j} = Reefer\ kWh \cdot SFOC \quad (9.2.1)$$

      Where:

$FC_{electrical\_reefer,j}$ (Reefer fuel oil consumption) represents the estimated fuel consumption attributed to in-use refrigerated containers carried.

$Reefer\ kWh$ is measured on the vessel by the kWh meter counter on the vessel.

$SFOC$ represents the specific fuel consumption in g/kWh as a weighted average of the engines used to provide the electrical power, as per the EEDI/EEXI Technical File or the NOx Technical File. In the case of ships without a Technical File, a default value of 175 g/kWh for 2 stroke engines and 200 g/kWh for 4 stroke engines may be applied.

b. For ships that do not have the ability to monitor reefer electrical consumption, the ship may calculate reefer kWh consumption as follows:

$$FC_{electrical\_reefer,j} = C_{\chi} \cdot 24 \cdot SFOC_{avg} \cdot \left(Reefer\_days_{sea} + \sum Reefer\_days_{port}\right) \quad (9.2.2)$$

Where:

C_{χ} represents a default reefer consumption of 2.75 kW/h.

$Reefer\_days_{sea}$ represents the number of in-use reefer-days over the declared period and may be derived using the number of reefer containers as recorded in the BAPLIE file multiplied by the number of days at sea.

$SFOC_{avg}$ represents the specific fuel consumption in g/kWh as a weighted average of the engines used to provide the electrical power, as per the EEDI/EEXI Technical File or NOx Technical File. In the case of ships without a Technical File, a default value of 175 g/kWh for 2 stroke engines and 200 g/kWh for 4 stroke engines may be applied.

In ports where shore-power is not used, the number of in-use reefers at port should be calculated as:

$$Reefer\_days_{port} = \frac{No_c Arrival + No_c Departure}{2} \cdot Days_{port}$$

Where:

$Days_{port}$ represents number of days in port.

$Reefer\_days_{port}$ represents the number of in-use reefer days while at port.

$No_c Arrival$ represents number of reefer containers on arrival.

$No_c Departure$ represents number of reefer containers at departure.

2. For Gas Carriers and LNG Carriers with electrical cargo cooling systems or reliquefication plants. The correction factor $FC_{electrical}$ may be applied as follows:

$$FC_{electrical\_cooling,j} = Cooling\ kWh \cdot SFOC \quad (9.2.3)$$

Where:

$FC_{electrical\_cooling,j}$ (cargo cooling fuel oil consumption) represents the estimated fuel consumption attributed to cooling of gas cargoes.

$Cooling\ kWh$ is measured on the vessel by the kWh meter counter on the vessel.

$SFOC$ represents the specific fuel consumption in g/kWh associated with the relevant source of electrical power as per the EEDI/EEXI Technical File or NOx Technical File. In the case of ships without a Technical File, a default value of 175 g/kWh for 2 stroke engines and 200 g/kWh for 4 stroke engines may be applied.

3. For tankers with directly or indirectly electrically powered discharge pumps, the correction factor $FC_{electrical}$ may be applied as follows:

$$FC_{electrical\_dischare,j} = Discharge\ kWh \cdot SFOC \quad (9.2.4)$$

   Where:

   $FC_{electrical\_dischare,j}$ (cargo discharge fuel oil consumption) represents the estimated fuel consumption attributed to use of cargo discharge pumps.

   $Discharge\ kWh$ is measured on the vessel by the kWh meter counter on the vessel.

   $SFOC$ represents the specific fuel oil consumption in g/kWh associated with the relevant source of electrical power as per the EEDI/EEXI Technical File or NOx Technical File. In the case of ships without a Technical File, a default value of 175 g/kWh for 2 stroke engines and 200 g/kWh for 4 stroke engines may be applied.

$FC_{boiler,j}$ is the mass (in grams) of fuel of type j, consumed by the oil-fired boiler during the calendar year which may be deducted from the calculation of the attained CII, for the purposes of cargo heating and cargo discharge on tankers. This correction factor may be applied for the period that the cargo heating or discharge pumps are in operation:

- In the case of boilers used for cargo heating, the amount of fuel used by the boiler (FC_{boiler}) should be measured by accepted means, e.g. tank soundings, flow meters.
- For tankers which use steam driven cargo pumps, the amount of fuel used by the boiler (FC_{boiler}) should be measured by accepted means, e.g. tank soundings, flow meters.

Some amount of fuel consumed by the boiler during cargo heating or discharge operations may be attributed to other purposes, e.g. calorifiers. It is not necessary to split these out from reporting.

$FC_{others,j}$ is the mass (in grams) of fuel of type j, consumed by standalone engine driven cargo pumps during discharge operations on tankers which may be deducted from the calculation of the attained CII. The amount of fuel used for the period that the discharge pumps are in operation should be measured by accepted means, e.g. tank soundings, flow meters.

f_i is the capacity correction factor for ice-classed ships. Should be calculated as follows [5]:

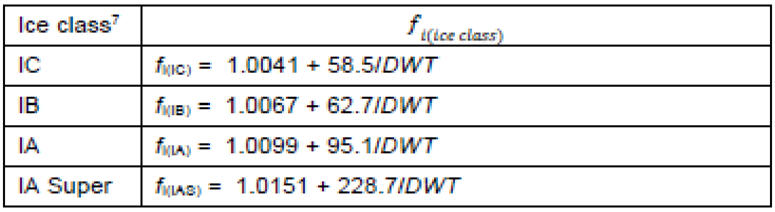
$$f_i = f_{i(ice\ class)} \cdot f_{iC_b} \quad (9.3)$$

Where $f_{i(ice\ class)}$ is the capacity correction factor for ice-strengthening of the ship, which can be obtained from *Table 4*. f_{iC_b} is the capacity correction factor for improved ice-going capability and should not be less than 1.0. f_{iC_b} should be calculated as follows:

$$f_{iC_b} = \frac{C_{b\ reference\ design}}{C_b} \quad (9.3.1)$$

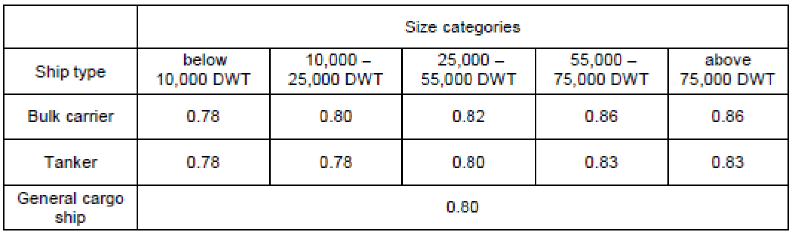
Where $C_{b\ reference\ design}$ is the average block coefficient for the ship type, which can be obtained from *Table 5* for bulk carriers, tankers and general cargo ships, and Cb is the block coefficient of the ship. For ship types other than bulk carriers, tankers and general cargo ships, $f_{iC_b} = 1.0$.

Table 4: Capacity correction factor for ice-strengthening of the hull. [5]



Ice class[7]	$f_{i(ice\ class)}$
IC	$f_{i(IC)} = 1.0041 + 58.5/DWT$
IB	$f_{i(IB)} = 1.0067 + 62.7/DWT$
IA	$f_{i(IA)} = 1.0099 + 95.1/DWT$
IA Super	$f_{i(IAS)} = 1.0151 + 228.7/DWT$

Table 5: Average block coefficients $C_{b\ reference\ design}$ for bulk carriers, tankers, and general cargo ships. [5]



	Size categories				
Ship type	below 10,000 DWT	10,000 – 25,000 DWT	25,000 – 55,000 DWT	55,000 – 75,000 DWT	above 75,000 DWT
Bulk carrier	0.78	0.80	0.82	0.86	0.86
Tanker	0.78	0.78	0.80	0.83	0.83
General cargo ship	0.80				

f_m is the factor for ice-classed ships having IA Super or IA. Should apply as $f_m = 1.05$ [5].

f_c represents the cubic capacity correction factor for chemical tankers. It is expressed by the following formula [5]:

$$f_c = \begin{cases} R^{-0.7} - 0.014, & R < 0.98 \\ 1.000, & R \geq 0.98 \end{cases} \quad (9.4)$$

Where *R* is the is the capacity ratio of the deadweight of the ship (tonnes) divided by the total cubic capacity of the cargo tanks of the ship (m3).

f_{iVSE} represents the correction factor for ship specific voluntary structural enhancement and is expressed by the following formula [5]:

$$f_{iVSE} = \frac{DWT_{reference\ design}}{DWT_{enhanced\ design}} \quad (9.5)$$

Where:

$$DWT_{reference\ design} = \Delta_{ship} - lightweight_{reference\ design} \quad (9.5.1)$$

$$DWT_{enhanced\ design} = \Delta_{ship} - lightweight_{enhanced\ design} \quad (9.5.2)$$

For this calculation the same displacement (Δ) for reference and enhanced design should be taken. $DWT_{reference\ design}$ is the deadweight prior to application of the structural enhancements. $DWT_{enhanced\ design}$ is the deadweight following the application of voluntary structural enhancement.

$Capacity$ is deadweight or gross tonnage as defined in *2.2.1 Reference Lines*.

D_{χ} represent distance travelled (in nautical miles) for voyage periods which may be deducted from CII calculation.

2.2.4 Rating

As defined in [26], an operational energy efficiency performance rating should be annually assigned to each ship in a transparent and robust manner, based on the deviation of the attained annual operational carbon intensity indicator (CII) of a ship from the required value. To facilitate the rating assignment, four boundaries are defined for the five-grade rating mechanism. Superior boundary separates A and B rating, lower boundary separates B and C rating, upper boundary separates C and D rating, and inferior boundary separates D and E rating. The boundaries are set based on the distribution of CIIs of individual sips in the year 2019.

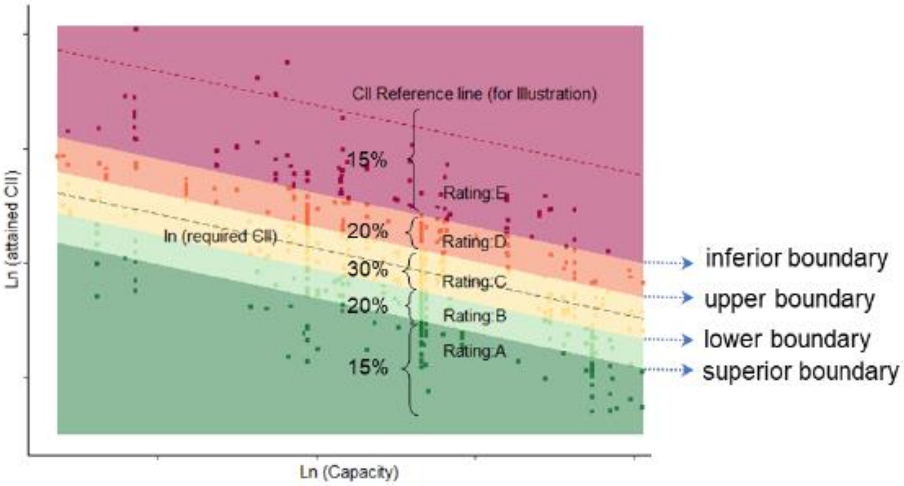


Figure 4: Operational energy efficiency performance rating scale. [26]

The rating boundaries can be established using the necessary annual operational CII along with the vectors, indicating the direction and distance they deviate from the necessary value (denoted as dd vectors).

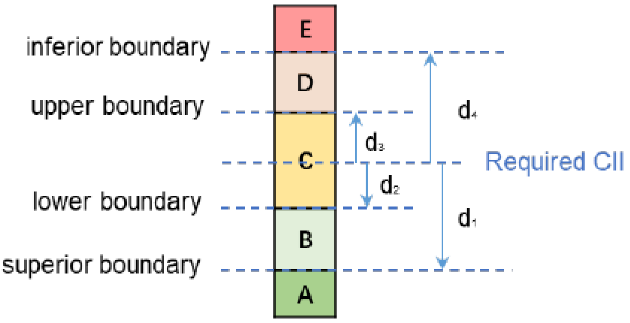


Figure 5: Rating boundaries. [26]

Through an exponential transformation of each dd vector, the four boundaries can be derived based on the required annual operational carbon intensity indicator (required CII), as follows [26]:

$$superior\ boundary = \exp(d1) \cdot required\ CII$$

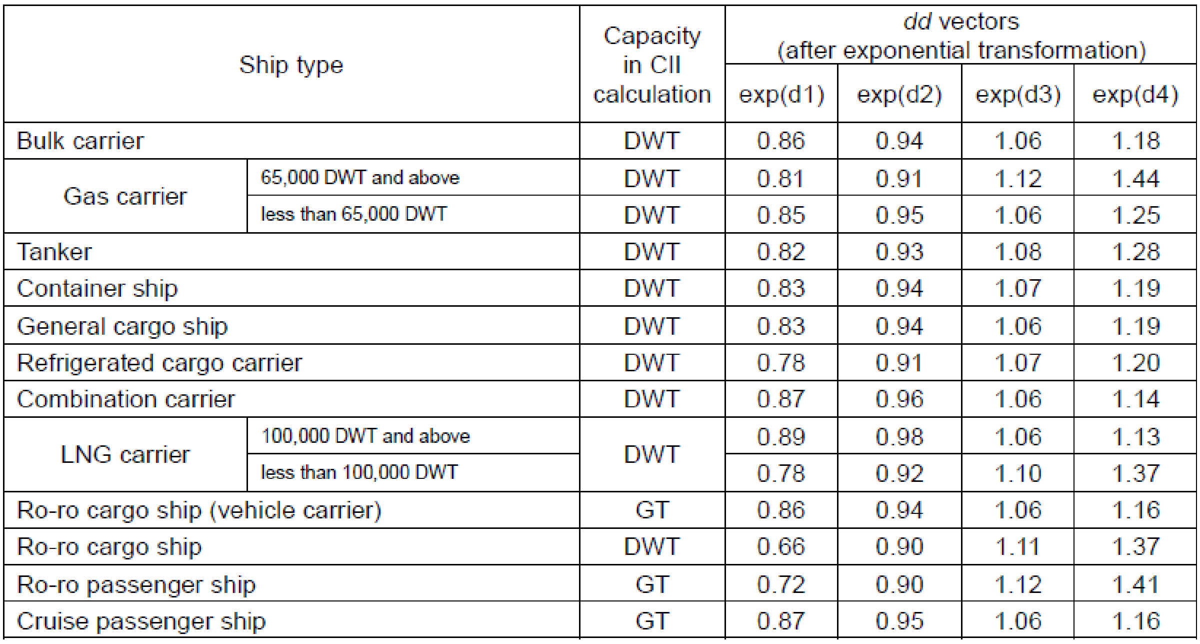
$$lower\ boundary = \exp(d2) \cdot required\ CII$$

$$upper\ boundary = \exp(d3) \cdot required\ CII$$

$$inferior\ boundary = \exp(d4) \cdot required\ CII$$

The estimated dd vectors after exponential transformation for determining the rating boundaries of ship types are as follows:

Table 6: dd vectors for determining the rating boundaries of ship types. [26]



Ship type		Capacity in CII calculation	*dd* vectors (after exponential transformation)			
			exp(d1)	exp(d2)	exp(d3)	exp(d4)
Bulk carrier		DWT	0.86	0.94	1.06	1.18
Gas carrier	65,000 DWT and above	DWT	0.81	0.91	1.12	1.44
	less than 65,000 DWT	DWT	0.85	0.95	1.06	1.25
Tanker		DWT	0.82	0.93	1.08	1.28
Container ship		DWT	0.83	0.94	1.07	1.19
General cargo ship		DWT	0.83	0.94	1.06	1.19
Refrigerated cargo carrier		DWT	0.78	0.91	1.07	1.20
Combination carrier		DWT	0.87	0.96	1.06	1.14
LNG carrier	100,000 DWT and above	DWT	0.89	0.98	1.06	1.13
	less than 100,000 DWT		0.78	0.92	1.10	1.37
Ro-ro cargo ship (vehicle carrier)		GT	0.86	0.94	1.06	1.16
Ro-ro cargo ship		DWT	0.66	0.90	1.11	1.37
Ro-ro passenger ship		GT	0.72	0.90	1.12	1.41
Cruise passenger ship		GT	0.87	0.95	1.06	1.16

A rating can therefore be given by comparing the annual operational CII of a particular ship with the four boundaries.

2.2.5 Corrective actions

A ship rated as D for three consecutive years or rated as E shall develop a plan of corrective actions to achieve the required annual operational CII. The SEEMP shall be examined, taking into consideration the policies that the Organization will establish, to include the plan of corrective actions accordingly. The Administration or any entity properly authorized by it must receive the amended SEEMP for review. Ideally, this should occur concurrently with, but in no case later than one month after reporting the achieved yearly operational CII [10].

2.3 Importance and impact of CII

The ships' business performance may be significantly impacted by the CII ratings. Recently, banks, insurance companies, cargo owners, and charterers all made pledges to cut back on emissions from their various maritime supply chains and portfolios. Therefore, poor CII ratings in the future will drastically lessen the ships' commercial allure. They will not be attractive to charterers since the framework Sea Cargo Charter, which was established to assess and disclose the climate alignment of ship chartering activities, uses carbon intensity as a means of compliance. Their insurance costs will go up. They will not have priority docking in ports and their port fees will go up throughout the world because port authorities use environmental criteria for port access or fees. Also, Companies with high profile ESG reporting (such as IKEA, Walmart, and Amazon) are expected to insert clauses in charter contracts that will require the use of vessels with better CII ratings per [27]. Lastly, ships with poor CII ratings will have limited access to finance since Poseidon Principles was established to assess the climate alignment of ship finance portfolios and uses CII as the index of compliance.

The CII regulation is likely to alter the traditional division of responsibilities between owners and charterers and may significantly change the way vessels are operated. In a time charterparty context, following Charterers' orders in relation to the employment of the vessel could negatively impact the vessel's Attained Annual Operational CII and, in turn, its CII Rating. External circumstances that are beyond the parties' control, such as adverse weather that affects the vessel's carbon intensity over a journey, may also be at play. On the one hand, it would seem unjust to ask Owners to take entire responsibility for this, especially because the CII regime is not under Owners' control. However, charterers have the right to demand that their instructions be followed in exchange for hire since doing otherwise would jeopardize their use of the vessel and expose them to third-party claims for breach of subcontract.

Starting with some important considerations, there must be cooperation and transparency between owner and charterers so that they are aligned in their actions and expectations. Also, continuous evaluation of carbon intensity by both owner and charterer is required to reduce carbon intensity and achieve a good CII rating. Voyages will need to be evaluated for emissions before execution. Moreover, it is essential for both owners and charterers to choose and show what measures they took throughout the calendar year with respect to meeting the agreed CII rating for a vessel. Adding to the above there is uncertainty about the shortcomings of CII. First and foremost, there is no information about the reduction factor after 2026. There is also uncertainty regarding the operational profile of the ships in the next years, which means the trading routes might change, and therefore the commercial setup could be shaken up.

That is where the tool comes to addresses the regulatory uncertainty after 2026 since there is the capability to create a plethora of scenarios after 2026, changing the reduction factor every 5 years until 2050. It also calculates the CII of the ship, giving the users freedom to generate whichever operational profile they conceptualize. Last but not least, there is a wide variety of measures that the users can select for their ship, therefore they can schedule the measures that need to be taken so as to the ship remains to a certain standard throughout the years.

3. Methodology and tool Development

In this chapter the objectives of the tool will be referred, and there will be described the way in which the tool has been formulated. The chapter includes the representation and display of the flowchart, the preview of the tool, as well as the description of the modules and calculations.

3.1 Tool objectives

The purpose of the tool is to calculate the CII for every type of ship, to model the different required CII reduction factor scenarios that will come to effect in the future, and to present different solutions to the users regarding the compliance with the CII regulation. More specifically the tool:

- calculates the CII for every type of ship that falls under the CII regulation dynamically, allowing the users to alter the operational profile, fuel consumption, and the correction factors of the ship, easily.
- offers flexibility and creativity to the users regarding the reduction factor scenarios after 2026 up until 2050. In this way, the ship's CII can be projected until 2050 depending on the IMO strategy that the user will select.
- offers adaptability to ships, as there are measures integrated in the tool that reduce the fuel consumption of main engine(s), auxiliary engines, and boiler(s).

3.2 Flowchart of the tool

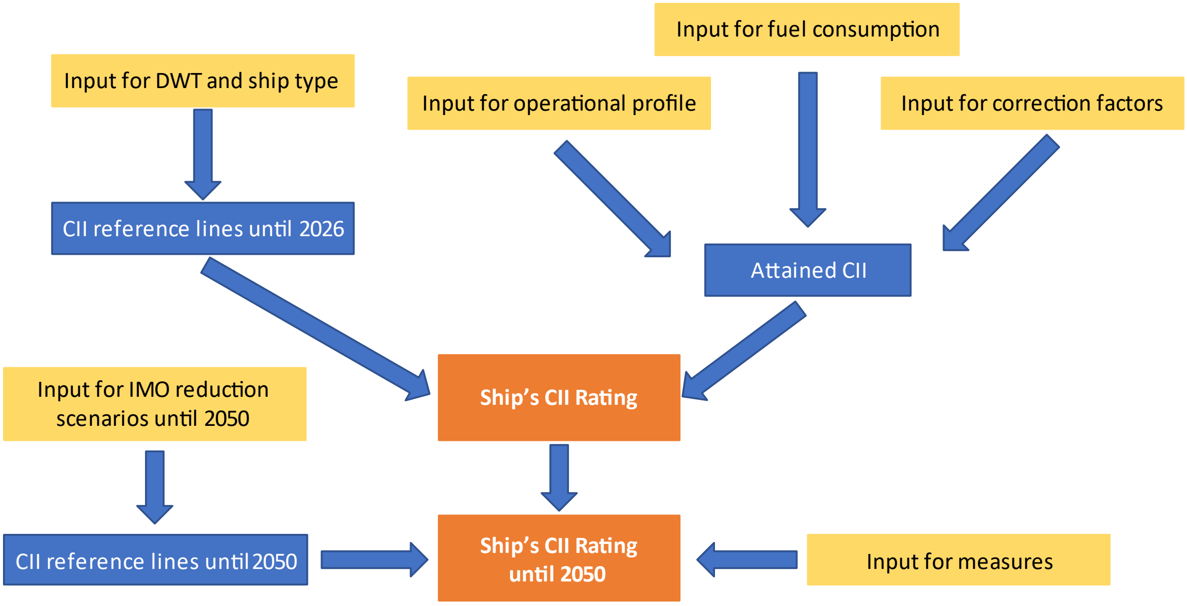


Figure 6: Flowchart of the tool

3.3 Tool description

The tool requires specific data as inputs to compute the desired reference lines of the users past the year 2026 and up until 2050, the CII of the ship in the precise year that the users have chosen. Lastly a variety of measures can be selected so that the attained CII of the ship drops.

For the creation of the reference lines the ship's main particulars shall be filled in. The main particulars of the ship are its name, IMO number, Ship type and Capacity, whether that is the Deadweight or Gross Tonnage of the ship depending on the ship type. The name and IMO number of the ship are optional for the calculations.

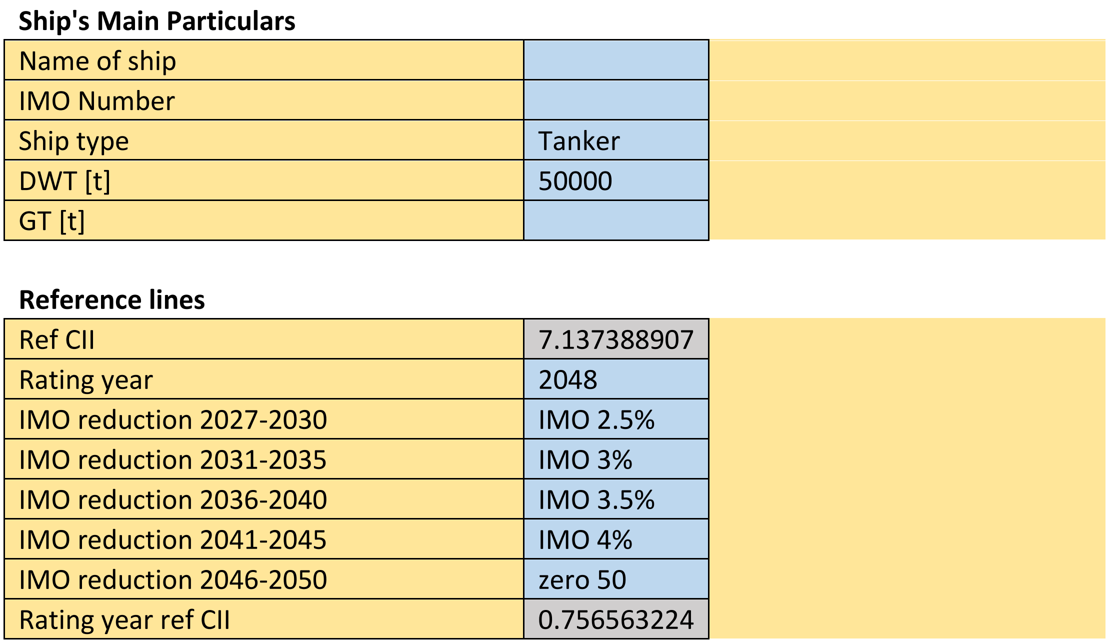
Then, the users have the ability to choose scenarios for the annual drop of CII in the upcoming years. The annual drop is defined as Z by the IMO as stated in *2.2.2 Required CII - Annual reduction of reference value*. The basic assumptions that have been considered are that the drop rate of CII will be reviewed every 5 years starting from 2030 from the Maritime Environment Protection Committee. The annual drop of required CII scenarios that the user can select in the tool are:

- 2% reduction each year in comparison with 2019.
- 2.5% reduction each year in comparison with 2019.
- 3% reduction each year in comparison with 2019.
- 3.5% reduction each year in comparison with 2019.
- 4% reduction each year in comparison with 2019.
- the zero 50 scenario in which the CII is reduced by a specific percentage so that in year 2050 the value of CII equals 0.

As stated in [1], it is important to note that zero 50 is now the adopted scenario by IMO, according to [28], which was not known throughout the writing of this thesis.

Regarding the interface of the tool, it should also be noted that the color light blue illustrates the input cells, gold provides the value explanation, color gray indicates calculation, white color pinpoints that no input is required.

Table 7: Tool's user interface for the input of the main particulars and the required CII reduction factor scenario.



Ship's Main Particulars

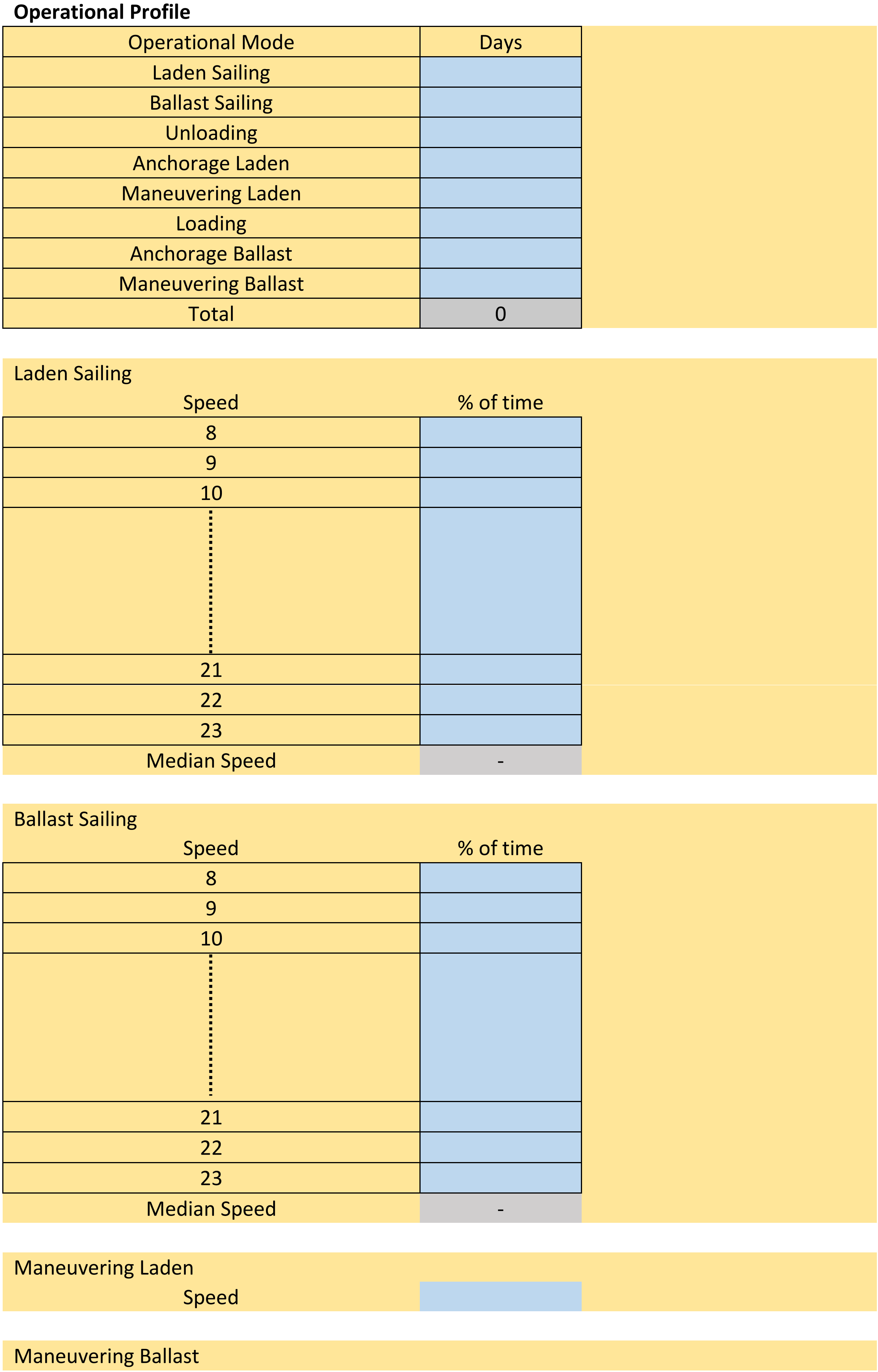
Name of ship		
IMO Number		
Ship type	Tanker	
DWT [t]	50000	
GT [t]		

Reference lines

Ref CII	7.137388907	
Rating year	2048	
IMO reduction 2027-2030	IMO 2.5%	
IMO reduction 2031-2035	IMO 3%	
IMO reduction 2036-2040	IMO 3.5%	
IMO reduction 2041-2045	IMO 4%	
IMO reduction 2046-2050	zero 50	
Rating year ref CII	0.756563224	

Subsequently, the operational profile of the ship is needed so that the distance travelled yearly can be calculated. The operating profile includes the sailing modes of laden, ballast, maneuvering laden, and maneuvering ballast as well as the non-sailing modes of unloading, loading, anchorage ballast, and anchorage laden. The input to be filled in is the days for each operating mode in a year. Also, the percentage of time per year for each speed ranging from 8-23 knots, for ballast and laden mode, are required for the calculation of the nautical miles travelled annually. Lastly the users can input the speed that the ship used while maneuvering in ballast and laden condition.

Table 8: Tool's user interface for the input of the operational profile.



Operational Profile

Operational Mode	Days
Laden Sailing	
Ballast Sailing	
Unloading	
Anchorage Laden	
Maneuvering Laden	
Loading	
Anchorage Ballast	
Maneuvering Ballast	
Total	0

Laden Sailing

Speed	% of time
8	
9	
10	
⋮	
21	
22	
23	
Median Speed	-

Ballast Sailing

Speed	% of time
8	
9	
10	
⋮	
21	
22	
23	
Median Speed	-

Maneuvering Laden

Speed	

Maneuvering Ballast

Speed		

Moreover, to compute fuel consumption in a calendar year, the users shall insert the fuel consumption curve per day, for ballast and laden mode of the ship. The data required for the determination of the fuel consumption curve are the Main Engine(s)’, Auxiliary Engine(s)’, and Boiler(s)’ fuel consumption for each speed ranging from 8-23 knots. Then, the 1st, 2nd, and 3rd type of fuel, and the percentage of which they were used during each mode for the year is needed. Ships generally use Heavy Fuel Oil (HFO), Marine Diesel Oil (MDO), and Low Sulfur Fuel Oil (LSFO) which is a mix of HFO and MDO meaning that ships generally use 2 types of fuel. In case a ship is propelled with a dual fuel engine, it might use 3 types of fuel, 2 for Main Engine and 1 different for Auxiliary Engine(s) and Boiler(s). This is the reason that the users can insert data for 3 types of fuel.

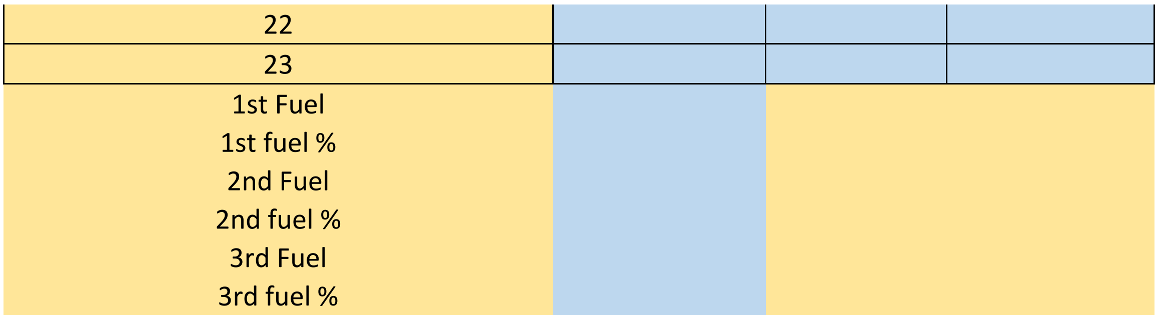
Table 9: Tool's user interface for the input of the fuel consumption when the vessel sails.

Laden Sailing Fuel Consumption

FC Curve			
Speed	ME FC[tn/d]	AE FC[tn/d]	Boiler FC[tn/d]
8			
9			
10			
⋮			
21			
22			
23			
1st Fuel			
1st fuel %			
2nd Fuel			
2nd fuel %			
3rd Fuel			
3rd fuel %			

Ballast Sailing Fuel Consumption

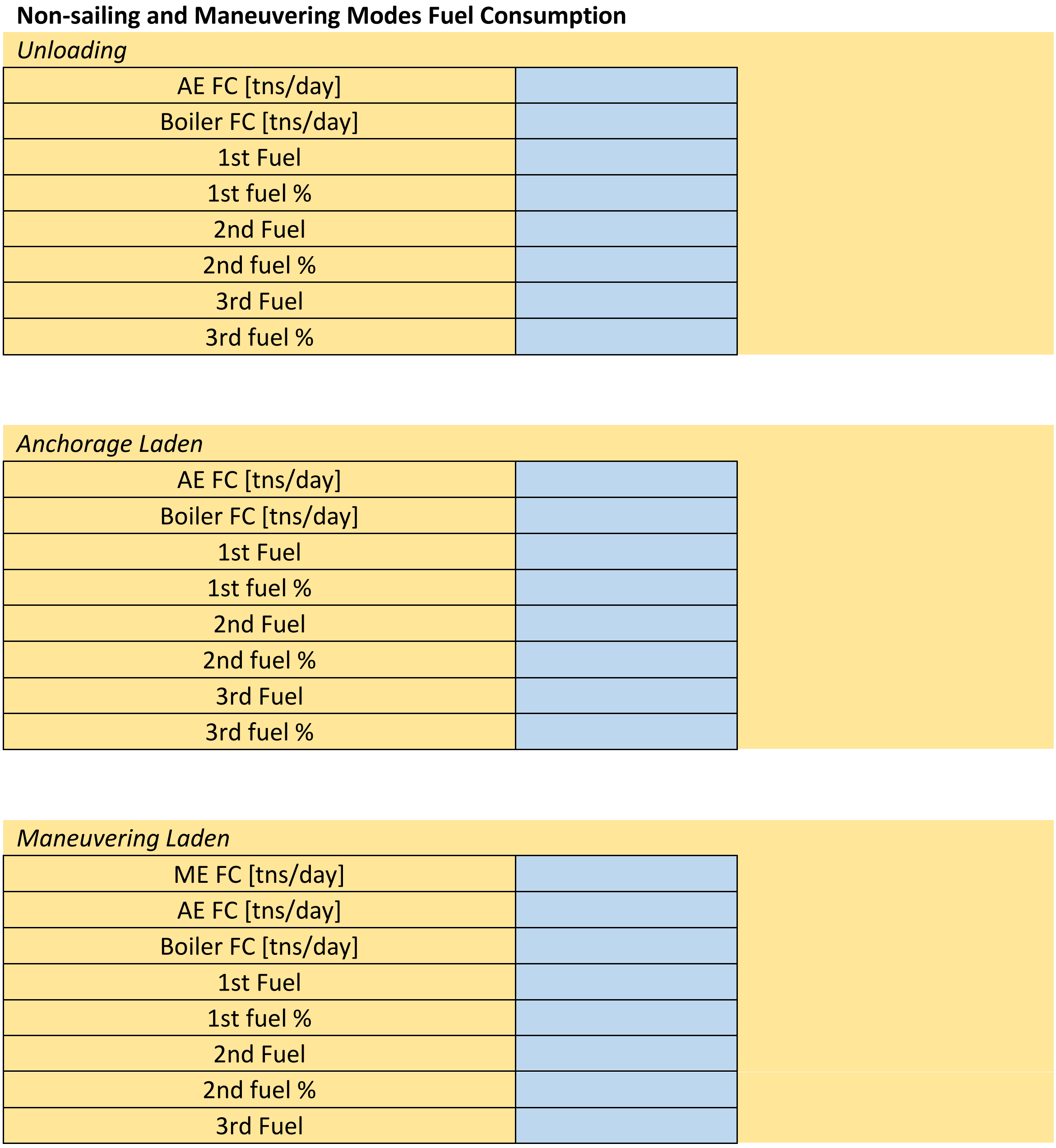
FC Curve			
Speed	ME FC[tn/d]	AE FC[tn/d]	Boiler FC[tn/d]
8			
9			
10			
⋮			
21			



22			
23			
1st Fuel			
1st fuel %			
2nd Fuel			
2nd fuel %			
3rd Fuel			
3rd fuel %			

On the other hand, the necessary data for the fuel consumption of the non-sailing modes and maneuvering modes are much less. The users shall only compile the average main engine(s)', auxiliary engine(s)', and boiler(s)' fuel consumption per day, for the aforementioned non-sailing modes. Also, the 1st, 2nd, and 3rd type of fuel, as well as the percentage of usage for each, in the year, needs to be filled in.

Table 10: Tool's user interface for the input of fuel consumption when the ship is either stationary or manoeuvres.



Non-sailing and Maneuvering Modes Fuel Consumption

Unloading

AE FC [tns/day]	
Boiler FC [tns/day]	
1st Fuel	
1st fuel %	
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Anchorage Laden

AE FC [tns/day]	
Boiler FC [tns/day]	
1st Fuel	
1st fuel %	
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Maneuvering Laden

ME FC [tns/day]	
AE FC [tns/day]	
Boiler FC [tns/day]	
1st Fuel	
1st fuel %	
2nd Fuel	
2nd fuel %	
3rd Fuel	

3rd fuel %	

Loading	
AE FC [tns/day]	
Boiler FC [tns/day]	
1st Fuel	
1st fuel %	
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

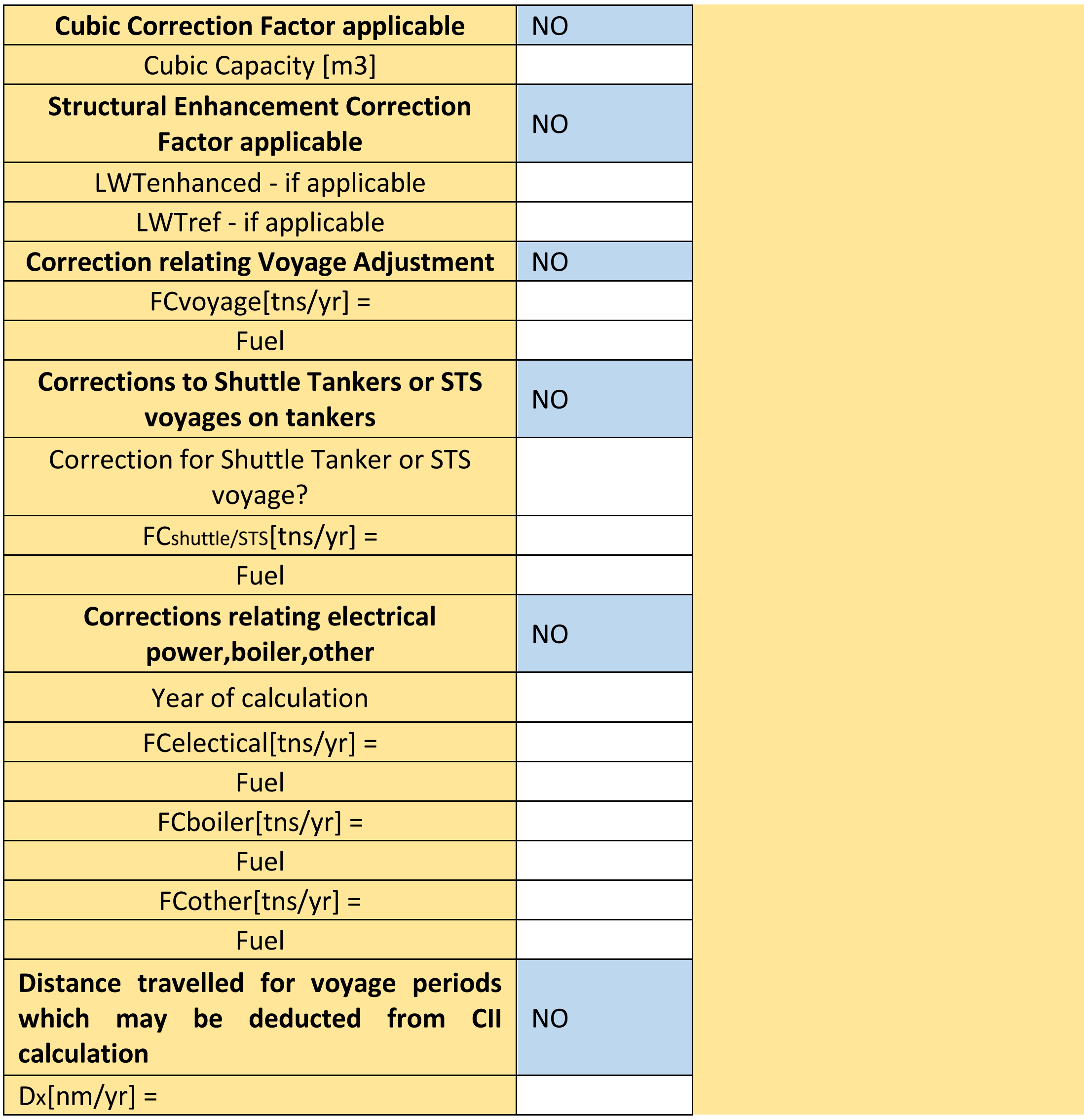
Anchorage Ballast	
AE FC [tns/day]	
Boiler FC [tns/day]	
1st Fuel	
1st fuel %	
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Maneuvering Ballast	
ME FC [tns/day]	
AE FC [tns/day]	
Boiler FC [tns/day]	
1st Fuel	
1st fuel %	
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Ultimately, regarding the calculation of CII, the tool has entries for the specific data needed to evaluate the correction factors based on the operation and construction of the ship, as defined in *2.2.3 Attained CII*.

Table 11: Tool's user interface for the input of correction factors.

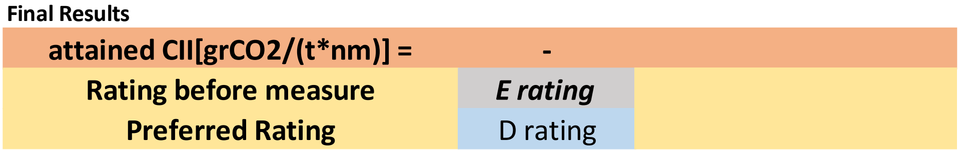
Correction Factors	
Ice class applicable	NO
Type of Ice Class	
Length [m]	
Breadth [m]	
Depth [m]	
Volume of displacement [m3]	



Cubic Correction Factor applicable	NO
Cubic Capacity [m3]	
Structural Enhancement Correction Factor applicable	NO
LWTenhanced - if applicable	
LWTref - if applicable	
Correction relating Voyage Adjustment	NO
FCvoyage[tns/yr] =	
Fuel	
Corrections to Shuttle Tankers or STS voyages on tankers	NO
Correction for Shuttle Tanker or STS voyage?	
FC$_{shuttle/STS}$[tns/yr] =	
Fuel	
Corrections relating electrical power,boiler,other	NO
Year of calculation	
FCelectical[tns/yr] =	
Fuel	
FCboiler[tns/yr] =	
Fuel	
FCother[tns/yr] =	
Fuel	
Distance travelled for voyage periods which may be deducted from CII calculation	NO
D$_x$[nm/yr] =	

Lastly, the tool displays the CII as a number as well as in a graph so that the user has a holistic view of the rating of the ship until year 2050. There is the ability to select 6 out of 40 measures, so that the CII of the ship drops, and the rating improves. Also, the users can input the desired rating that they want for the ship in the upcoming years, and the projection of the year that the ship hits that specific rating is shown for each measure that is chosen. A projection of the years that the ship hits ratings B, C, D, D+2, and E without and with measures applied, is presented in the tool.

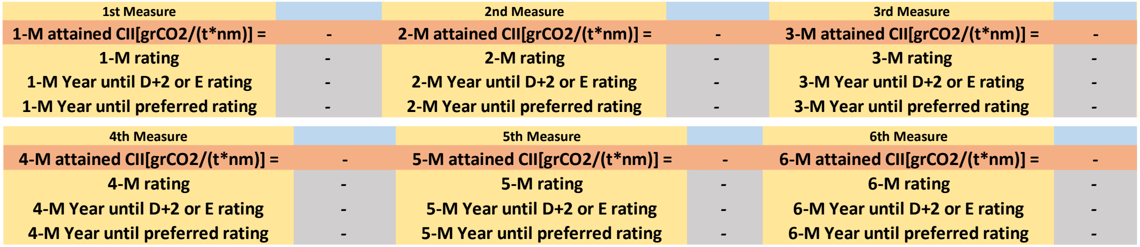
Table 12: Tool's user interface of the results with no additional measure installed.



Final Results

attained CII[grCO2/(t*nm)] =	-
Rating before measure	***E rating***
Preferred Rating	D rating

Table 13: Tool's user interface of the results for each of the 6 measures chosen.



1st Measure		2nd Measure		3rd Measure	
1-M attained CII[grCO2/(t*nm)] =	-	2-M attained CII[grCO2/(t*nm)] =	-	3-M attained CII[grCO2/(t*nm)] =	-
1-M rating	-	2-M rating	-	3-M rating	-
1-M Year until D+2 or E rating	-	2-M Year until D+2 or E rating	-	3-M Year until D+2 or E rating	-
1-M Year until preferred rating	-	2-M Year until preferred rating	-	3-M Year until preferred rating	-
4th Measure		**5th Measure**		**6th Measure**	
4-M attained CII[grCO2/(t*nm)] =	-	5-M attained CII[grCO2/(t*nm)] =	-	6-M attained CII[grCO2/(t*nm)] =	-
4-M rating	-	5-M rating	-	6-M rating	-
4-M Year until D+2 or E rating	-	5-M Year until D+2 or E rating	-	6-M Year until D+2 or E rating	-
4-M Year until preferred rating	-	5-M Year until preferred rating	-	6-M Year until preferred rating	-

Table 14: Year that the CII of the ships hits every rating boundary without and with decarbonization measures selected.

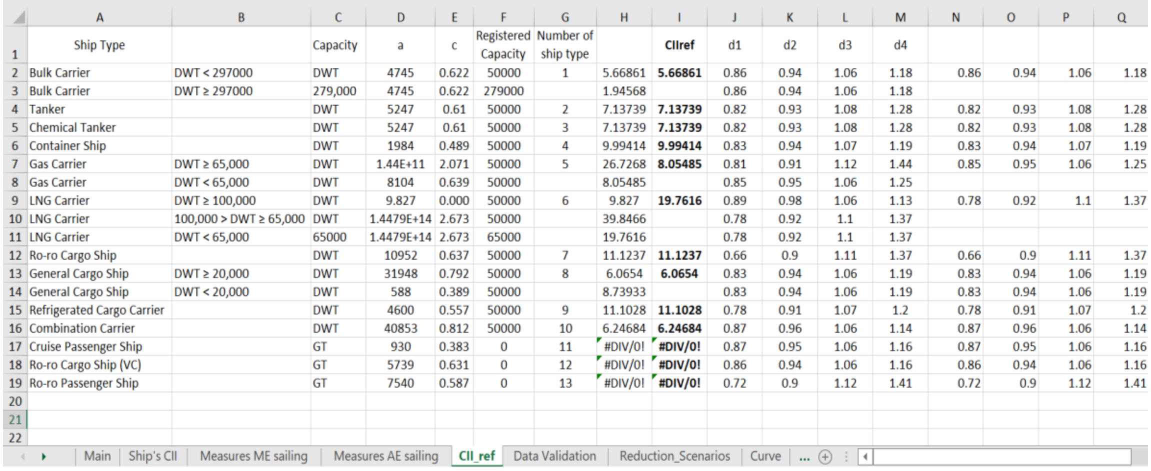
	Year of hit B rating	Year of hit C rating	Year of hit D rating	Year of hit D+2 rating	Year of hit E rating
0-Measure	-	-	-	-	-
1-Measure	-	-	-	-	-
2-Measure	-	-	-	-	-
3-Measure	-	-	-	-	-
4-Measure	-	-	-	-	-
5-Measure	-	-	-	-	-
6-Measure	-	-	-	-	-

Figure 7: Tool's graphical display of the ship's operational energy efficiency performance.

3.4 Descriptions of Modules and calculations

3.4.1 Reference Lines

For the calculation of the reference value of 2019, a worksheet is created where CIIref is computed for every ship type. For the ship types of which the CIIref equation changes based on the deadweight (e.g. Bulk Carrier, LNG Tanker etc.), CIIref is calculated with the IF function- which in excel performs logical comparisons between values-, depending on the input for the deadweight. Then, using a lookup built-in Excel function (VLOOKUP), based on the input for the ship type of the user, the tool displays the specific CIIref in the Main worksheet. Also, regarding the ship types of which the rating boundaries change based on the deadweight (e.g. Bulk Carrier, LNG Tanker etc.), with the IF the necessary rating borders are applied.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	Ship Type		Capacity	a	c	Registered Capacity	Number of ship type		**CIIref**	d1	d2	d3	d4				
2	Bulk Carrier	DWT < 297000	DWT	4745	0.622	50000	1	5.66861	**5.66861**	0.86	0.94	1.06	1.18	0.86	0.94	1.06	1.18
3	Bulk Carrier	DWT ≥ 297000	279,000	4745	0.622	279000		1.94568		0.86	0.94	1.06	1.18				
4	Tanker		DWT	5247	0.61	50000	2	7.13739	**7.13739**	0.82	0.93	1.08	1.28	0.82	0.93	1.08	1.28
5	Chemical Tanker		DWT	5247	0.61	50000	3	7.13739	**7.13739**	0.82	0.93	1.08	1.28	0.82	0.93	1.08	1.28
6	Container Ship		DWT	1984	0.489	50000	4	9.99414	**9.99414**	0.83	0.94	1.07	1.19	0.83	0.94	1.07	1.19
7	Gas Carrier	DWT ≥ 65,000	DWT	1.44E+11	2.071	50000	5	26.7268	**8.05485**	0.81	0.91	1.12	1.44	0.85	0.95	1.06	1.25
8	Gas Carrier	DWT < 65,000	DWT	8104	0.639	50000		8.05485		0.85	0.95	1.06	1.25				
9	LNG Carrier	DWT ≥ 100,000	DWT	9.827	0.000	50000	6	9.827	**19.7616**	0.89	0.98	1.06	1.13	0.78	0.92	1.1	1.37
10	LNG Carrier	100,000 > DWT ≥ 65,000	DWT	1.4479E+14	2.673	50000		39.8466		0.78	0.92	1.1	1.37				
11	LNG Carrier	DWT < 65,000	65000	1.4479E+14	2.673	65000		19.7616		0.78	0.92	1.1	1.37				
12	Ro-ro Cargo Ship		DWT	10952	0.637	50000	7	11.1237	**11.1237**	0.66	0.9	1.11	1.37	0.66	0.9	1.11	1.37
13	General Cargo Ship	DWT ≥ 20,000	DWT	31948	0.792	50000	8	6.0654	**6.0654**	0.83	0.94	1.06	1.19	0.83	0.94	1.06	1.19
14	General Cargo Ship	DWT < 20,000	DWT	588	0.389	50000		8.73933		0.83	0.94	1.06	1.19	0.83	0.94	1.06	1.19
15	Refrigerated Cargo Carrier		DWT	4600	0.557	50000	9	11.1028	**11.1028**	0.78	0.91	1.07	1.2	0.78	0.91	1.07	1.2
16	Combination Carrier		DWT	40853	0.812	50000	10	6.24684	**6.24684**	0.87	0.96	1.06	1.14	0.87	0.96	1.06	1.14
17	Cruise Passenger Ship		GT	930	0.383	0	11	#DIV/0!	**#DIV/0!**	0.87	0.95	1.06	1.16	0.87	0.95	1.06	1.16
18	Ro-ro Cargo Ship (VC)		GT	5739	0.631	0	12	#DIV/0!	**#DIV/0!**	0.86	0.94	1.06	1.16	0.86	0.94	1.06	1.16
19	Ro-ro Passenger Ship		GT	7540	0.587	0	13	#DIV/0!	**#DIV/0!**	0.72	0.9	1.12	1.41	0.72	0.9	1.12	1.41
20																	
21																	
22																	

Figure 8: Calculation of reference CII and rating boundaries for each ship type inside the tool.

When it comes to the calculation of the reference CII after year 2026, depending on the user's choice from the required CII reduction factor scenarios of the tool for the period of 2027-2030, 2031-2035, 2036-2040, 2041-2045, 2046-2050, the reduction factor will get greater linearly for the separate time periods. The deduction for the scenarios of IMO 2%, IMO 2.5%, IMO 3%, IMO 3.5%, IMO 4% is 0.02, 0.025, 0.03, 0.035, 0.04 respectively. The difficult part of this calculation was for the scenario of zero50, as the deduction is different for each period. The constant reduction for every period of the zero50 scenario is calculated in the tool as follows:

$$zero50\_1 = factor\ of\ refCII_{2026}/(2050-2026) \quad (10.1)$$

$$zero50\_2 = factor\ of\ refCII_{2030}/(2050-2030) \quad (10.2)$$

$$zero50\_3 = factor\ of\ refCII_{2035}/(2050-2035) \quad (10.3)$$

$$zero50\_4 = factor\ of\ refCII_{2040}/(2050-2040) \quad (10.4)$$

$$zero50\_5 = factor\ of\ refCII_{2045}/(2050-2045) \quad (10.5)$$

Where the factor of refCII equals to 1 minus the reduction factor for the specific year. The scenario zero50-1, zero50-2, zero50-3, zero50-4, and zero50-5 correspond to the period 2027-2030, 2031-2035, 2036-2040, 2041-2045, and 2046-2050 respectively.

3.4.2 CII Calculation

For the calculation of the ship's CII, the nautical miles travelled annually, the CO_2 emitted during the year, and the correction factors that are eligible to be applied for the ship are needed.

Starting with the nautical miles, the tool may determine the distance traveled by the ship annually after the user inputs the days for each operational mode and the percentages during the year for 16 speeds, ranging from 8 to 23 knots with a step of 1 knot, that the ship sails in laden and ballast mode. Also, if the ship maneuvered during the year, the users shall input the speed in which the ship maneuvered in ballast and laden, so that the total nautical miles travelled can be computed. The calculation is completed as follows:

$$sum_{sailing\ modes}\left[\frac{days}{year}\right] = ballast + laden + maneuvering_{ballast} + maneuvering_{ballast} \tag{11.1}$$

$$sum_{non-sailing\ modes}\left[\frac{days}{year}\right] = unloading + loading + anchorage_{ballast} + anchorage_{ballast} \tag{11.2}$$

$$sum_{operational-modes}\left[\frac{days}{year}\right] = sum_{sailing\ modes}\left[\frac{days}{year}\right] + sum_{non-sailing\ modes}\left[\frac{days}{year}\right] \tag{12}$$

$$nm_{ballast} = \left(\sum_{23\ kn}^{i=8\ kn} i \cdot percentage_i \left[\frac{nm}{hour}\right]\right) \cdot 24\left[\frac{hours}{day}\right] \cdot sum_{operational-modes}\left[\frac{days}{year}\right] \tag{13.1}$$

$$nm_{laden} = \left(\sum_{23\ kn}^{i=8\ kn} i \cdot percentage_i \left[\frac{nm}{hour}\right]\right) \cdot 24\left[\frac{hours}{day}\right] \cdot sum_{operational-modes}\left[\frac{days}{year}\right] \tag{13.2}$$

$$nm_{maneuvering\ ballast} = \left(speed \cdot percentage\left[\frac{nm}{hour}\right]\right) \cdot 24\left[\frac{hours}{day}\right] \cdot \left(\frac{days\ maneuvering_{ballast}}{year}\right) \tag{13.3}$$

$$nm_{maneuvering-laden} = \left(speed \cdot percentage\left[\frac{nm}{hour}\right]\right) \cdot 24\left[\frac{hours}{day}\right] \cdot \left(\frac{days\ maneuvering_{laden}}{year}\right) \tag{13.4}$$

$$\boldsymbol{nm_{total} = nm_{ballast\ mode} + nm_{laden\ mode} + nm_{maneuvering-laden} + nm_{maneuvering-laden}} \tag{14}$$

Based on the fuel consumption curve used for the main engine(s), auxiliary engine(s), and boiler(s) that the user enters in the data entry, the annual fuel consumption is estimated for the sailing modes. The first calculation of the tool is:

$$FC - ME_{ballast} = \left(\sum_{23\ kn}^{i=8\ kn}(FC_{ME})_i \cdot percentage_i\left[\frac{tns}{day}\right]\right) \cdot sum_{operational-modes}\left[\frac{days}{year}\right] \tag{15.1}$$

$$FC - AE_{ballast} = \left(\sum_{23\ kn}^{i=8\ kn}(FC_{AE})_i \cdot percentage_i\left[\frac{tns}{day}\right]\right) \cdot sum_{operational-modes}\left[\frac{days}{year}\right] \tag{15.2}$$

$$FC - boiler_{ballast} = \left(\sum_{23\ kn}^{i=8\ kn}(FC_{boiler})_i \cdot percentage_i\left[\frac{tns}{day}\right]\right) \cdot sum_{operational-modes}\left[\frac{days}{year}\right] \tag{15.3}$$

$$FC - ME_{laden} = \left(\sum_{23\ kn}^{i=8\ kn}(FC_{ME})_i \cdot percentage_i\left[\frac{tns}{day}\right]\right) \cdot sum_{operational-modes}\left[\frac{days}{year}\right] \tag{15.4}$$

$$FC - AE_{laden} = \left(\sum_{23\ kn}^{i=8\ kn}(FC_{AE})_i \cdot percentage_i\left[\frac{tns}{day}\right]\right) \cdot sum_{operational-modes}\left[\frac{days}{year}\right] \tag{15.5}$$

$$FC - boiler_{laden} = \left(\sum_{23\ kn}^{i=8\ kn}(FC_{boiler})_i \cdot percentage_i\left[\frac{tns}{day}\right]\right) \cdot sum_{operational-modes}\left[\frac{days}{year}\right] \tag{15.6}$$

Then with the VLOOKUP function the tool finds the emission factor of the fuel(s) used for each of the ship's fuel consumers. Also, with the percentage for each of the fuels used annually that the user provides, the CO_2 emitted can be estimated as follows:

$$CO_2 - ME_{ballast} = \left(\sum_{n}^{i=1}(FC - ME_{ballast}) \cdot C_{fi} \cdot fuel\_percentage_i\right) \tag{16.1}$$

$$CO_2 - AE_{ballast} = \left(\sum_{n}^{i=1}(FC - AE_{ballast}) \cdot C_{fi} \cdot fuel\_percentage_i\right) \tag{16.2}$$

$$CO_2 - boiler_{ballast} = \left(\sum_{n}^{i=1}(FC - boiler_{ballast}) \cdot C_{fi} \cdot fuel\_percentage_i\right) \tag{16.3}$$

$$CO_2 - ME_{laden} = \left(\sum_{n}^{i=1}(FC - ME_{laden}) \cdot C_{fi} \cdot fuel\_percentage_i\right) \tag{16.4}$$

$$CO_2 - AE_{laden} = \left(\sum_{n}^{i=1}(FC - AE_{laden}) \cdot C_{fi} \cdot fuel\_percentage_i\right) \tag{16.5}$$

$$CO_2 - boiler_{laden} = \left(\sum_{n}^{i=1}(FC - boiler_{laden}) \cdot C_{fi} \cdot fuel\_percentage_i\right) \tag{16.6}$$

Where *i* stands for the variety of fuels. Thus, the total amount of CO_2 that the ship emits while at sea is:

$$CO_{2\ ballast} = CO_2 - ME_{ballast} + CO_2 - AE_{ballast} + CO_2 - boiler_{ballast} \tag{17.1}$$

$$CO_{2\ laden} = CO_2 - ME_{laden} + CO_2 - AE_{laden} + CO_2 - boiler_{laden} \tag{17.2}$$

$$\boldsymbol{CO_{2\ sailing}\left[\frac{tons}{year}\right] = CO_{2\ ballast} + CO_{2\ laden}} \qquad (18)$$

As for the non-sailing and manoeuvrings modes, the data are in a simpler format, because the user inputs the tons per year consumed and the fuel(s) used for each mode, and there are no fuel consumptions from the Main Engine. Therefore, the CO_2 emissions from the non-sailing modes are computed by the tool as follows:

$$CO_2\, AE_{unloading} = \left(\sum_n^{i=1}\left(FC - AE_{unloading}\right)\cdot C_{fi}\cdot fuel\_percentage_i \cdot \left(\frac{days\ unloading}{year}\right)\right) \qquad (19.1)$$

$$CO_2\, boiler_{unloading} = \left(\sum_n^{i=1}\left(FC - boiler_{unloading}\right)\cdot C_{fi}\cdot fuel\_percentage_i \cdot \left(\frac{days\ unloading}{year}\right)\right) \qquad (19.2)$$

$$CO_2\, AE_{loading} = \left(\sum_n^{i=1}\left(FC - AE_{loading}\right)\cdot C_{fi}\cdot fuel\_percentage_i \cdot \left(\frac{days\ loading}{year}\right)\right) \qquad (19.3)$$

$$CO_2\, boiler_{loading} = \left(\sum_n^{i=1}\left(FC - boiler_{loading}\right)\cdot C_{fi}\cdot fuel\_percentage_i \cdot \left(\frac{days\ loading}{year}\right)\right) \qquad (19.4)$$

$$CO_2\, AE_{anchorage\ ballast} = \left(\sum_n^{i=1}\left(FC - AE_{anchorage\ ballast}\right)\cdot C_{fi}\cdot fuel\_percentage_i \cdot \left(\frac{days\ anchorage\ ballast}{year}\right)\right) \qquad (19.5)$$

$$CO_2\, boiler_{anchorage\ ballast} = \left(\sum_n^{i=1}\left(FC - boiler_{anchorage\ ballast}\right)\cdot C_{fi}\cdot fuel\_percentage_i \cdot \left(\frac{days\ anchorage\ ballast}{year}\right)\right) \qquad (19.6)$$

$$CO_2\, AE_{anchorage\ laden} = \left(\sum_n^{i=1}\left(FC - AE_{anchorage\ laden}\right)\cdot C_{fi}\cdot fuel\_percentage_i \cdot \left(\frac{days\ anchorage\ laden}{year}\right)\right) \qquad (19.7)$$

$$CO_2\, boiler_{anchorage\ laden} = \left(\sum_n^{i=1}\left(FC - boiler_{anchorage\ laden}\right)\cdot C_{fi}\cdot fuel\_percentage_i \cdot \left(\frac{days\ anchorage\ laden}{year}\right)\right) \qquad (19.8)$$

$$CO_2\, AE_{maneuver\ laden} = \left(\sum_n^{i=1}\left(FC - AE_{maneuver\ laden}\right)\cdot C_{fi}\cdot fuel\_percentage_i \cdot \left(\frac{days\ maneuver\ laden}{year}\right)\right) \qquad (19.9)$$

$$CO_2\, boiler_{maneuver\ laden} = \left(\sum_n^{i=1}\left(FC - boiler_{maneuver\ laden}\right)\cdot C_{fi}\cdot fuel\_percentage_i \cdot \left(\frac{days\ maneuver\ laden}{year}\right)\right) \qquad (19.10)$$

$$CO_2\, AE_{maneuver\ ballast} = \left(\sum_n^{i=1}\left(FC - AE_{maneuver\ ballast}\right)\cdot C_{fi}\cdot fuel\_percentage_i \cdot \left(\frac{days\ maneuver\ ballast}{year}\right)\right) \qquad (19.11)$$

$$CO_2\, boiler_{maneuver\ ballast} = \left(\sum_n^{i=1}\left(FC - boiler_{maneuver\ ballast}\right)\cdot C_{fi}\cdot fuel\_percentage_i \cdot \left(\frac{days\ maneuver\ ballast}{year}\right)\right) \qquad (19.12)$$

Where *i* represents the number of different fuels. Hence, the sum of the ship's CO_2 emissions from the non-sailing modes are:

$$CO_{2\ unloading} = CO_2\, AE_{unloading} + CO_2\, boiler_{unloading} \qquad (20.1)$$

$$CO_{2\ loading} = CO_2\, AE_{loading} + CO_2\, boiler_{loading} \qquad (20.2)$$

$$CO_{2\ anchorage\ ballast} = CO_2\, AE_{anchorage\ ballast} + CO_2\, boiler_{anchorage\ ballast} \qquad (20.3)$$

$$CO_{2\ anchorage\ laden} = CO_2\, AE_{anchorage\ laden} + CO_2\, boiler_{anchorage\ laden} \qquad (20.4)$$

$$CO_{2\ maneuvering\ ballast} = CO_2\, AE_{maneuver\ ballast} + CO_2\, boiler_{maneuver\ ballast} \qquad (20.5)$$

$$CO_{2\ maneuvering\ laden} = CO_2\, AE_{maneuver\ laden} + CO_2\, boiler_{maneuver\ laden} \qquad (20.6)$$

$$\boldsymbol{CO_{2\ non\ sailing}\left[\frac{tons}{year}\right] = CO_{2\ unloading} + CO_{2\ loading} + CO_{2\ anchorage\ ballast} + CO_{2\ anchorage\ laden}} \qquad (21.1)$$

$$\boldsymbol{CO_{2\ maneuvering}\left[\frac{tons}{year}\right] = CO_{2\ maneuvering\ ballast} + CO_{2\ maneuvering\ laden}} \qquad (21.2)$$

Ultimately, the total CO$_2$ emitted from the ship annually are:

$$\boldsymbol{CO_{2\ total\ annually} = CO_{2\ sailing} + CO_{2\ non\ sailing} + CO_{2\ maneuvering}} \quad (22)$$

Finally, regarding the calculation of CII, the computation of the correction factors is done in *2.2.3 Attained CII* where they are thoroughly outlined according to equations (9.1) - (9.5).

3.4.3 Rating attribution

To attribute the ship rating is not difficult since the rating boundaries and the ship's CII are established by the tool. The rating of the ship is estimated with the following algorithm:

Algorithm 1

```
IF $attained\ CII \leq refCII_{rating\ year} \cdot d1$
THEN $Ship\ Rating = A$
    ELSEIF $attained\ CII \leq refCII_{rating\ year} \cdot d2$
    THEN $Ship\ Rating = B$
        ELSEIF $attained\ CII \leq refCII_{rating\ year} \cdot d3$
        THEN $Ship\ Rating = C$
            ELSEIF $attained\ CII \leq refCII_{rating\ year} \cdot d4$
            THEN $Ship\ Rating = D$
                ELSE $Ship\ Rating = E$
                END
            END
        END
    END
END
```

However, the calculation of the year that the ship hits rating B, C, D, D+2, and E is more challenging. For each of the rating boundaries, there are 6 linear curves, separate lines between 2023-2026, 2026-2030, 2030-2035, 2035-2040, 2045-2050. The equation of a line is known to be $y = a \cdot x + b$. Therefore, the parameters a and b need to be calculated for 24 equations, as there are 6 linear curves and 4 rating boundaries. For the A-B boundary, that is expressed as d1, the factors are computed as follows:

$$a_{d1\ 23-26} = \frac{CII_{d1\ 2026} - CII_{d1\ 2023}}{2026-2023} \quad (23.1)$$

$$a_{d1\ 26-30} = \frac{CII_{d1\ 2030} - CII_{d1\ 2026}}{2030-2026} \quad (23.2)$$

$$a_{d1\ 30-35} = \frac{CII_{d1\ 2035} - CII_{d1\ 2030}}{2035-2030} \quad (23.3)$$

$$a_{d1\ 35-40} = \frac{CII_{d1\ 2040} - CII_{d1\ 2035}}{2040-2035} \quad (23.4)$$

$$a_{d1\ 40-45} = \frac{CII_{d1\ 2045} - CII_{d1\ 2040}}{2045-2040} \quad (23.5)$$

$$a_{d1\ 45-50} = \frac{CII_{d1\ 2050} - CII_{d1\ 2045}}{2050-2045} \quad (23.6)$$

$$b_{d1\ 23-26} = CII_{d1\ 2023} - a_{d1\ 23-26} \cdot 2023 \quad (24.1)$$

$$b_{d1\ 26-30} = CII_{d1\ 2026} - a_{d1\ 23-26} \cdot 2026 \quad (24.2)$$

$$b_{d1\ 30-35} = CII_{d1\ 2030} - a_{d1\ 23-26} \cdot 2030 \quad (24.3)$$

$$b_{d1\ 35-40} = CII_{d1\ 2035} - a_{d1\ 23-26} \cdot 2035 \quad (24.4)$$

$$b_{d1\ 40-45} = CII_{d1\ 2040} - a_{d1\ 23-26} \cdot 2040 \quad (24.5)$$

$$b_{d1\ 45-50} = CII_{d1\ 2045} - a_{d1\ 23-26} \cdot 2045 \quad (24.6)$$

Where $a_{d1\ 23\text{-}26}$ represents the a factor of the d1's curve for the years 2023-2026, $a_{26\text{-}30}$ for the years 2026-2030, etc. The same applies to the b factor. Moreover, $CII_{d1\ 2023}$, $CII_{d1\ 2026}$, $CII_{d1\ 2030}$, $CII_{d1\ 2035}$, $CII_{d1\ 2040}$, $CII_{d1\ 2045}$, $CII_{d1\ 2050}$ are the values of the CII border between A and B ratings for the years 2023, 2026, 2030, 2035, 2040, 2045, 2050 respectively. The same holds true for the rating borders d2, d3, d4.

Having established the curve parameters, the tool calculates the year that the ship hits each rating. The year that the ship hits B rating is estimated with the following algorithm:

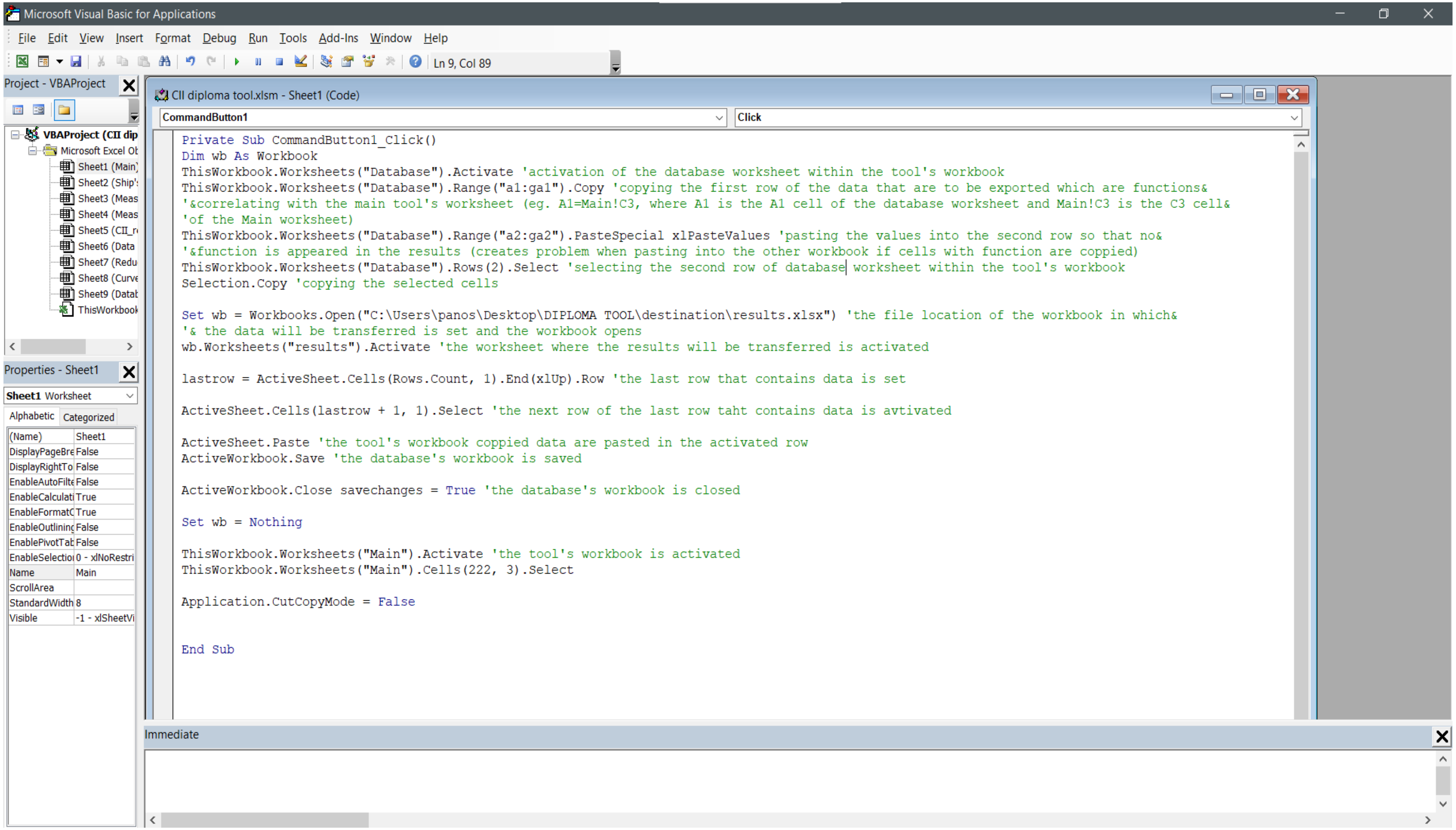
Algorithm 2

```
IF $attained\ CII > CII_{d1\ 2026}$
THEN $T_{d1} = \left(\frac{attained\ CII - b_{d1\ 23-26}}{a_{d1\ 23-26}}\right)$
    ELSEIF $attained\ CII > CII_{d1\ 2030}$
    THEN $T_{d1} = \left(\frac{attained\ CII - b_{d1\ 26-30}}{a_{d1\ 26-30}}\right)$
        ELSEIF $attained\ CII > CII_{d1\ 2035}$
        THEN $T_{d1} = \left(\frac{attained\ CII - b_{d1\ 30-35}}{a_{d1\ 30-35}}\right)$
            ELSEIF $attained\ CII > CII_{d1\ 2040}$
            THEN $T_{d1} = \left(\frac{attained\ CII - b_{d1\ 35-40}}{a_{d1\ 35-40}}\right)$
                ELSEIF $attained\ CII > CII_{d1\ 2045}$
                THEN $T_{d1} = \left(\frac{attained\ CII - b_{d1\ 40-45}}{a_{d1\ 40-45}}\right)$
                    ELSEIF $attained\ CII > CII_{d1\ 2050}$
                    THEN $T_{d1} = \left(\frac{attained\ CII - b_{d1\ 45-50}}{a_{d1\ 45-50}}\right)$
                    END
                END
            END
        END
    END
END
```

The same applies for ratings C, D, and E, by changing the factors to the rating borders accordingly.

3.4 Database

An excel workbook which is used as a database of the inputs and results was designed with Visual Basic for Application (VBA). A button was created, named ‘Export Results’, in the input worksheet within the excel workbook of the tool. It exports the ship’s main particulars (Length between perpendiculars, Moulded Breadth, Scantling Draught, Deadweight, Ship type), the operational profile, the fuel consumption curves at ballast and laden modes corresponding to speeds between 8 and 23 knots with step of 1 knot, the fuel consumption of the non-sailing modes, the different types of fuel used during the year in each operational mode, the correction factors applied, the attained CII, the rating before the use of measures, the selected measure(s), the new attained CII, and the new rating. The code that transfers the inputs and results of the user, from the tool’s workbook to the database’s workbook, is presented in the following screenshot.



(Name)	Sheet1
DisplayPageBre	False
DisplayRightTo	False
EnableAutoFilte	False
EnableCalculati	True
EnableFormatC	True
EnableOutlining	False
EnablePivotTab	False
EnableSelectio	0 - xlNoRestri
Name	Main
ScrollArea	
StandardWidth	8
Visible	-1 - xlSheetVi

```vba
Private Sub CommandButton1_Click()
Dim wb As Workbook
ThisWorkbook.Worksheets("Database").Activate 'activation of the database worksheet within the tool's workbook
ThisWorkbook.Worksheets("Database").Range("a1:ga1").Copy 'copying the first row of the data that are to be exported which are functions&
'&correlating with the main tool's worksheet (eg. A1=Main!C3, where A1 is the A1 cell of the database worksheet and Main!C3 is the C3 cell&
'of the Main worksheet)
ThisWorkbook.Worksheets("Database").Range("a2:ga2").PasteSpecial xlPasteValues 'pasting the values into the second row so that no&
'&function is appeared in the results (creates problem when pasting into the other workbook if cells with function are coppied)
ThisWorkbook.Worksheets("Database").Rows(2).Select 'selecting the second row of database worksheet within the tool's workbook
Selection.Copy 'copying the selected cells

Set wb = Workbooks.Open("C:\Users\panos\Desktop\DIPLOMA TOOL\destination\results.xlsx") 'the file location of the workbook in which&
'& the data will be transferred is set and the workbook opens
wb.Worksheets("results").Activate 'the worksheet where the results will be transferred is activated

lastrow = ActiveSheet.Cells(Rows.Count, 1).End(xlUp).Row 'the last row that contains data is set

ActiveSheet.Cells(lastrow + 1, 1).Select 'the next row of the last row taht contains data is avtivated

ActiveSheet.Paste 'the tool's workbook coppied data are pasted in the activated row
ActiveWorkbook.Save 'the database's workbook is saved

ActiveWorkbook.Close savechanges = True 'the database's workbook is closed

Set wb = Nothing

ThisWorkbook.Worksheets("Main").Activate 'the tool's workbook is activated
ThisWorkbook.Worksheets("Main").Cells(222, 3).Select

Application.CutCopyMode = False


End Sub
```

Figure 9: Code used in VBA for the extraction of data to the database workbook.

4. Decarbonization Alternatives

In this section an overview of the decarbonization measures and technologies, that the users can select inside the tool, will be presented so as to define their potential reduction. It is important to note that for all the measures, the same deduction in fuel is applied in each speed and draft which is not realistic, but not entirely inaccurate.

4.1 Machinery Technologies

4.1.1 Waste Heat Recovery

A significant amount of thermal energy is produced as a by-product of the combustion process in a diesel engine. Parts of this thermal energy can be transformed into electrical power using a waste heat recovery (WHR) system. In the system the exhaust gas from the engine is used to generate steam for a turbine-driven generator. An exhaust gas economizer and a turbo generator which consists of a steam turbine, gears, and an electrical generator are typical components of a WHR installation. Depending on the engine's size and the complexity of the WHR system, either a steam turbine alone or a steam turbine and power turbine combination is typically used, with the latter enhancing efficiency. Depending on the kind, size, and power of the engine, a waste heat recovery system will have varied efficiency and output. The reduction potential of a WHR system will range from 20% to 50% of AE fuel consumption, depending on system complexity, engine type, ship type, and whether the ship is maneuvering or not. A WHR system is applicable for both 2-stroke and 4-stroke engines. When a WHR system is installed, the main engine may be tuned to achieve the highest efficiency for the sum of the main engine and WHR system [29].

Table 15: Characteristics of waste heat recovery as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Waste heat recovery	30-50% of AE FC when sailing and 20% AE FC when manoeuvring	RF and NB[2]	YES

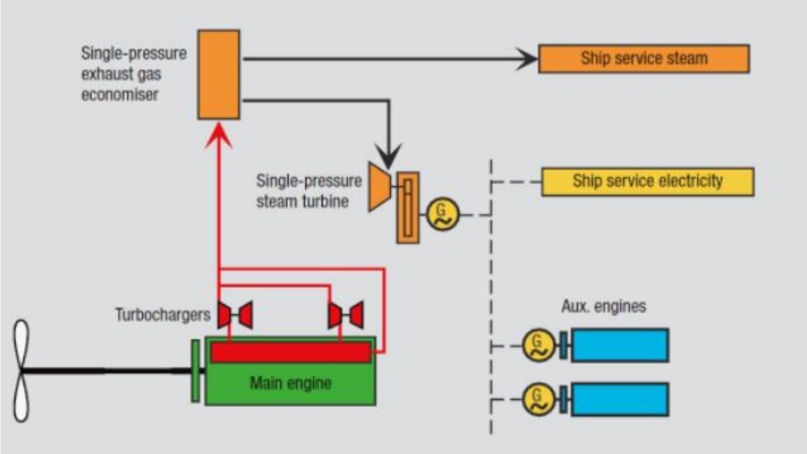


Figure 10: Wartsila Waste Heat Recovery Plant. [30]

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[2] RF is an abbreviation of Retrofit and NB is an abbreviation of Newbuild.

4.1.2 Exhaust gas boilers on auxiliary engines

As per [31], exhaust gas boilers recover the heat from the exhaust gas of auxiliary diesel engines to generate steam and/or hot water, or useful heat for process heating. Depending on system design, these boilers can enhance the efficiency of the auxiliary engine system by up to 20%, leading to lower overall process costs. Applicable for ship types of all ages not fitted with shaft generator where an auxiliary engine will be in service in all operational modes (seagoing and in port). Excessive heat from the engine exhaust could then be recovered and utilized. The benefit from the measure might relate to reduced fuel consumption on the auxiliary engine itself due to lower need for auxiliary power for e.g. process heating, where both steam and electricity can be used for heating purposes. Alternatively, and likely more frequent, the benefit may come as reduced fuel oil consumption on an oil-fired boiler in cases of insufficient steam production from main engine exhaust gas economizer. To simplify the benefit, the savings are estimated as total percentage saving of the auxiliary engine's fuel oil consumption. The estimated reduction potential is 0% to 5% of the auxiliary engine's fuel consumption.

Table 16: Characteristics of exhaust gas boilers on auxiliary engines as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Exhaust gas boilers on auxiliary engines	0-5% of total AE FC	RF and NB	NO

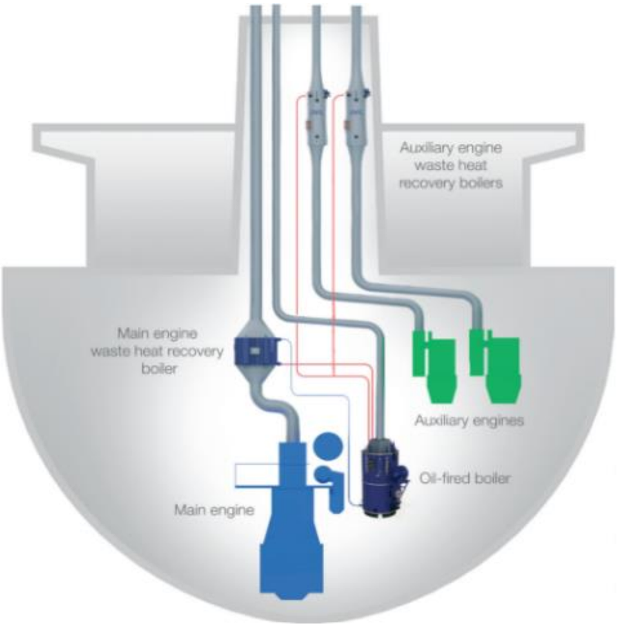

Figure 11: Schematics of traditional main and auxiliary engine set up, with exhaust gas boiler on both. [31]

4.1.3 Shaft Generator - Power take-off (PTO)

Shaft generators on board ships are driven by the main engine to supply power to the main switchboard. It is applicable for vessels with diesel mechanic propulsion, for all ages. The latest shaft generator configurations can be used independently of shaft speed and maintain a stable voltage and frequency output; this makes it possible to optimize each route with parallel auxiliary operation. Installing a shaft generator on the typical main engine is by itself more efficient than producing the same power via a smaller and less efficient auxiliary, but for many cases the shaft generator would in addition increase the total load of the main engine closer to the optimum load point with minimum specific fuel oil consumption. Shaft generator is an option for many types of vessels, especially those in need of a larger amount of power for heating or cooling and sailing long transits. The deduction potential is 30-50 % of AE fuel consumption [32].

Table 17: Characteristics of shaft generator (PTO) as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Shaft generator - PTO	30-50% of AE FC when sailing	RF and NB	YES

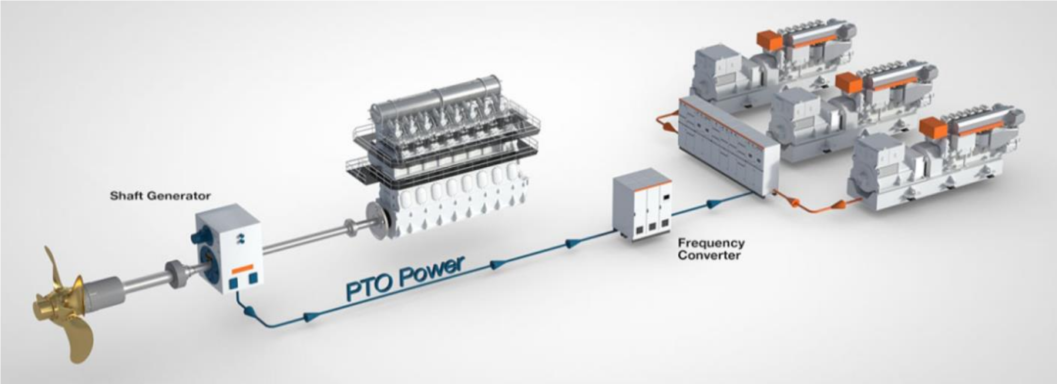

Figure 12: Shaft Generator used for Power Take-off.

4.1.4 Auxiliary systems optimization

Optimizing auxiliary systems to vessel specific operational profiles can lead to significantly reduced energy consumption. Auxiliary systems are often designed to support engines at extreme ambient conditions. Most of these systems experience supporting primary engines and systems at loads from 80% and down most of the time, which can induce accelerated wear and can increase the need, cost, energy consumption and complexity of maintenance. Auxiliary systems optimization is applicable for all vessels with auxiliary systems, regardless of ship type and age. Through simulation and optimization potential to save energy and fuel can be revealed via control strategies of cooling water systems, replacement of heat exchangers with new more efficient heat exchangers, adjusted room ventilation, and better control strategies, redesign of piping and instruments, and others. The reduction potential is 1% to 5% of total ship fuel consumption [33]. The reduction potential estimate is highly dependent on whether or not the case is a newbuild or retrofit, complexity in auxiliary system design, etc.

Table 18: Characteristics of auxiliary systems optimization as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Auxiliary systems optimization	1-5 % of total FC	RF and NB	NO

4.1.5 Engine performance testing and tuning

As described in [34] and [35], a potential lies within ensuring accurate insight to the engine's condition and performance, enabling both optimizing the engine's fuel efficiency and verification of the optimization's effect. For some part of the existing fleet this potential is only possible to realize manually, unless costly retrofits are made, whereas for the rest existing vessels this potential can be realized automatically. Improved balance of the cylinder pressures, and maximum combustion pressures closer to the rated values, is the detailed aim of this measure. The cylinder pressure balance is one important goal to improve the engine condition, enabling more efficient combustion. Peak engine efficiency is another important goal targeted by maximizing the ratio of maximum combustion pressure (P_{max}) over the compression pressure (P_{comp}), and subsequently the mean effective pressure (P_{mep}), within acceptable limits. Optimizing an engine to increase efficiency is however usually the opposite of reducing NO_x-emissions, which is important to note. The deduction potential is estimated at 1% to 4% of total ship fuel consumption.

Table 19: Characteristics of engine performance testing and tuning as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Engine performance testing and tuning	1-4 % of total FC	RF and NB	NO

4.1.6 Engine de-rating

The main engines of almost all existing vessels are both designed and optimized for one specific vessel speed and engine load. The introduction of slow steaming in many ship segments has drastically lowered the actual transit speed from design levels, thus leaving the vessel and its engines operating at none-optimized load levels. De-rating the engine offers the possibility to lower the vessel's maximum speed, specified maximum continuous rating (MCR), and thereby optimize actual load point with design load point. This results in higher efficiency with reduced specific fuel oil consumption (SFOC) at the new optimum design point. This measure is suitable for all ship types and ages where a top speed reduction of 10% to 15% can be expected. The measure is especially relevant in today's slow-steaming markets. However, many ship owners are hesitant to reduce the vessels' top speed. Flexible and reversible de-ratings already exist and can be very attractive, keeping the option easy, and with low cost, speed up again if the market changes. Measures to achieve this include installing shims between the crosshead and piston rod to reduce stroke length, cutting out one or several turbochargers, either with permanent or flexible flanges, cutting out/deactivating cylinders, and others. The deduction potential is estimated at 2% to 10% of main engine total fuel consumption [36].

Table 20: Characteristics of engine de-rating as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Engine de-rating	2-10 % of ME FC	RF	YES

4.1.7 Improved auxiliary engine load

As per [37], improved engine load in this measure relates to the engine load of the auxiliary power producing engines which provide electrical power to the ship. The engine performance and efficiency aspects of the auxiliaries are quite similar to the large 2-stroke propulsion engines as they are often more efficient at higher loads. The key of this measure relates to the fact that many vessels run more auxiliary engines simultaneously than are actually needed regarding power consumption vs. production-basis during normal deep-sea transit. This is amongst others related to risk aversion of black-out, however during deep sea transit in calm weather it is typically not critical to experience a black-out. In order to minimize the fuel consumption on the auxiliaries through increasing the average engine load, the number of auxiliary engines running must be minimized at all times. This could be included in a ship specific auxiliary engine operation guideline. The average engine load is as such on its own a good performance indicator to work from, but it must not contribute to compromising safety, and a risk-based approach is as such advised. The reduction potential is estimated at 0% to 20% on fuel consumption on auxiliary engine.

Table 21: Characteristics of improved auxiliary engine load as a decarbonization measure

Decarbonization measure	**Reduction potential**	**Fitting**	**EEDI - EEXI effect**
Improved auxiliary engine load	0-20 % of AE FC	RF	NO

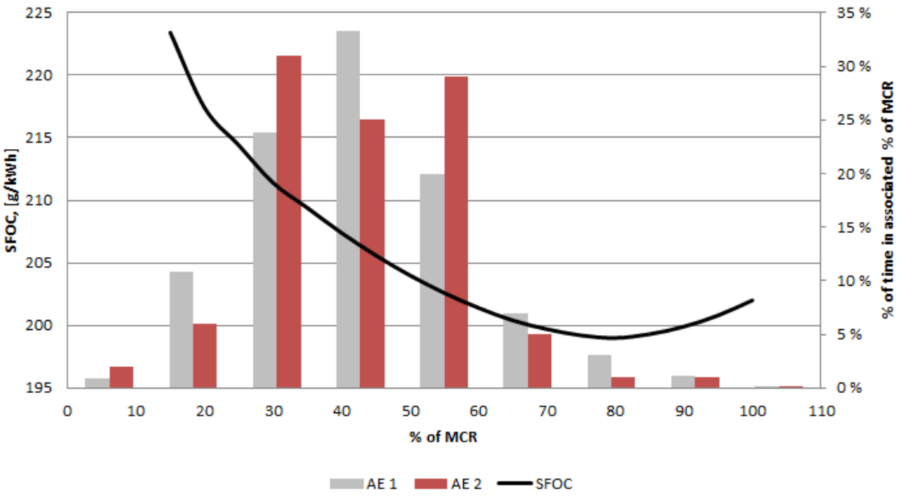

Figure 13: Specific Fuel Oil Consumption curve and percentage of time that the Auxiliary Engines are used in associated percentage of MCR. [37]

4.1.8 Shore Power

When a ship docks, it no longer needs energy for propulsion. However, ships may still be large consumers of energy when stationary as several of the ship functions are still operating. Consequently, the generators are running when in port, resulting in local noise and air emissions as well as global climate driving emission. Rather than letting the generators on board make the electricity this can come from shore power. Shore power can be installed for all types of vessels and for all ages with need for power in harbour. For the larger vessels with higher power requirements (100 kW up to 10 to 15 MW) it gets complicated. To serve these vessels with shore power, costly installations are required, both on land and on board the vessels. This may include upgrading the grid capacity, frequency converters and complex high-power connectors. Consequently, relatively few vessels and ports can make use of shore power, even though the environmental upsides are considerable. Still, cold ironing may be regarded as a mature technology that has been in regular use since the 1980s [38]. The reduction potential is 25% to 100% in port for the electrical motors on board.

Table 22: Characteristics of Shore Power as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Shore Power	25-90 % of AE FC when in port depending on ship type	RF and NB	NO

4.1.9 Steam plant operation improvement

Experience has shown that there is an improvement potential for boiler operation in terms of general use and maintenance of the boiler and steam plant system. As mentioned in [39], this measure is most valid for crude and product tankers, of all ages, as they are the ship types most frequently equipped with large oil-fired boilers, where cargo handling and discharge can be vast steam consuming operations. The measure involves updating the related procedures, installing/using some new sensor equipment, minor retrofits like new insulation for steam piping on deck, training of crew and some additional maintenance to minimize steam consumption and leakages, and optimize efficiency of steam production. For boiler performance several aspects are important, but especially control and adjustment of excess air on boiler, feed water temperature, drum pressure, and ambient air temperature and humidity. The estimated deduction potential is 10% to 30% of the boiler engine’s fuel consumption.

Table 23: Characteristics of steam plant operation improvement as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Steam plant operation improvement	10-30 % of boiler FC	RF	NO

4.1.10 Variable Frequency Drives (VFD)

Fans and pumps related to machinery and the machinery space often operate binarily, the unit is either off or operating at full capacity. A pump might e.g. operate at full power even in cases where significantly less power would be sufficient. Steering gear hydraulic pumps, cooling water pumps and engine room fans are typical examples where the units could be dynamically operated depending on the requirements related to cooling capacity and ambient pressure, which vary with ambient conditions. The main benefits from VFD are reduction of wasted energy by turning the output energy to the required input energy, potentially reduced wear and tear, reduced electric energy consumption which is often equivalent to lower fuel oil consumption, and less pressure pulses in the steering gear system. The main barriers for VFD are fear of providing e.g. the cooling system with an insufficient amount of cooling water, and more systems which might fail in the engine room. The reduction potential is estimated at 2% to 10% of the total fuel consumption for auxiliary engines [40].

Table 24: Characteristics of Variable Frequency Drives (VFD)as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Variable Frequency Drives (VFD)	2-10% of AE FC	RF and NB	NO

4.1.11 Energy-efficient lighting system

Use of energy efficient lighting equipment such as low energy halogen lamps, fluorescent tubes, and LED (light emitting diode) in combination with electronically controlled systems for dimming, automatic shut off, etc. is continuously developed as the focus on energy and environment has increased. The new technology has been applied only to a limited extent to the shipping industry and standard normal design does not include low energy lighting. Implementing energy efficient light system will in addition reduce the maintenance hours and operating cost. The emission reduction potential is estimated from the total auxiliary engine consumption on normal merchant ships and is assessed to be in the range of 0.25% to 5% [41].

Table 25: Characteristics of energy-efficient lighting system as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Energy-efficient lighting system	0.25-5 % of AE FC	RF and NB	NO

4.1.12 Optimization of cargo handling systems (Cargo discharge operation)

Discharges of crude oil cargo require a lot of energy and are carried out by intricate machinery systems, including personnel spread throughout the ship. Based on actual data from a discharge operation, model-based methodologies are used to evaluate the performance and enhance the operation of the discharge system (from the boiler's primary energy conversion to the discharge of the cargo pumps). This model-based study will evaluate overall performance based on an examination of operational discharge data. It is offering improvement techniques and estimating their potential for savings based on the findings. Only crude oil carriers with cargo pumps powered by a steam turbine are subject to this measure, regardless of age. These are typically fitted on tankers that are Aframax or larger. The accuracy of the measured and sent data from the vessel has a significant impact on the outcomes. Depending on the starting point, e.g. how well the operation is optimized before, the total fuel deduction on boiler consumption is in the range of 5% to 15% [42].

Table 26: Characteristics of cargo discharge operation as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Optimization of cargo handling systems	5-15 % of boiler FC when unloading	RF	NO

4.2 Energy Recovery

4.2.1 Hard sails or wings

As described om [43], fixed installations on the ship in the form of a flexible sail, rigid sail or turbosail can make use of the wind to replace some of the propulsion power needed. All possibilities have pros and cons and must be chosen to best suit the ship type, trade and size. The savings are highly dependent on the wind conditions in which the ship operates. These initiatives are only applicable for ships with enough space and therefore not container ships. There is no vessel age restriction for fixed sails or wings. Stability due to the high placement of additional weight and force from the sails is not assumed to be an issue for the ships. It is assumed that the sails only will be operational 15% of the time. The effect and applicability of this measure is also dependent on operating speed (most useful in the lower speed range). The likely reduction potential is estimated to be in the range of 1% to 10% on main engine fuel consumption.

Table 27: Characteristics of hard sails or wings as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Hard sails or wings	1-10 % of ME FC when sailing	NB	YES

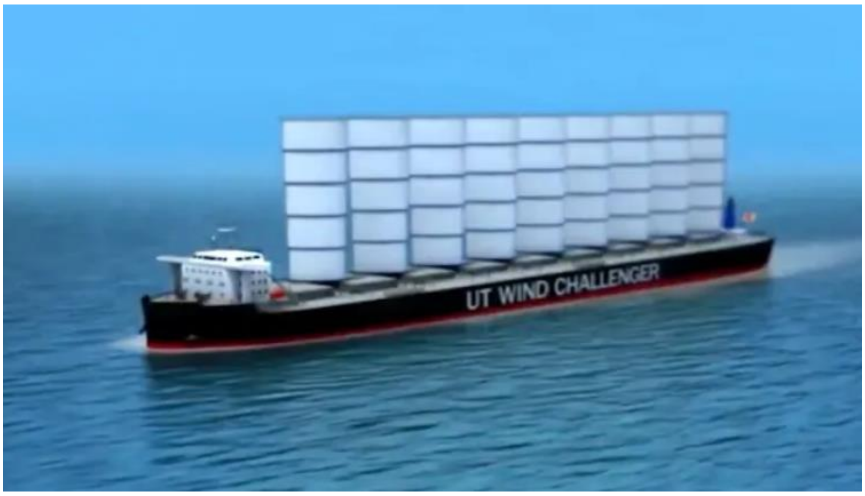

Figure 14: Bulk Carrier equipped with wing sails.

4.2.2 Rotor sails

Rotor sails are vertical cylinders that spin and gain lift as the wind blows across them thanks to the Magnus effect. Manoeuvrability of sail rotors is constrained by wind speed and direction, and lift and propulsion force must be developed mechanically. The force produced provides thrust. Such rotor propulsion on ships is frequently referred to as Flettner rotors after the German inventor who installed the first one on board a ship at the start of the 1920s. Rotor sails can help a ship consume less energy, but they cannot serve as the primary source of propulsion. The rotating cylinders generating thrust are applicable for vessels with a sufficient free deck-surface and it is important that no objects block the accessibility to free wind. Operational height restrictions must be considered, for instance, if they interfere with operationally important structures or infrastructure barriers along the path. The healing action that affects the stability and strength of the cylinder foot must be appropriately supported since it is subject to significant strains to ensure that the vessel's seaworthiness remains good. In general, the rotor’s sails principle operates in sideways winds and is influenced by wind and vessel speed. Therefore, the trade route and weather have an impact on how well the rotors work. The reduction potential of rotor sails is 3% to 15% on main engine fuel consumption depending on vessel size, segment, operation profile and trading areas [44].

Table 28: Characteristics of rotor sails as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Rotor sails	3-15 % of ME FC when sailing	RF and NB	YES

Figure 15: Rotor sails fitted with rotor sails.

4.2.3 Kite

As per [45], the kite works from wind power which is transferred to the ship and results in less engine power needed to move the ship. Under typical circumstances, the kite will tug on the ship, which can be converted into an equivalent amount of engine power. Regardless of the age of the vessel, the system performs best at speeds under 16 knots. The length of time the kites may be flown and produce results is a significant additional factor. It is believed that the kites can only be employed 20% and 30% of the time for small and large ships, respectively, due to prevailing winds and other kite system restrictions. On extensive international trades, kites are more advantageous. The expected reduction potential is in the range of 1% to 5% on main engine fuel consumption.

Table 29: Characteristics of kite as a decarbonization measure.

Decarbonization measure	**Reduction potential**	**Fitting**	**EEDI - EEXI effect**
Kite	1-5 % of ME FC when sailing	RF and NB	YES

Figure 16: Applied computer-controlled kite rig on a Multi-Purpose General Cargo Vessel.

4.2.4 Solar panels

The name "solar panels" refers to equipment that uses solar energy to transform light from the sun into electricity. Currently, solar panels are not very prevalent on ships, but several installations have been made in recent years. All types of ships trading in places with sunlight can use solar panels. Additionally, only ships that are not reliant on deck space may make use of the technology because installing solar panels requires a sizable area. (e.g. car carriers). In comparison to installations on land, shipboard solar panels must be more durable to function in a severe environment. The solar panels on vessels are installed to produce electricity and will be used to supplement the diesel generators and thus reduce the power required from these units. The solar power units can generate electricity both at sea and in ports, but only when it is daylight, thus the solar panels are programmed to generate electricity just half the time. Additionally, solar panels still generate power in cloud cover, albeit not to their full potential. The estimated reduction potential for solar panels is 0.5% to 2% on auxiliary engine fuel consumption [46].

Table 30: Characteristics of solar panels as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Solar panels	0.5-2 % of AE FC	RF and NB	YES

Figure 17: Solar panels on a tanker.

4.3 Technical solutions

4.3.1 Speed Management

As defined in [47], speed management includes different aspects of adjusting and planning for optimal vessel speed and engine load. With basis in the exponential relationship between fuel consumption and power (speed), a vessel sailing with variable speed will usually, for same distance and duration, consume more fuel compared to sailing with constant speed. Optimum speeds with regards to fuel efficiency can however often be challenging due to scheduling requirements from the charterer and other influences. Improved planning, better use of vessel specific knowledge, weather forecasts and communication between charterer, port and vessel can improve the speed profile during a voyage and consequently reduce the fuel consumption.

Slow steaming or ECO speed is the practice of significantly reducing the sailing speed to reduce fuel consumption not only for parts of a voyage, but for a period of voyages, a group of vessels or for a whole fleet. Speed reduction is a strategic measure. Large reductions can be made by sailing slower as the fuel consumption curve is exponential subject to speed. Slow steaming is relevant for all vessel types and has highest reduction potential for vessels in long transits. However, as a constant measure over longer periods slow steaming can inflict increased wear and tear on the engines as very low loads are experienced.

The deduction potential is 10% to 50% of ship main engine fuel consumption. It should be noted that in the tool there is no option of speed management as a CII reduction measure since the users are able to alter the operational profile of the ship dynamically.

Table 31: Characteristics of Speed Management as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Speed Management	10-50 % of ME FC	RF	NO

4.3.2 Trim and draft optimization

The ship's trim and/or draft affect the hull resistance, which has an impact on fuel usage. When loading the ship, optimal circumstances are typically not obtained because there is typically little consideration given to the trim and draft. One can actively arrange cargo loading to optimize the trim and draft, which will save fuel and lower emissions. The optimization of trim and draft is applicable to all vessel types and ages. Optimizing the trim and draft will typically result in a smaller reduction for full-body ships (such as tankers and bulk carriers) where viscous friction resistance is greater than wave friction, and similarly for ships with limited ballast flexibility. To be able to optimize the trim and draft additional equipment is required such as a better loading computer or a dedicated trim optimizer. In addition, the crew need training in the use of such equipment. Optimizing the trim and draft has been estimated to reduce the fuel consumption by 0.5% to 3% on main engine fuel consumption [48].

Table 32: Characteristics of trim and draft optimization as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Trim and draft optimization	0.5-3 % of ME FC when sailing	RF and NB	NO

4.3.3 Weather routing

The power required to propel a ship at a specific speed across ground will depend on the weather (wind and waves), ocean currents, and other factors. In order to limit the negative impact, it is crucial to take these things into account when planning a voyage. Intercontinental trades and larger ships have the greatest potential, as longer voyages sometimes involve time spent in sheltered waters where the influence of weather is making weather routing crucial. All ships at all ages can potentially install the system, and therefore it is assumed that the entire fleet can install the measure. The fastest and safest routes must be weighed against the most fuel-efficient route. The benefit of the measure will be a decrease in fuel consumption brought on by less wave and wind resistance. There might also be a benefit from less fatigue and weather damages. The potential reduction has been assessed to between 0% to 5% on main engine fuel consumption [49].

Table 33: Characteristics of weather routing as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Weather routing	0-5 % of ME FC when sailing	RF and NB	NO

4.4 Hydrodynamic Measures

4.4.1 Air Lubrication System (ALS)

The method involves injecting air onto wetted hull surfaces to enhance a ship's hydrodynamic properties. The system, driven by auxiliary engine producing the power, creates an air cushion on the flat bottom part of the ship. Air lubrication systems are already in place today. When using an air lubrication system, the wetted surface decreases, which reduces fouling build-up on the hull and reduces drag. The benefit of the measure will be in the reduced fuel consumption brought on by the decreased hull resistance and therefore the decrease in the main engine load. For low Froude number ships, such as bulkers, tankers, and containers, where frictional resistance predominates, air lubrication systems are appropriate for new buildings. To trap the air and produce the air cushion, the air lubrication system necessitates the installation of additional pumps and pipes for the air in addition to alterations to the hull design. Such a system might need shielded propellers or additional protection, depending on the design, to prevent air from streaming to the propeller. It is claimed that the system is able to achieve 15% to 40% drag reduction and up to 10% fuel reduction on the main engine [50].

Table 34: Characteristics of Air Lubrication System (ALS) as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Air Lubrication System (ALS)	5-10 % reduction of ME FC with 10-20 % additional AE FC	NB	YES

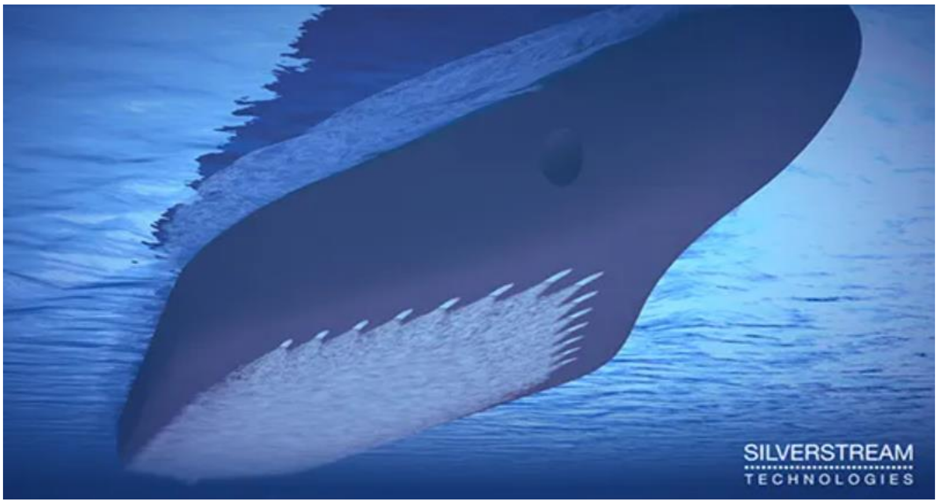

Figure 18: Carpet of microbubbles produced by an Air Lubrication System. [51]

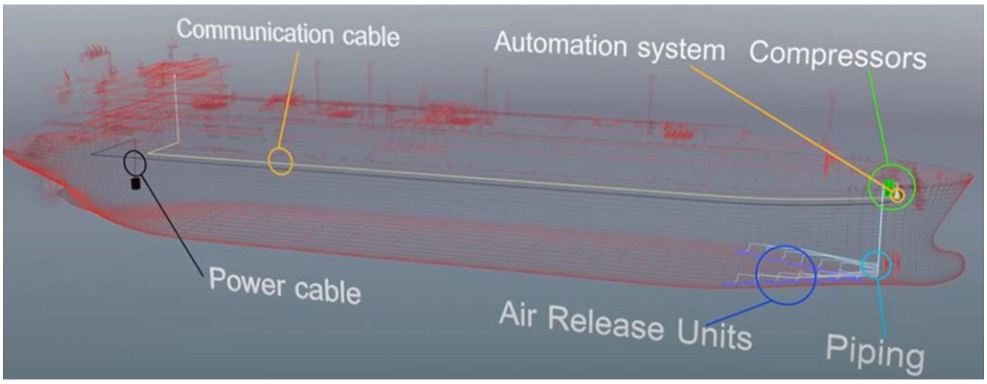

Figure 19: Components of Air Lubrication Systems. [51]

4.4.2 Hull coating

The coatings will lessen the ship's hull's resistance to water flow, hence requiring less engine power and lowering fuel consumption. Savings will be achieved when combined with effective hull condition monitoring and maintenance. All vessel types and ages are suitable for hull coating. Ships are typically recoated every five years, and hull resistance can be decreased by using high performance coating. Full-bodied ships like bulkers and tankers will have a better potential for reducing frictional resistance. For existing ships there is also a higher potential on segments with a relatively high average ship age. For these segments it is assumed that hull sandblasting will be needed to obtain the full effect. The reduction potential is dependent on vessel size, segment, operation profile and trading areas and is in the range of 2% to 5% on main engine fuel consumption [52].

Table 35: Characteristics of hull coating as a decarbonization measure.

Decarbonization measure	**Reduction potential**	**Fitting**	**EEDI - EEXI effect**
Hull coating	2-5 % of ME FC	RF	NO

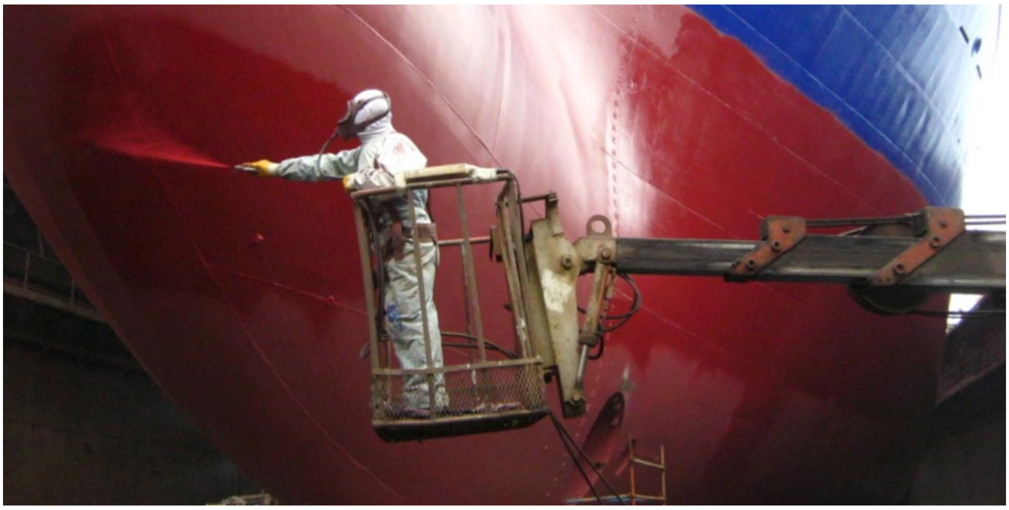

Figure 20: Application of Hull Coating on a ship during drydock.

4.4.3 Hull form optimization

Ship design is closely linked to optimization and in general the owner has three alternatives when purchasing a new-build when it comes to hull form optimization: accept standard design, modify existing design, or develop a new design. The two last alternatives include optimizing the vessel’s hull for a particular service condition and optimizing the forebody and stern form design. Lowering hull resistance will result in less fuel consumption. The degree of hull form and propeller optimization varies significantly between shipyards, despite the fact that main particulars are typically adequately optimized. To properly optimize a hull form, a thorough set of model tests and computational fluid dynamic (CFD) analyses are required. Shipyards frequently focus their optimization efforts on the design draft and speed specifications, while paying little to no attention to ballast draft efficiency or partial load conditions. Hull form optimization can be applied to all vessel types and ages. There is larger potential for fuel saving where the expected operating profile differs from the standard design. A CFD analysis typically includes three or more iterations of lines refinement and should be carried out with multiple trims and drafts. A deduction of 4% to 8% on main engine fuel consumption is likely [53].

Table 36: Characteristics of hull form optimization as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Hull form optimization	4-8 % of ME FC when sailing	RF and NB	YES

4.4.4 Bulbous bow retrofit

Existing ships frequently have a bulbous bow that is designed for high-speed range performance while neglecting slow steaming speeds and shallow drafts. As high speeds are no longer frequently used, there is significant potential to be gained by modifying the bulbous bow form for an operating profile that encompasses both moderate speeds and mild draft circumstances. A typical retrofit of a bulbous bow provides weighted average savings in the range of 5–10%, with potential for up to 20% in specific operating conditions. One of the primary factors affecting the improvement level the target operational profile (speed/draft combinations and the weights that go with them) in comparison to the vessel's initial design point. The predicted savings increase with the size of the difference between the two. Also, another driver for the improvement level is the shape of the rounded bow. Blunt, voluminous, or downstream bulbous bows are frequently unsuitable for use at low speeds and moderate drafts. Finally, the kind of vessel influences the potential savings. Full blocked boats with predominately viscous resistance components are less promising than slender vessels with greater speeds because the bulbous bow optimization primarily effects the wave pattern resistance (Froude numbers).

Table 37: Characteristics of bulbous bow retrofit as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Bulbous bow retrofit	5-10% of ME FC	RF	YES

Figure 21: Retrofitting of bulbous bow for a container ship.

4.4.5 Propeller retrofit

As per [54], on older vessels, altered operational profiles with changing speeds sometimes result in subpar propeller designs. Typically, these propellers have been engineered for maximum speed and minimal cavitation. By switching to a high-efficiency propeller, the overall fuel consumption can be decreased. Propeller retrofitting is suitable for all vessel types and ages with slow steaming, especially container and large vessel series. The exchange of the propeller with an upgraded design assures operation at peak efficiency. Computational fluid dynamics should be used to undertake an engineering analysis (CFD).

Table 38: Characteristics of propeller retrofit as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Propeller retrofit	0-3 % of ME FC	RF	YES

Figure 22: Propeller retrofitting during drydock. [55]

4.4.6 Propulsion Improving Devices (PIDs)

Propulsion improving devices (PIDs) are different ducts, fins, nozzles, bulbs or other modifications made to the hull or propeller to improve efficiency. Alterations take place in front of the propeller as pre-swirl devices that aim to improve the propeller inflow conditions. Or behind the propeller as post-swirl devices which are used to recover parts of the rotational energy in the propeller slipstream. The PIDs are presented below in more detail.

Rudder Bulb with Efficiency Rudder

The use of a rudder bulb, along with efficiency rudders, is successfully utilized in a wide range of projects and configurations. The most effective solution is the rudder bulb fitted to a twisted rudder and in combination with a suitable propeller hub cap. Savings of up to 5% in power have been observed for fast twin screw vessels using High Efficiency Rudder Systems, which include twisted rudders with rudder bulbs and an appropriate, properly aligned propeller hub cap. Typical savings in power to be expected from the application of a Rudder Bulb up to 2%; from the application of a Rudder Bulb in combination with a Twisted Rudder of up to 4%. As retrofitting a rudder bulb consequently may require a strengthening of the rudder stock and/or enlarging the steering gear, it is not recommended as a valid retrofit option.

Table 39: Characteristics of Rudder Bulb with Efficiency Rudder as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Rudder Bulb with Efficiency Rudder	Up to 4% of ME FC when sailing	RF and NB	YES

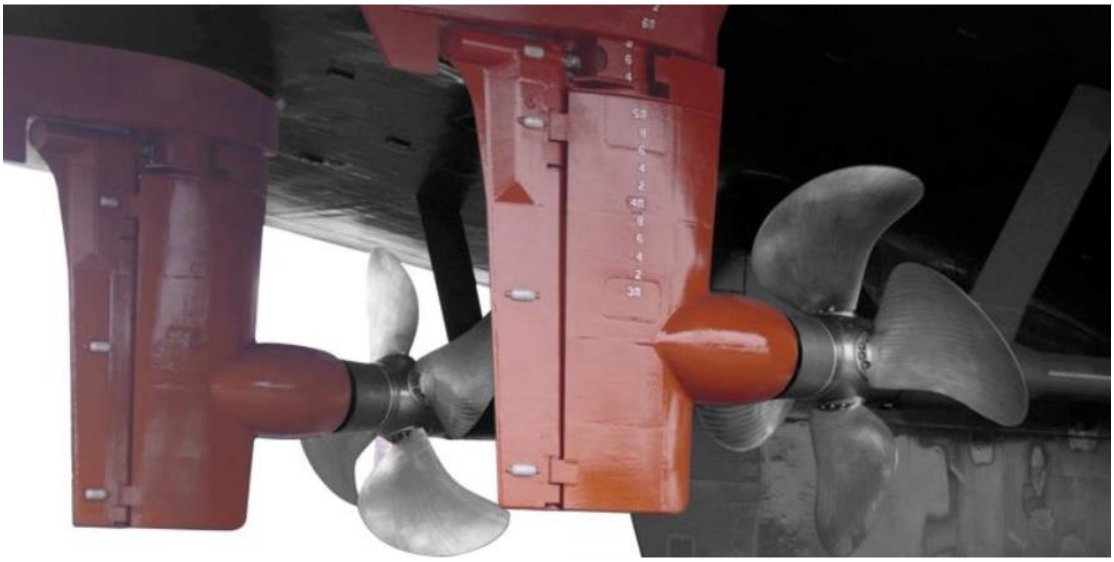

Figure 23: Rudder bulb equipped on a ship. [56]

Pre-swirl Duct (PSD)

A relatively novel approach for a PID is the Pre-Swirl Duct (PSD), which is marketed under the trademark Mewis Duct®. The wake equalizing duct and integrated pre-swirl fin system that are part of this power-saving technology are located in front of the propeller. By pre-correcting the flow into the propeller, the device essentially reduces the rotational losses in the resulting propeller slipstream and increases the flow velocity towards the inner radii of the propeller. Vessels having a high block coefficient and speeds under 20 knots are well suited for the PSD. PSD savings are virtually independent of ship draught and speed and depend on the quality of the ship's wake field and propeller loading. Typical savings in power to be expected from the installation of a Mewis Duct® at state-of-the-art full block vessels are between 6% and 8%.

Table 40: Characteristics of Pre-swirl Duct (PSD) as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Pre-swirl Duct (PSD)	6-8 % of ME FC when sailing	RF and NB	YES

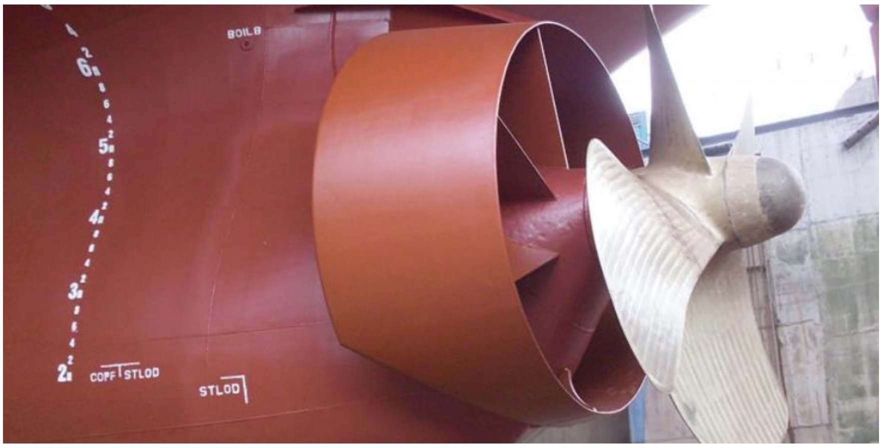

Figure 24: Pre-swirl duct fitted in front of a propeller. [57]

Pre-swirl stator

The pre-swirl stator concept consists of three to four stator blades mounted on the boss end of the hull in front of the propeller. The stator does not on its own save energy or create forward thrust, in fact it adds to the resistance. Despite the added resistance the stator blades induce a favourable asymmetric inflow to the propeller and thus improve the propulsion efficiency. In the case of a four-blade stator, three blades are arranged on the port side and one blade is arranged on the starboard side. The main role of the three blades on the port side is to reduce the slip loss of the propeller encountered when the blades pass upwards on the port side. The single blade on the starboard side is adopted to increase the wake fraction for higher hull efficiency while at the same time minimizing any unfavourable effect on propeller cavitation. Typical savings in power to be expected from the installation of Pre-Swirl Stators at Container Vessels are between 3.5% and 4.5%. For full block vessels like Bulk Carriers and Tankers the potential savings typically are higher, ranging between 4.5% and 6.5%.

Table 41: Characteristics of pre-swirl stator as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Pre-swirl stator	3.5-4.5 % of ME FC at fine-form vessels and 4.5-6.5 % of ME FC at full block vessels	RF and NB	YES

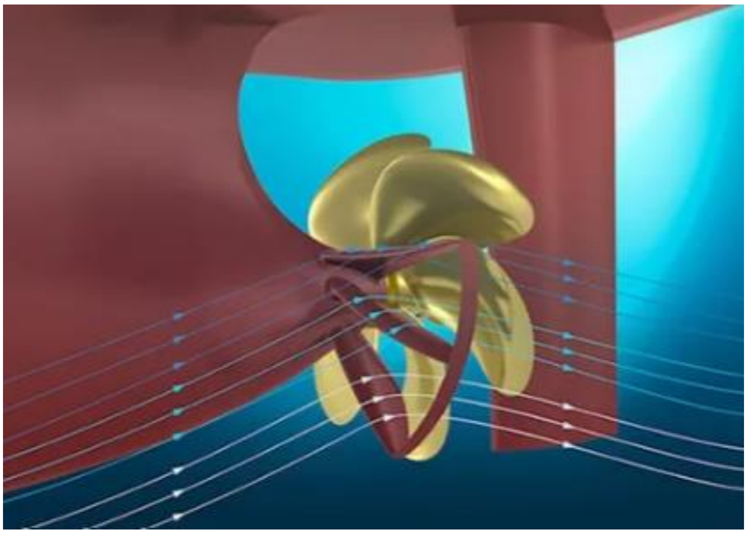

Figure 25: Propeller's slipstream due to the application of a pre-swirl stator. [58]

Post Stator

The post stator concept includes X-shaped fins located aft of the propeller and are combined with an integrated propeller cap and rudder bulb. This concept aims at reducing the losses due to propeller hub vortex and at recovering energy from the rotational losses in the propeller slipstream like the thrust fin concept. Compared to the pre-swirl stator, the post stator is relatively moderate in size (less than 80% of the propeller diameter) and does not have any effect on the propeller cavitation. Typical savings in power to be expected from the installation of a Post Stator aft of the propeller are up to 4%.

Table 42: Characteristics of post stator as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Post Stator	Up to 4% of ME FC when sailing	RF and NB	YES

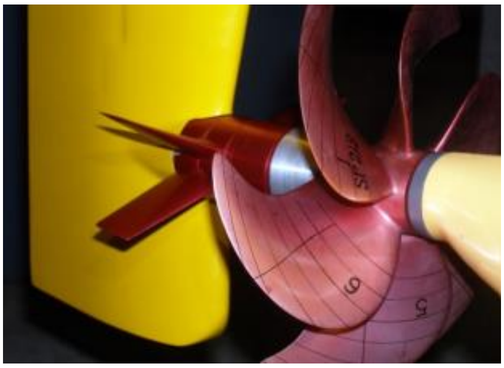

Figure 26: Post stator aft of the propeller. [59]

Saver fins

Saver fins, also called Vortex Generator Fins (VGF), are applied in containerships to improve the inflow to the propeller and thus reducing pressure pulses and the vibration level in the aft superstructure above the propeller. These fins properly arranged typically reduce pressure pulses by about 50%. Regarding the full block vessels, saver fins are applied to reduce the bilge vortex and thus reduce flow separations in the aft body. Reducing the flow separations in the aft body results in lower resistance and thus better propulsive efficiency. Typical savings in power to be expected from the installation of Vortex Generator Fins (VGF) at full block vessels like Bulk Carriers and Tankers are up to 3.5%. At containerships the savings in power are expected to be 2%.

Table 43: Characteristics of saver fins as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Saver fins	2 % of ME FC at fin-form ships and up to 3.5 % of ME FC at full-block vessels	RF and NB	YES

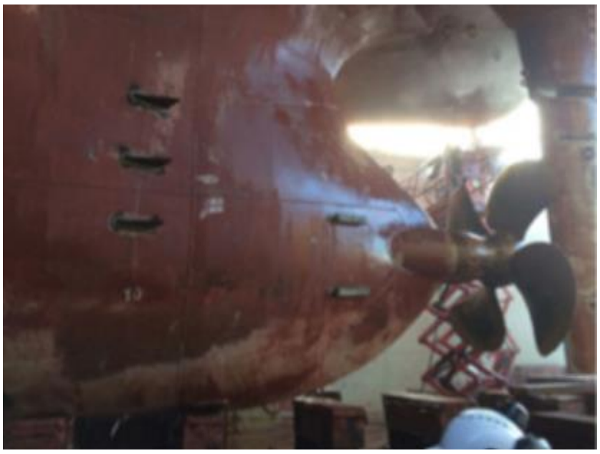

Figure 27: Vortex generators installed on the vessel's hull. [60]

Propeller Boss Cap Fins (PBCF)

PBCF is state of the art and become more and more indispensable with respect to environment and ecologically conscious behaviour in naval architecture. This device aims at reducing the losses arising from the propeller hub vortex. A hub vortex is caused by the joining boundary vortices of the different blades. Each blade develops an individual vortex – which consumes energy – and these vortices merge behind the hub cap and form a concentrated vortex. The shape and intensity of this vortex depends on the propeller design and the load distribution along the propeller blade and on the type of the hub cap. A streamlined hub cap for example supports the development of the hub vortex and thus typically features the biggest losses. Already a simple cylindrical or a conical hub cap can save power of up to 2% compared to a traditional streamlined shaped hub cap. Hub caps with fins (preferably with the same number of fins as the number of propeller blades) can diminish the joining and improve the propeller efficiency at best. Hub caps with fins are usually designed from experience and can hardly be tested in a model basin. Typical savings in power to be expected from the installation of a PBCF compared to a modern, state-of-the-art cylindrical hub cap are between 1.5% and 2.5%. Therefore, PBCF can save power of up to 3.5% - 4.5% compared to a traditional streamlined shaped hub cap.

Table 44: Characteristics of Propeller Boss Cap Fins (PBCF) as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Propeller Boss Cap Fins (PBCF)	3.5-4.5 % of ME FC when sailing	RF and NB	YES

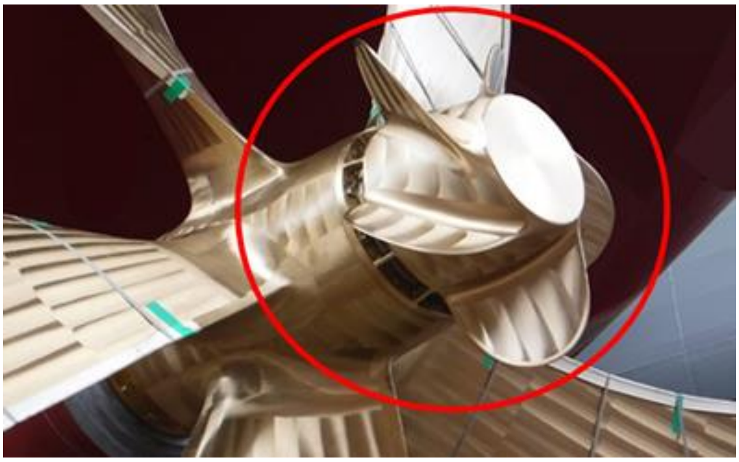

Figure 28: Propeller Boss Cap fins fitted on the back of a propeller.

Thrust fin

Thrust fin is a concept that has been developing for several years. Both X-shaped thrust fin configurations with four blades and thrust fins consisting of only two blades have been investigated. The thrust fins are designed such that the blades generate thrust in the rotating propeller slipstream. The design of the twisted blades requires high sophisticated numerical simulations and vast experience. During model tests the generated thrust can be recognised in a reduced thrust deduction fraction. This results in higher hull efficiency and thus better propulsive efficiency. Typical savings in power to be expected from the installation of a Thrust Fin aft of the propeller are up to 4%.

Table 45: Characteristics of thrust fin as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Thrust fin	Up to 4 % of ME FC when sailing	RF and NB	YES

Figure 29: Thrust fins fitted on a rudder.

Wake Equalizing Duct (WED)

The WED is well recognized in the shipbuilding industry and has been successfully applied to all type and sizes of ships. The asymmetric arrangement of two half ducts aims at improving the quality of the inflow to the propeller and at the same time reduces separations in the aft body and rotational losses in the propeller slipstream. Typical savings in power to be expected from the installation of a Wake Equalizing Ducts (WED) at full block vessels like Bulk Carriers and Tankers are between 3% and 5%.

Table 46: Characteristics of Wake Equalizing Duct (WED) as a decarbonization measure.

Decarbonization measure	Reduction potential	Fitting	EEDI - EEXI effect
Wake Equalizing Duct (WED)	3-5 % of ME FC on full block vessels when sailing	RF and NB	YES

Figure 30: Wake Equalizing Duct fitted forward of the propeller.

4.5 Fuels

A shift to alternative low and zero-carbon fuels is needed, to meet the IMO targets to help cut GHG emissions from shipping, as technical and operational efficiency measures alone will not be able to deliver the targeted emissions reduction. In this context, a summary of different marine fuels is presented below.

4.5.1 Fuel Oil

Fuel oil is produced from processing crude oil. The products from processing crude oil are divided into distillates and residues. The production process is presented in the pictures below.

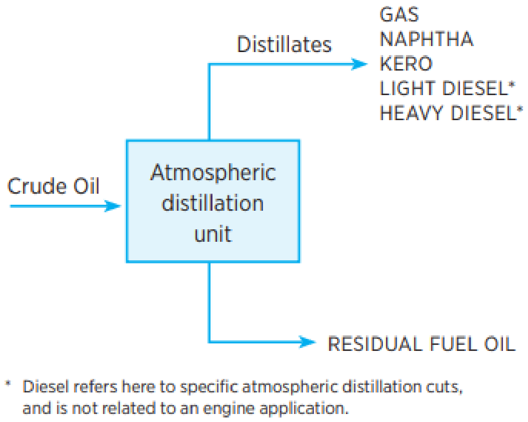

Figure 31: Straight run refinery. [61]

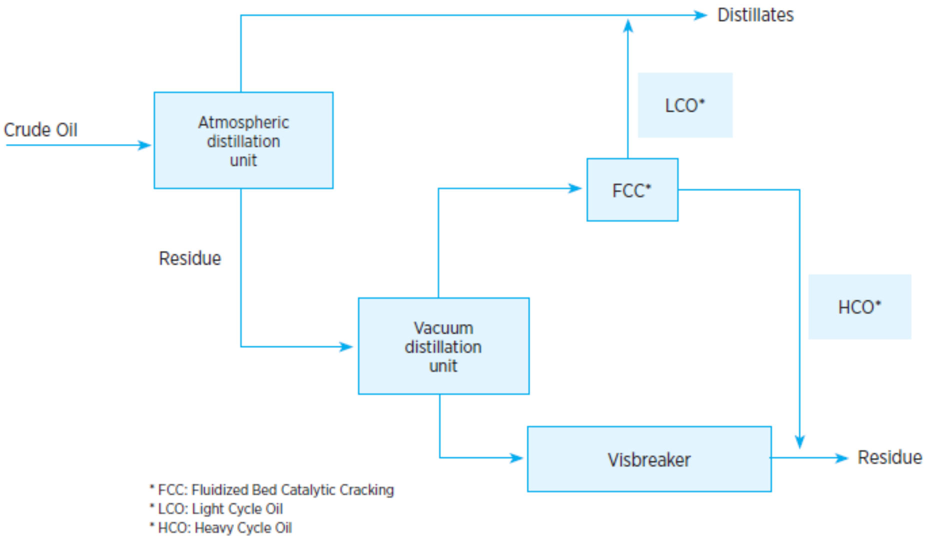

Figure 32: Complex refinery. [61]

IMO divides fuel oil into Diesel/Gas Oil, Light Fuel Oil (LFO), and Heavy Fuel Oil (HFO). The grades of Marine Gas Oil (MGO) are DMA, DMZ, and DMX and the grade of Marine Diesel Oil (MDO) is DMB. All the above are distillates as coded by the first letter of the grades. The emission factor of both MDO and MGO is 3.206 $\frac{t\ CO_2}{t\ fuel}$ and their Lower Heating Value is 42700 $\frac{kJ}{kg}$. Light Fuel Oil grades are split into RMA, RMB, RMD which are residues, and DMC which at first was classified as distillate but is reclassified as RMA10 [61]. LFO's emission factor is 3.151 $\frac{t\,CO_2}{t\,fuel}$ and its Lower Heating Value is 41200 $\frac{kJ}{kg}$. The Heavy Fuel Oil grades are RME, RMF, RMG, and RMH, its emission factor is 3.114 $\frac{t\,CO_2}{t\,fuel}$ and its Lower Heating Value is 40200 $\frac{kJ}{kg}$. In the past few years Low Sulphur Fuel Oil (VLSFO) has been used most of the time due to Sulphur regulations outside of ECA zones. VLSFO is a mix of MDO with HFO.

4.5.2 LNG

LNG as its abbreviation suggests, is Liquefied Natural Gas which is used due to its low volume resulting to easier and more efficient transport. More specifically, LNG's volume is 600 times lower than the volume of Natural Gas. Natural Gas is mainly composed of methane, in the range of 70-90%. In a ship, LNG is stored in atmospheric pressure and at -162°C, meaning that storage tanks shall have higher breaking strength in brittle fracture. It is neither flammable nor corrosive. However, Boil Off Gases (BOG) are flammable but there are ways to avoid this problem, etc. by reliquefication. The emission factor of LNG is 2.750 $\frac{t\,CO_2}{t\,fuel}$ and its LHV is 48000 $\frac{kJ}{kg}$.

4.5.3 LPG

Several Natural Gas Liquids, that are part of Natural Gas during its extraction but are separated later, form Liquefied Petroleum Gas (LPG). The referred Natural Gas Liquids are propane and butane. The production percentage of LPG due to Natural Gas is 60%. The remaining 40 % comes through crude oil processing in the refinery. LPG is stored at higher pressure than LNG but not at that low temperature. It is neither flammable nor corrosive, but because it is a cryogenic fuel there are Boil Off Gases that need to be assessed, just like LNG. The emission factor of propane is 3.000 $\frac{t\,CO_2}{t\,fuel}$ and its LHV is 46300 $\frac{kJ}{kg}$, whereas butane's emission factor is 3.030 $\frac{t\,CO_2}{t\,fuel}$ and its LHV is 45700 $\frac{kJ}{kg}$.

4.5.4 Methanol

There are four types of methanol. Grey Methanol which is produced from Natural Gas, Black Methanol which is produced from coal, Blue Methanol that is produced by the reaction of CO_2 with hydrogen, and Green Methanol the reaction of which is CO_2 free. Methanol is a volatile and corrosive fuel with low viscosity, that is why it requires double-skin piping. It is also very flammable; however, it should be noted that is not as volatile as LPG or LNG. The emission factor of Methanol is 1.375 $\frac{t\,CO_2}{t\,fuel}$ and its LHV is 19900 $\frac{kJ}{kg}$.

4.6 Database of Energy Saving Devices (ESD)

In the tool, the users are capable of selecting between the previously stated measures. There are created eight worksheets inside the tool's workbook. The three are for the reduction potential of Main Engine, Auxiliary Engine and Boiler when the ship is sailing. The next three are for the reduction potential of the 3 fuel consumers when the ship is manoeuvring. The two remaining are for the reduction potential of Auxiliary Engine and Boiler when the ship is not sailing. The ship types that are able to harness the deduction potential of the Energy Saving Devices are Bulk Carriers, Chemical Tankers, Container Vessels, LNG and LPG Carriers, and Tankers. A further categorisation relative to the deadweight in tonnes carried was determined as follows:

- For Bulk Carriers:
    - $DWT < 10000\,t$
    - $10000\,t \leq DWT < 35000\,t$
    - $35000\,t \leq DWT < 60000\,t$
    - $60000\,t \leq DWT < 100000\,t$

    - $100000\ t \leq DWT < 200000\ t$
    - $DWT \geq 200000\ t$
- For Chemical Tankers:
    - $DWT < 5000\ t$
    - $5000\ t \leq DWT < 10000\ t$
    - $10000\ t \leq DWT < 20000\ t$
    - $20000\ t \leq DWT < 40000\ t$
    - $DWT \geq 40000\ t$
- For Container Vessels:
    - $DWT < 13250\ t$
    - $13250\ t \leq DWT < 26200\ t$
    - $26200\ t \leq DWT < 39300\ t$
    - $39300\ t \leq DWT < 63500\ t$
    - $63500\ t \leq DWT < 96500\ t$
    - $96500\ t \leq DWT < 136500\ t$
    - $136500\ t \leq DWT < 161000\ t$
    - $161000\ t \leq DWT < 206500\ t$
    - $DWT \geq 206500\ t$
- For LNG and LPG Carriers:
    - $DWT < 22500\ t$
    - $22500\ t \leq DWT < 45000\ t$
    - $45000\ t \leq DWT < 90000\ t$
    - $DWT \geq 90000\ t$
- Tankers
    - $DWT < 5000\ t$
    - $5000\ t \leq DWT < 10000\ t$
    - $10000\ t \leq DWT < 20000\ t$
    - $20000\ t \leq DWT < 60000\ t$
    - $60000\ t \leq DWT < 80000\ t$
    - $80000\ t \leq DWT < 120000\ t$
    - $120000\ t \leq DWT < 200000\ t$
    - $DWT \geq 200000\ t$

With the IF function of Excel, a number from 1 to 32 is shown - representing the different categories of ship types and deadweight that were described below – based on the ship type and deadweight filled. Then with the INDEX-MATCH function of excel, the tool matches the ship type category with the Energy Saving Device chosen by the users and applies the possible reduction into the CII formula by deducting the fuel consumption depending on the decarbonization path chosen.

4.7 Compatibility of Energy Saving Devices

In the tool there is the option to apply more than one measure to the ship. However, in many cases the reduction potential of 2 ESDs is not adding up, and the likelihood that the fuel deduction will be added decreases when there are more than two ESDs. For this reason, a table which shows the compatibility of the measures is created.

Inside the tool, the deduction potential of the measures is added whether the measures are compatible or not, therefore it is necessary for the users to check the ESDs compatibility worksheet inside the tool workbook, before adding another technology for the reduction of CII. If the users select more than two measures, the ESDs shall all be compatible with one another. The table that indicates the compatibility of the measures is shown below.

Table 47: Compatibilty of decarbonization measures.

	Propeller Boss Cap Fins	Thrust Fin	Post Stator	Saver fins	Wake Equalizing Duct	Pre-Swirl Duct	Costa bulb	Costa bulb with twisted rudder	Bulbous bow Retrofit	High-Efficiency Propeller	Propeller retrofitting	Pre Swirl Stator	Auxiliary Systems Optimization	Aerodynamic Optimization of Superstructures	Energy-efficient lighting system	Engine de-rating	Engine performance testing and tuning	Exhaust gas boilers on auxiliary engines	Foils on bow	Foils on stern	Hard sails or wings	Hull coating	Hull form optimization	Improved auxiliary engine load	Kite	Optimization of cargo handling systems	Optimizing turbocharging at lower engine loads (exhaust gas bypass	Reduced ballast design	Rotor sails	Shore Power	Solar Power	Steam plant operation improvement	Trim and draft optimization	Variable engine speed	Variable frequency drive (VFD) controlled pumps, fans and motors	Weather routing	Wind Turbine	Waste heat recovery	Air Lubrication System	Shaft Generator - PTO
Propeller Boss Cap Fins	-	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
Thrust Fin	✗	-	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
Post Stator	✗	✗	-	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
Saver fins	✗	✗	✗	-	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
Wake Equalizing Duct	✗	✗	✗	✗	-	✗	✗	✗	✗	✓	✗	✗	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
Pre-Swirl Duct	✗	✗	✗	✗	✗	-	✗	✗	✗	✓	✗	✗	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
Costa bulb	✗	✗	✗	✗	✗	✗	-	✗	✗	✓	✗	✗	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
Costa bulb with twisted rudder	✗	✗	✗	✗	✗	✗	✗	-	✗	✓	✗	✗	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
Bulbous bow Retrofit	✗	✗	✗	✗	✗	✗	✗	✗	-	✓	✗	✗	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
High-Efficiency Propeller	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✗	✗	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
Propeller retrofitting	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	-	✗	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
Pre Swirl Stator	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	-	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
Auxiliary Systems Optimization	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗
Aerodynamic Optimization of Superstructures	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Energy-efficient lighting system	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Engine de-rating	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗
Engine performance testing and tuning	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓
Exhaust gas boilers on auxiliary engines	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗
Foils on bow	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	-	✗	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
Foils on stern	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	✗	-	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
Hard sails or wings	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Hull coating	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Hull form optimization	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Improved auxiliary engine load	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✗
Kite	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	-	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Optimization of cargo handling systems	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Optimizing turbocharging at lower engine loads (exhaust gas bypass (EGB))	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗
Reduced ballast design	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
Rotor sails	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Shore Power	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	-	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
Solar Power	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	-	✓	✓	✓	✓	✓	✓	✓	✓	✓
Steam plant operation improvement	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓
Trim and draft optimization	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓
Variable engine speed	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	✓	✓	✗
Variable frequency drive (VFD) controlled pumps, fans and motors	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	✓	✗
Weather routing	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	✓
Wind Turbine	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓
Waste heat recovery	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓
Air Lubrication System	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓
Shaft Generator - PTO	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗	✓	✓	✓	✓	✓	✗	✓	✓	✗	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	-

5. Application Cases

This chapter contains the calculation and projection for the upcoming years of CII of 4 case studies, 2 of which are Tankers, 1 Aframax and 1 Very Large Crude Carrier (VLCC), 1 Bulk Carrier, and 1 Liquefied Petroleum Gas Carrier. The tool's outcomes will be showcased via these application cases.

5.1 Tanker - VLCC

For the 1st application case a Very Large Crude Carrier is selected. The DWT of the VLCC is 299430 tons. The ship sailed for approximately 260 days out of the entirety of the year, 142 days of which it was fully loaded, and the rest 118 days was sailing with ballast. The discharge operations did not take long throughout the year, since only 9 days out of the whole year the ship unloaded. However, the ship had to wait a total of 60 days during the year outside of the port in anchorage either loaded or unloaded. The days of which the ship maneuvered were 23 at 4 knots speed.

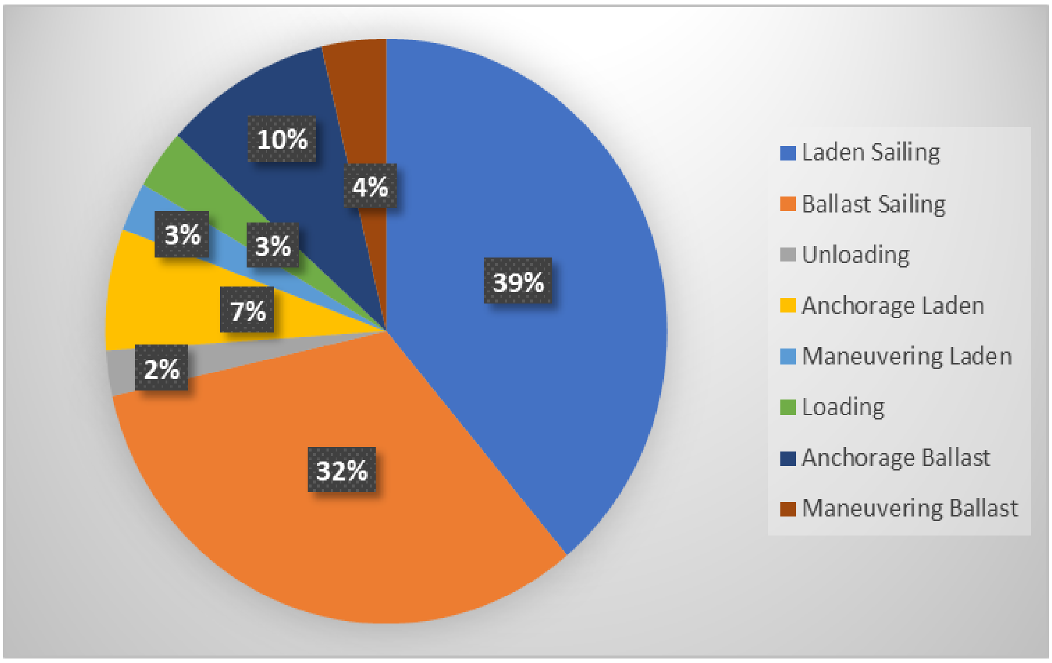

Figure 33: Operational profile of the VLCC throughout the year.

The ship, when sailing fully loaded was moving faster than when it was loaded only with ballast, as 12.09 knots was the laden mean speed, and 11.51 knots was the ballast mean speed. The chart below depicts the ship's speeds under ballast and laden conditions throughout the year.

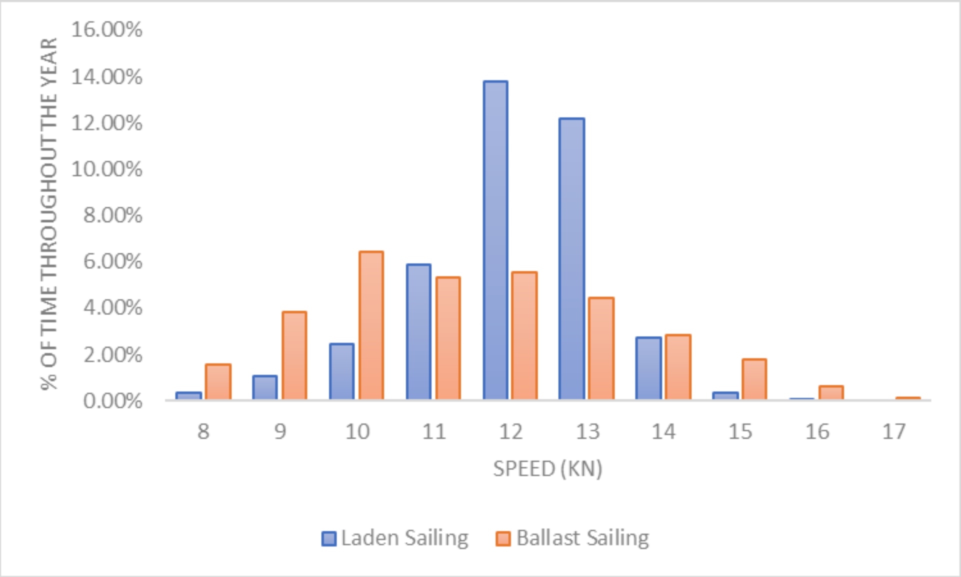

Figure 34: Speeds that the VLCC sailed during the year when in laden and ballast mode.

For all operational modes, the total fuel consumption was given at tones per day consumed for all the consumers -Main Engine, Auxiliary Engines, and Boilers-. Also, the fuel sharing of when the ship was sailing and when it was stationary, was 62.51% HFO, 34.89% LFO, and 2.60% MDO, meaning that the total fuel consumed by the Main Engine, Aux. Engines, and Boilers are known separately. When the ship was stationary, 66% of AEs and 34% of Boiler was used. It is considered that the AE’s and Boiler’s consumption are the same for all the speeds of the sailing modes. Therefore, only the Main Engine fuel consumption is altered when the speed changes. The ME fuel consumption - measured in tons per day- versus speed graph, for both sailing modes is shown below.

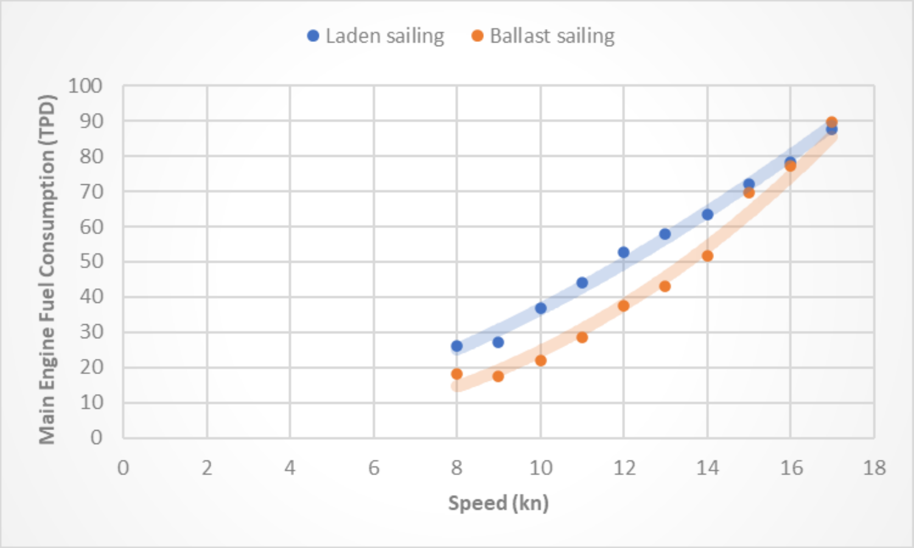

Figure 35: Fuel oil consumption at tons per day versus speed graph of the VLCC when in laden and ballast mode.

Regarding the correction factors, 250 tons of fuel annually can be used for FC_{boiler}.

The attained CII, the rating for the year 2023, and the distribution of CO_2 emissions from the 3 consumers are as follows.

Table 48: Results of the VLCC without measures applied.

Final Results

attained CII [grCO2/(t*nm)]	2.07440111
Rating before measure	*B rating*

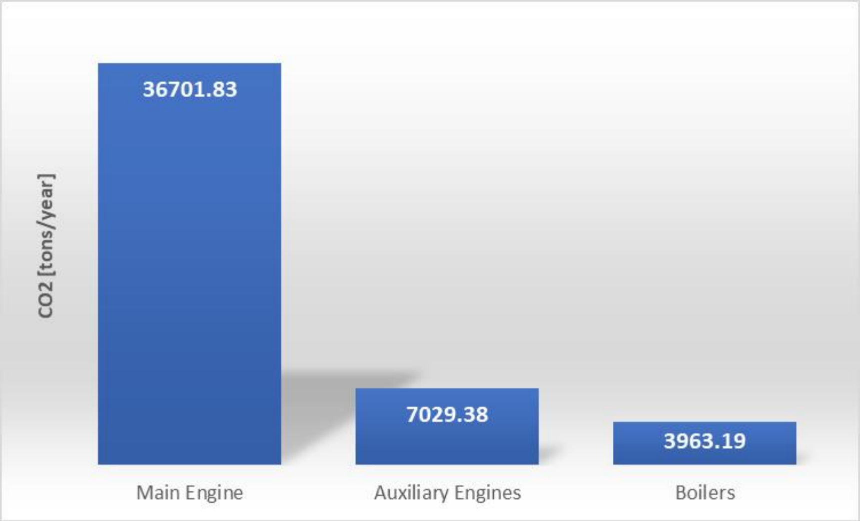

Figure 36: Tons CO_2 emitted by the VLCC's 3 fuel consumers for the year.

So that the CII of the ship drops 4 measures are taken into consideration for the VLCC. The decarbonization measures chosen are:

- Pre-Swirl Duct or Mewis Duct.
- Engine performance testing and tuning.
- Hard sails.
- Weather routing.

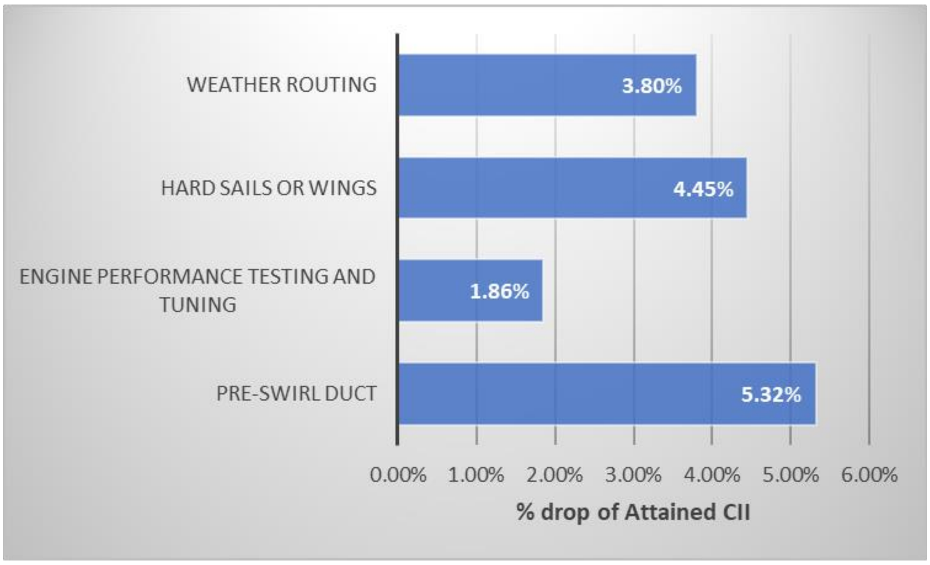

Figure 37: Percentage drop produced by the application of each of the 4 decarbonization measures to the attained CII of the VLCC.

The total percentage drop using the 4 measures reaches 15.44% reduction of the attained CII. The new CIIs applying each of the measures are:

Table 49: Calculated CII with the measures applied to the VLCC.

1st Measure	Pre-Swirl Duct
1 – Meas. CII	**1.963955487**
2nd Measure	Engine performance testing and tuning
1+2 – Meas. CII	**1.925443466**
3rd Measure	Hard sails or wings
1+2+3 – Meas. CII	**1.833066213**
4th Measure	Weather routing
1+2+3+4 – Meas. CII	**1.754176483**

Two required CII reduction factor scenarios are created, one more lenient and one stricter. The same four measures are integrated in the results of these two reduction factor scenarios. The inputs and results of the lenient reduction factor scenario are showcased below.

Table 50: Input of the lenient required CII reduction factor scenario for the VLCC.

Reference lines	
Ref CII	2.395360727
Rating year	2023
IMO reduction 2027-2030	IMO 2%
IMO reduction 2031-2035	IMO 2%
IMO reduction 2036-2040	IMO 2.5%
IMO reduction 2041-2045	IMO 2.5%
IMO reduction 2046-2050	IMO 3%
Rating year ref CII	2.275592691

Table 51: Projection years that the VLCC's CII will hit every rating with and without decarbonization measures applied for the lenient required CII reduction factor scenario.

	Year of hit B rating	Year of hit C rating	Year of hit D rating	Year of hit D+2 rating	Year of hit E rating
No measures	Already hit	2024	2031	2033	2036
With 4 measures	2026	2032	2036	2038	2041

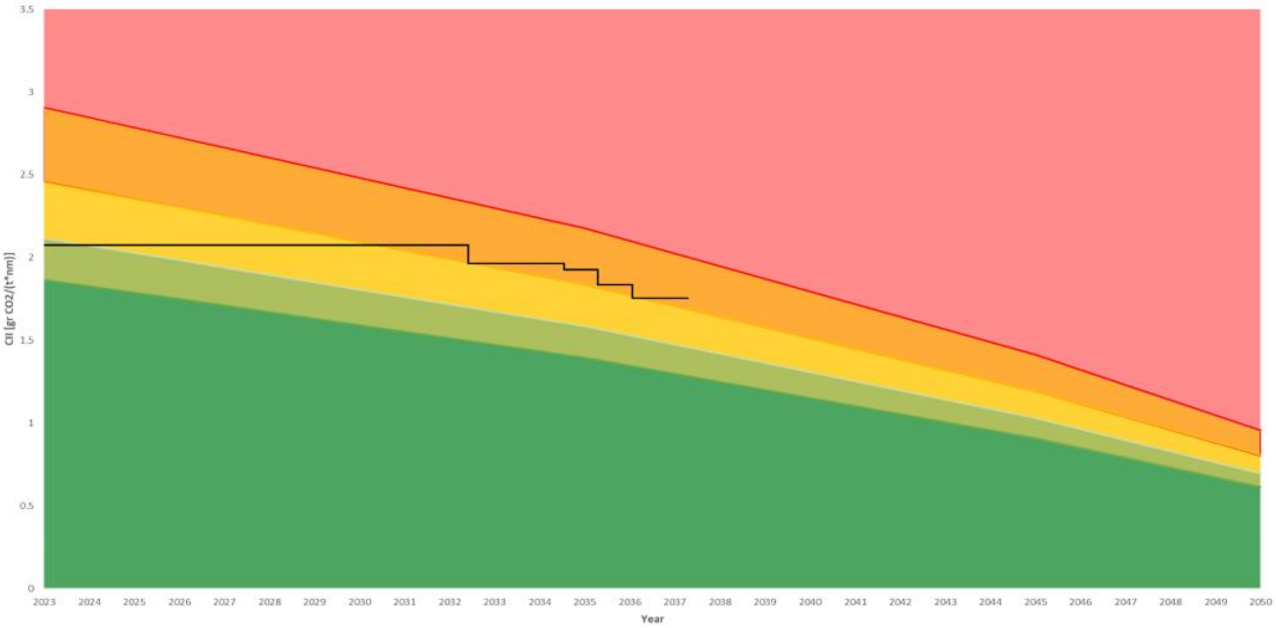

Figure 38: Graphical display of the VLCC's performance for the lenient reduction factor scenario.

The inputs and results of the strict reduction factor scenario are showcased below.

Table 52: Input of the strict required CII reduction factor scenario for the VLCC.

Reference lines	
Ref CII	2.395360727
Rating year	2023
IMO reduction 2027-2030	IMO 3.5%
IMO reduction 2031-2035	IMO 3.5%
IMO reduction 2036-2040	IMO 4%
IMO reduction 2041-2045	zero 50
IMO reduction 2046-2050	zero 50
Rating year ref CII	2.275592691

Table 53: Projection years that the VLCC's CII will hit every rating with and without decarbonization measures applied for the strict required CII reduction factor scenario.

	Year of hit B rating	Year of hit C rating	Year of hit D rating	Year of hit D+2 rating	Year of hit E rating
No measures	Already hit	2024	2029	2031	2033
With 4 measures	2026	2029	2033	2035	2035

As presented by *Table 53* and *Table 51*, the impact of the 4 decarbonization measures is visible to the ratings for the upcoming years. Also, the difference between the required CII reduction factor scenarios for the year that the ship hits D+2 rating is 2 without the measures and 3 with them. This means that in the lenient scenario the ship will sail for 2 or 3 more years without any punishment or development of a plan of corrective actions, harvesting much more profit in that time span in comparison with the strict scenario. To conclude, the strategy that IMO will take in the upcoming years is extremely important for the ship's CII rating and therefore its operation.

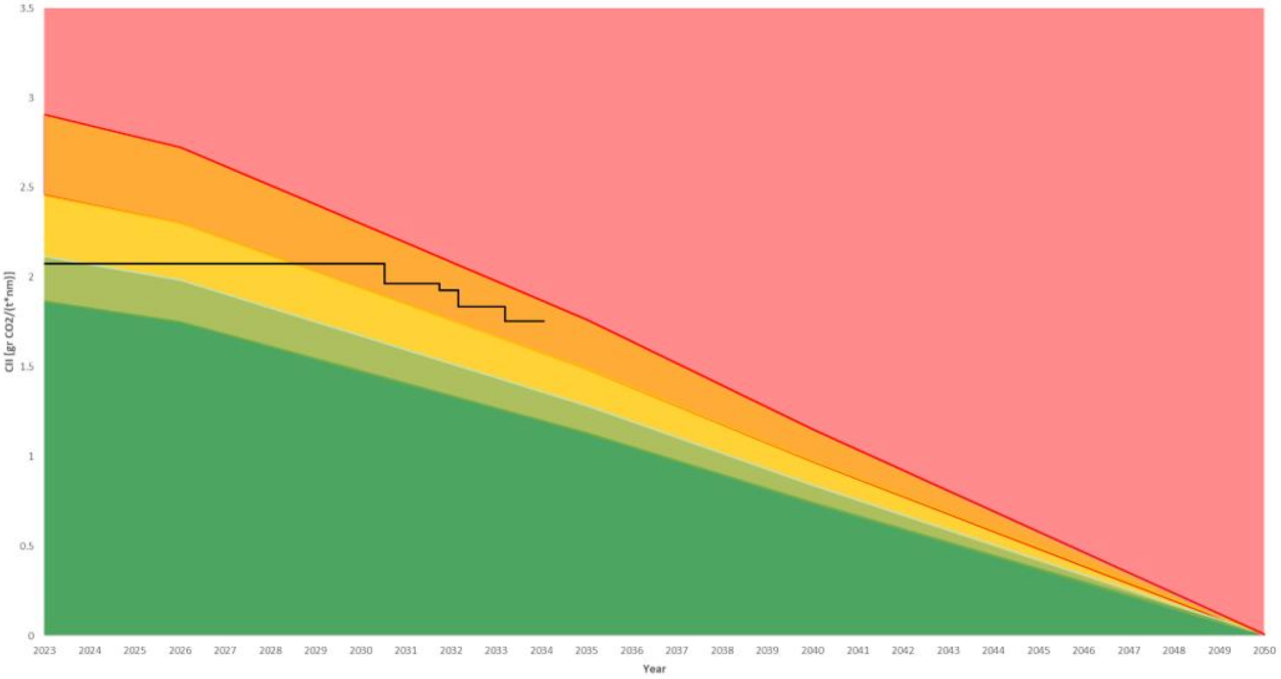

Figure 39: Graphical display of the VLCC's performance for the strict reduction factor scenario.

5.2 Aframax Tanker

For the 2nd application case an Aframax tanker is selected. The DWT of the tanker is 115000 tons. The ship sailed for approximately 193 days out of the entirety of the year, 122 days of which it was full loaded, and the rest 71 days was sailing at ballast condition. It is assumed that the ship loaded and unloaded cargo 12 times per year, and each operation lasted 2 days. This means that loading and unloading took 24 days each, during the year. Also, the ship had to wait a total of 124 days during the year outside of the port in anchorage either loaded or unloaded.

The ship's speed was similar when sailing fully loaded and when it was loaded only with ballast, as 11.94 knots was the laden mean speed, and 11.70 knots was the ballast mean speed. *Figure 41* depicts the ship's speeds under ballast and laden conditions throughout the year.

In this case study, only HFO was used during the year for all the operational modes. The fuel consumption was given separately for the 3 fuel consumers when the ship was sailing in ballast and laden conditions. The ME fuel consumption - measured in tons per day- versus speed graph, for both sailing modes is in *Figure 42*.

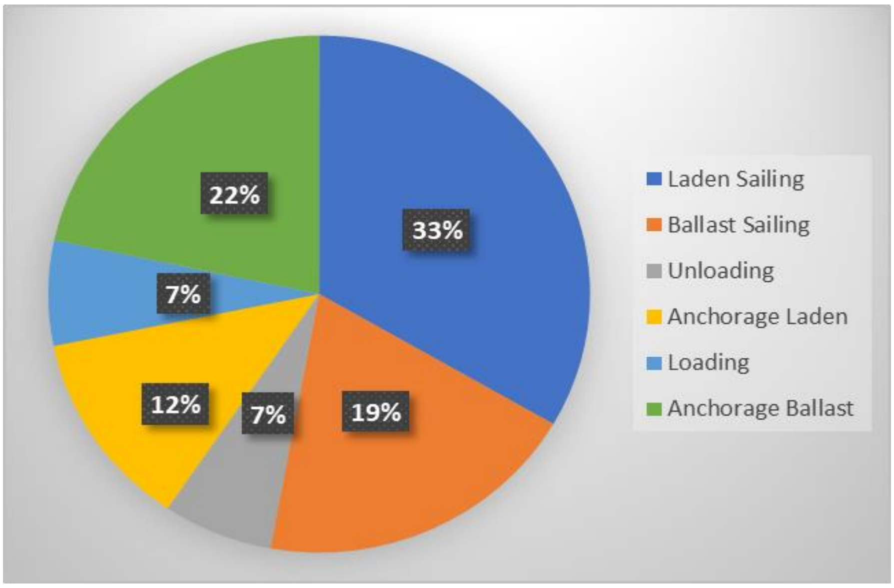

Figure 40: Operational profile of the Aframax tanker throughout the year.

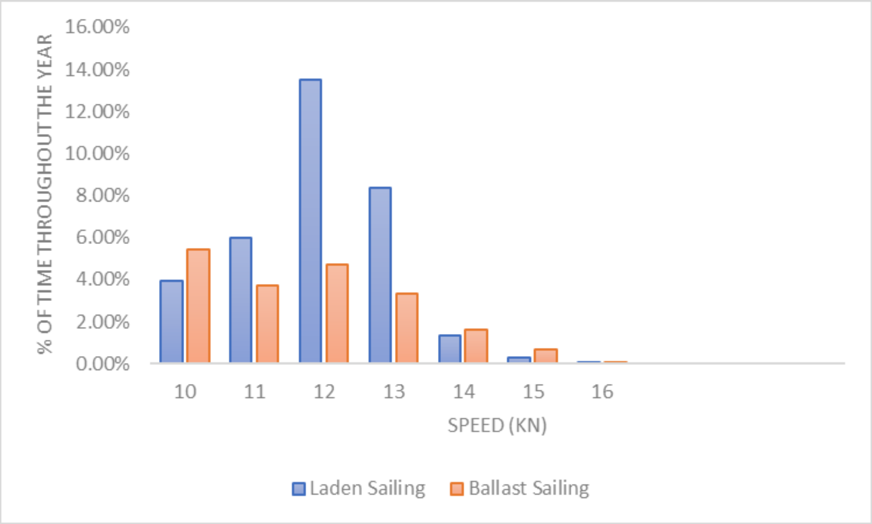

Figure 41: Speeds that the Aframax tanker sailed during the year when in laden and ballast mode.

Figure 42: Fuel oil consumption at tons per day versus speed graph of the Aframax tanker when in laden and ballast mode.

The fuel consumption per day was also given separately for the 2 fuel consumers when the ship was anchored and when it was loading. Regarding unloading, although the total consumption per day of both boiler and AEs is known when the Aframax was discharging cargo, the engine sharing for the fuel consumption per day is not given. It is assumed that the cargo oil pumps are driven by steam turbines, meaning that the boiler is used much more than the AEs during discharge operation. To calculate the boiler's consumption per day the following equation is used.

$$Boiler\_FC\left[\frac{t}{d}\right] = \frac{DWT[t]\cdot r\left[\frac{kg}{m^3}\right]}{\rho\left[\frac{t}{m^3}\right]\cdot 1000\left[\frac{kg}{t}\right]\cdot 2[d]} \quad (25)$$

Where:

- ρ is the density of the fuel and is considered 0.89 t/m^3.
- r is the fuel consumed by the boilers per cargo capacity discharged. For an Aframax tanker r is considered 0.52 kg/m^3.
- In the equation (24) it is assumed that the ship is fully loaded every time it arrives in port to unload cargo.
- Unloading of the fully loaded Aframax lasts 2 days.

No correction factor is taken into consideration for the CII calculation. The attained CII, the rating for the year 2023, and the distribution of CO_2 emissions from the 3 consumers are as follows.

Table 54: Results of the Aframax tanker without measures applied.

Final Results

attained CII [grCO2/(t*nm)]	**3.43773655**
Rating before measure	***B rating***

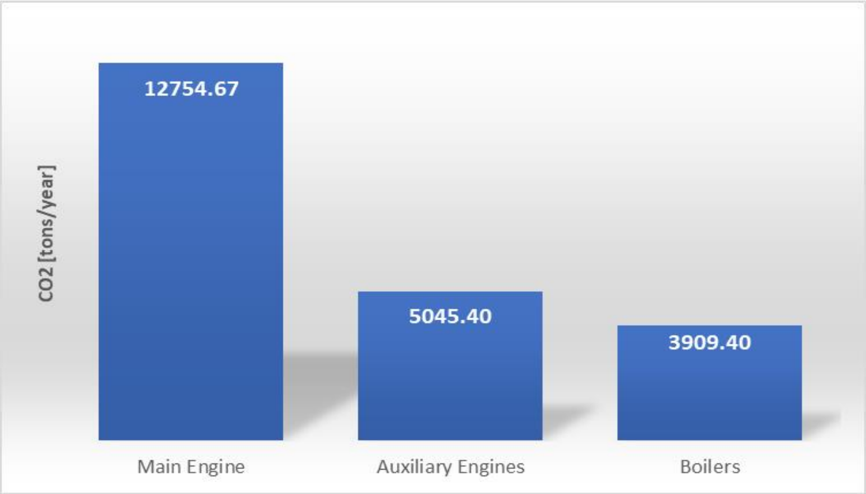

Figure 43: Tons of CO_2 emitted by the Aframax tanker's 3 fuel consumers for the year.

A moderate required CII reduction factor scenario when it comes to the drop of required CII is generated in this case study, the input of which is as follows.

Table 55: Input of required CII reduction factor scenario for the Aframax tanker.

Reference lines	
Ref CII	4.29423079
Rating year	2023
IMO reduction 2027-2030	IMO 2.5%
IMO reduction 2031-2035	IMO 3%
IMO reduction 2036-2040	IMO 3.5%
IMO reduction 2041-2045	IMO 3.5%
IMO reduction 2046-2050	zero 50
Rating year ref CII	4.079519251

In this case study there are developed 2 scenarios regarding the decarbonization measures applied. In the first one the measures that are applied are:

- Waste Heat Recovery (WHR).
- Shaft generator – Power Take Off (PTO).
- Bulbous Bow retrofit.
- Installation of Rotor Sails.

In the second scenario:

- The operational profile of the ship is changed.
- Foils on bow are fitted.

In the first scenario, the new CIIs, applying each of the measures, are:

Table 56: Calculated CII with the first scenario of measures applied to the Aframax tanker.

1st Measure	Waste heat recovery
1 - Meas. CII	**3.217293899**
2nd Measure	Shaft Generator - PTO
1+2 - Meas. CII	**2.996851246**
3rd Measure	Rotor sails
1+2+3 - Meas. CII	**2.799287406**
4th Measure	Bulbous bow Retrofit
1+2+3+4 – Meas. CII	**2.647807886**

The years that the CII of the ship will hit every rating with no measures, WHR only, WHR + PTO, WHR + PTO with Bulbous bow retrofit, WHR + PTO with Bulbous bow retrofit and Rotor sails are showcased below.

Table 57: Projection years that the Aframax tanker's CII will hit every rating for the first decarbonization measures scenario.

	Year of hit B rating	Year of hit C rating	Year of hit D rating	Year of hit D+2 rating	Year of hit E rating
No measure	Already hit	2028	2032	2034	2035
With WHR	2025	2030	2034	2036	2036
With WHR + PTO	2028	2032	2035	2037	2037

With WHR + PTO + Rotor sails + Bulbous bow retrofit	2030	2033	2036	2038	2039
With WHR + PTO + Rotor sails + Bulbous bow retrofit	2032	2035	2037	2039	2039

The percentage drop of CII from the use of the decarbonization proposals for the 1st scenario is shown in *Figure 44* and the tool's results in *Figure 45*.

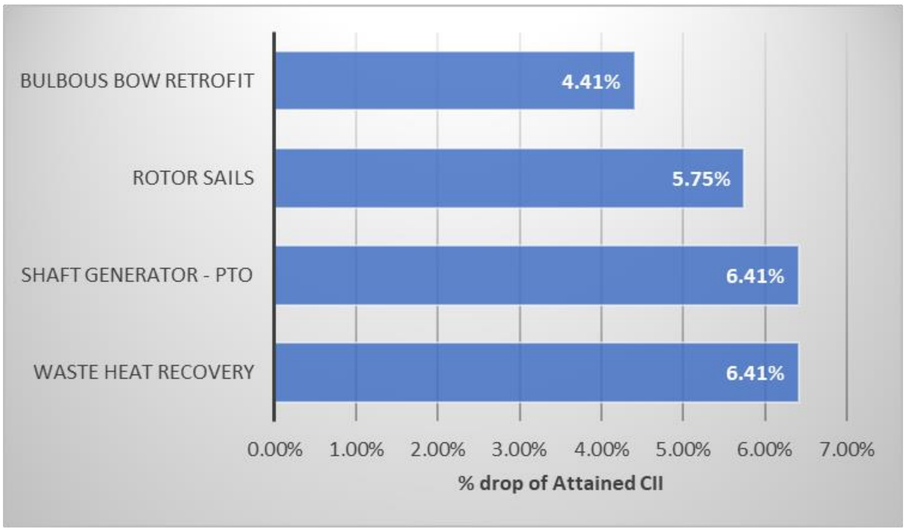

Figure 44: Percentage drop produced by each of the 4 decarbonization measures -applied in the first scenario of measures used- to the attained CII of the Aframax tanker.

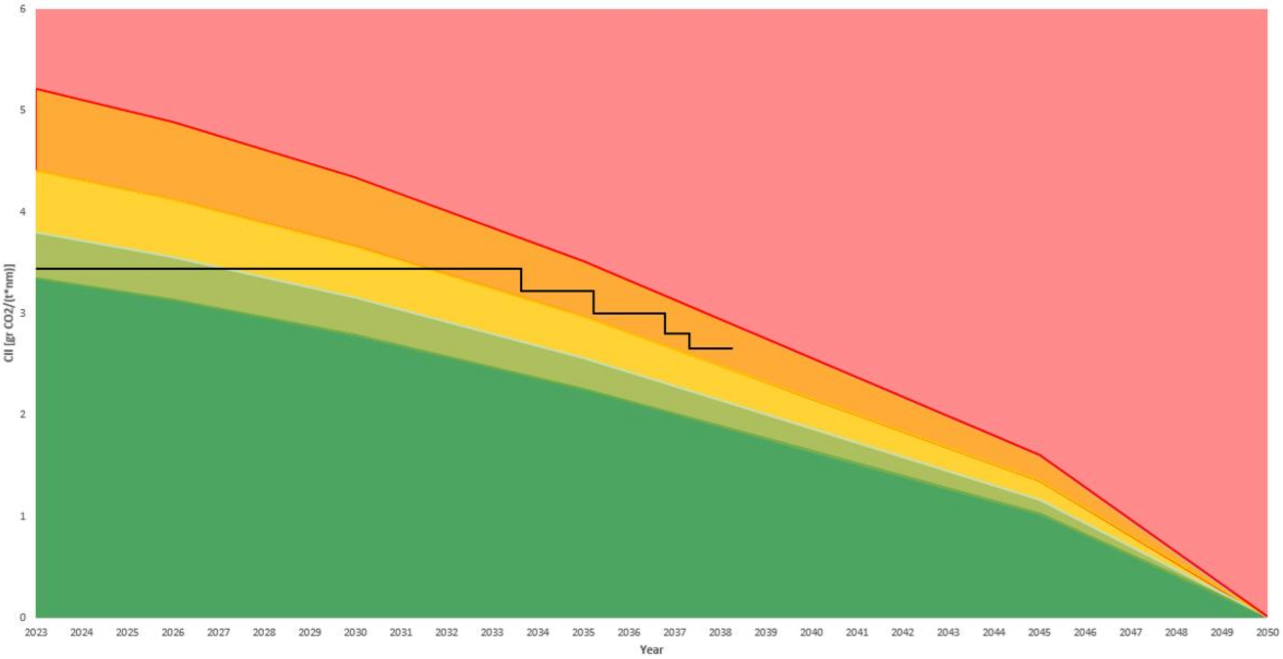

Figure 45: Graphical display of the Aframax tanker's performance for the first scenario of measures applied.

The new operational profile for the 2nd scenario of the applied measures is shown below.

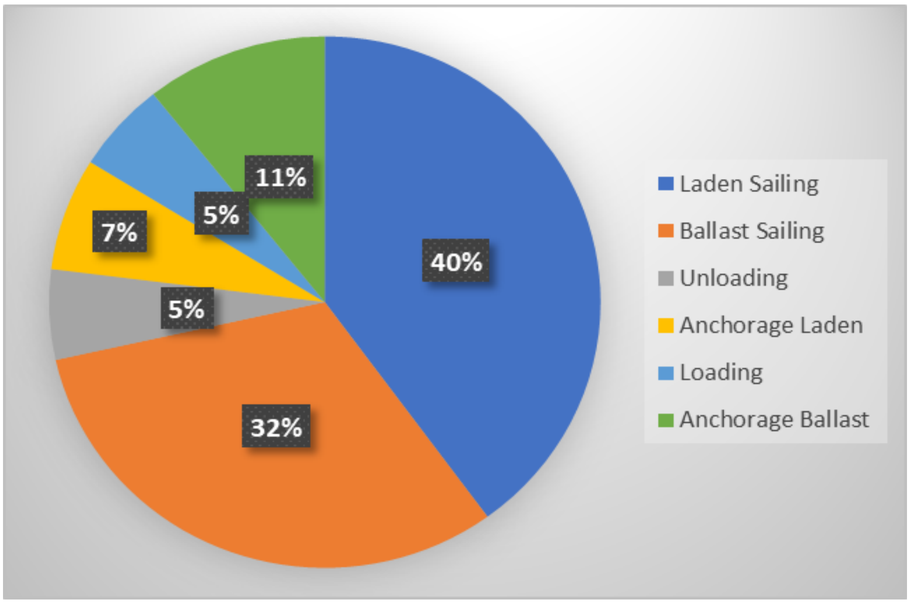

Figure 46: Second scenario revised operational profile of the Aframax tanker for the duration of a year.

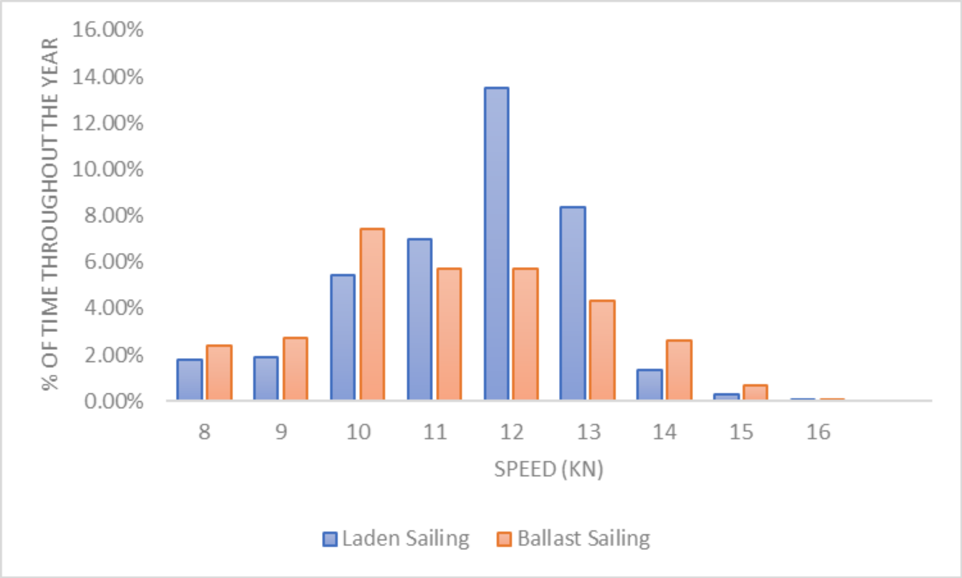

Figure 47: Second scenario revised speeds that the Aframax tanker can sail during a year when in laden and ballast mode.

In the second scenario, the tool's outputs are showcased in *Table 58* and *Figure 48*:

Table 58: Calculated CII with the second scenario of measures applied to the Aframax tanker.

1st Measure	Change of operational profile – Speed management
1 - Meas. CII	**2.772248324**
2nd Measure	Foils on bow
1+2 - Meas. CII	**2.629185764**

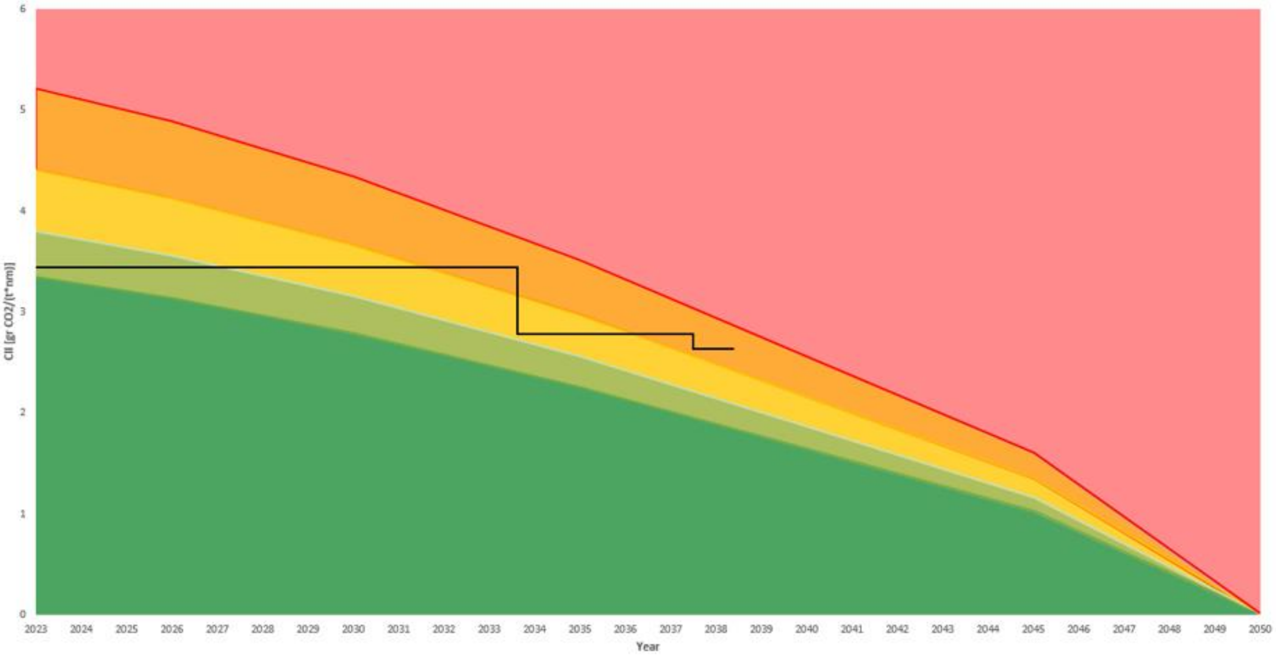

Figure 48: Graphical display of the Aframax tanker's performance for the second scenario of measures applied.

The years that the CII of the ship will hit every rating with no measures, alteration of operational profile only, and change of operational profile with the installation of Foils on bow are showcased below.

Table 59: Projection years that the Aframax tanker's CII will hit every rating for the second decarbonization measures scenario.

	Year of hit B rating	Year of hit C rating	Year of hit D rating	Year of hit D+2 rating	Year of hit E rating
No measure	Already hit	2028	2032	2034	2035
With Change of operational profile	2031	2034	2036	2038	2039
With Change of operational profile + Foils on bow	2032	2035	2037	2039	2039

The percentage drop of CII from the use of the decarbonization proposals for the 2nd scenario is shown in *Figure 49*.

As illustrated in *Figure 49* and *Figure 44*, as well as in *Figure 48* and *Figure 45*, the drop in CII by the adjustment of the Panamax's operating profile is massive compared with the rest decarbonization alternatives and it is not costly, whereas measures such as Waste Heat Recovery and Rotor Sails are marked at a high price. In conclusion, there should be put extra consideration into the operating profile of the ships, as it has great influence on CII, especially lower speeds.

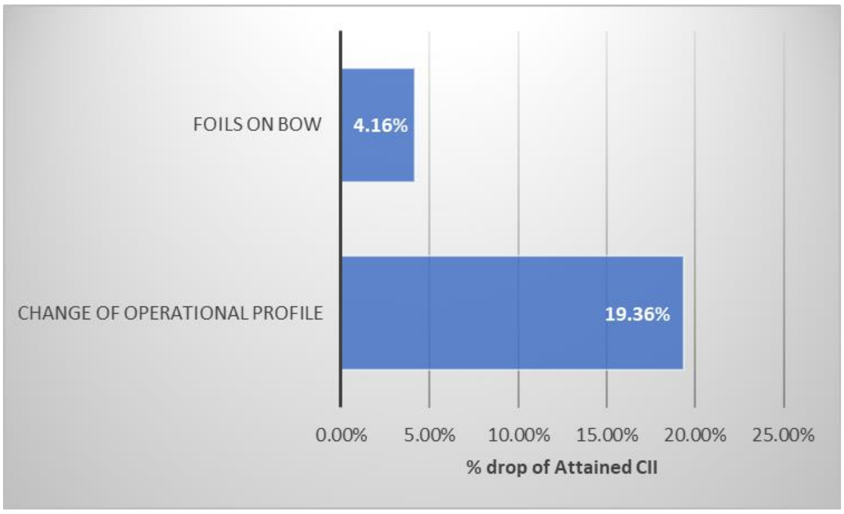

Figure 49: Percentage drop produced by each of the 2 decarbonization measures -applied in the second scenario of measures used- to the attained CII of the Aframax tanker.

5.3 LPG Carrier

For the 3rd application case an LPG Carrier is selected. The DWT of the vessel is 90000 tons. The ship is considered that will sail for approximately 296 days during the year, 160 days of which fully loaded, and the rest 136 days sailing with ballast. The ship loads and unloads a total of 54 days throughout the year. It is important to mention that the LPG Carrier did not have to wait a long time outside of the port in anchorage either loaded or unloaded, as the ship anchored in laden for 6 days and in ballast 8 days out of the entirety of the year.

The ship, when sailing fully loaded, was moving faster than when it was loaded only with ballast, as 15.73 knots was the laden mean speed, and 14.91 knots was the ballast mean speed. *Figure 51* portrays the ship's speeds under ballast and laden conditions throughout the year.

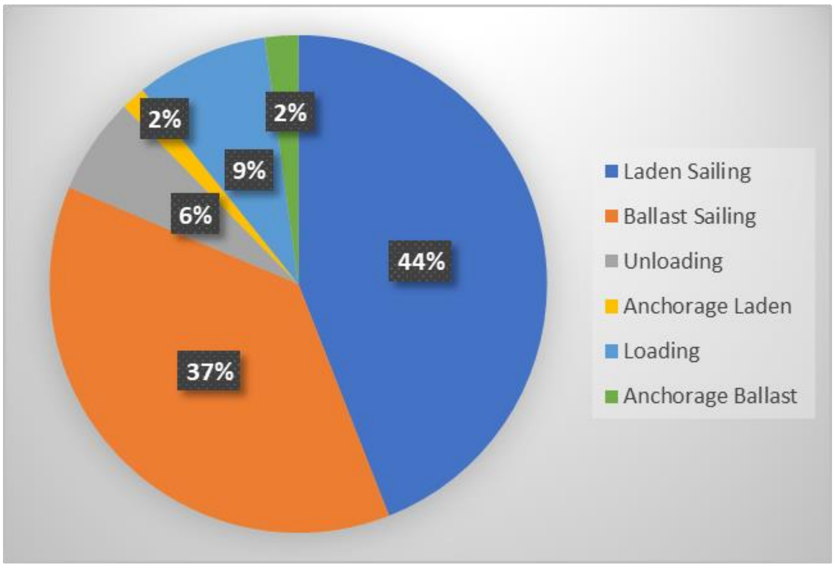

Figure 50: Operational profile of the LPG carrier throughout a year.

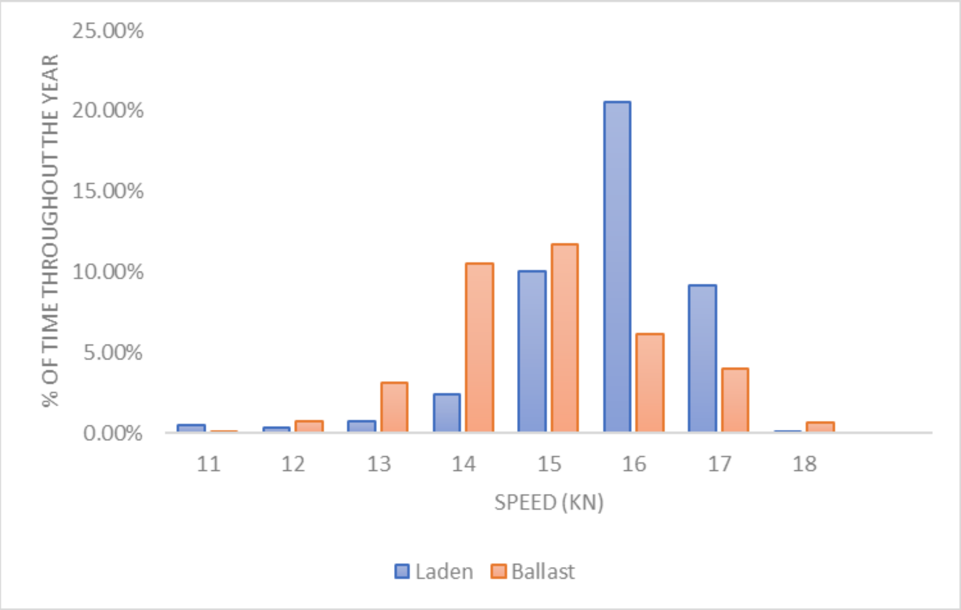

Figure 51: Speeds that the LPG carrier is projected to sail during a year when in laden and ballast mode.

In this case study, two scenarios are set up regarding the fuel consumption of Main Engine during laden and ballast sailing, one for a conventional engine that burns HFO (Diesel engine) and one for a Dual Fuel (DF) engine (LGIP) that burns LPG. The fuel consumption of all 3 fuel consumers is given for all the operational modes. More specifically about the DF case, the pilot and main fuel is given at TPD for all the running speeds. Consequently, the required by the tool fuel sharing during sailing, for all the consumers, is not difficult to calculate. The graphs below demonstrate the ME fuel usage per day versus speed for both DF and conventional MEs when the LPG carrier is sailing in laden and ballast conditions.

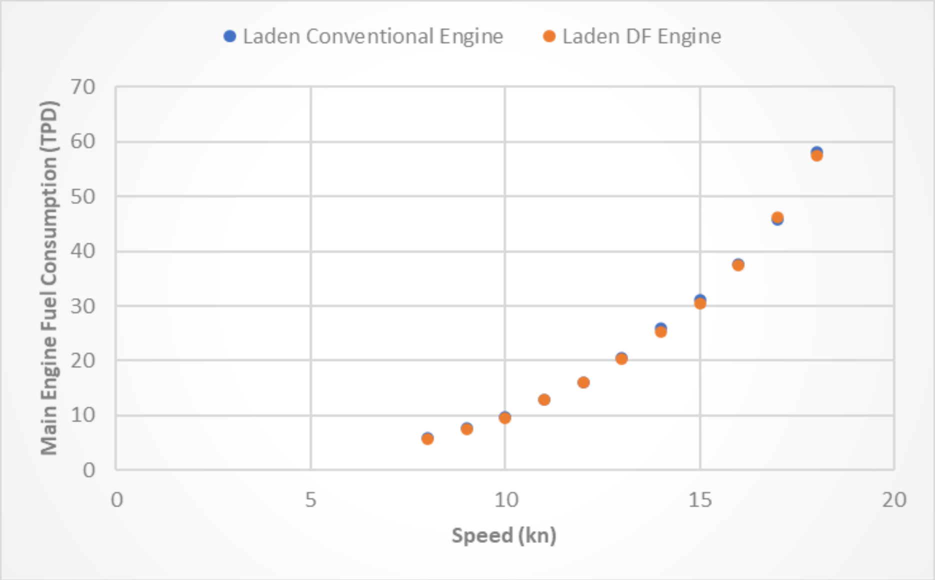

Figure 52: Fuel consumption per day - speed graph of the LPG carrier in laden mode when the ship uses HFO for the Main Engine versus when the ship uses LPG with MDO as pilot for the Main Engine.

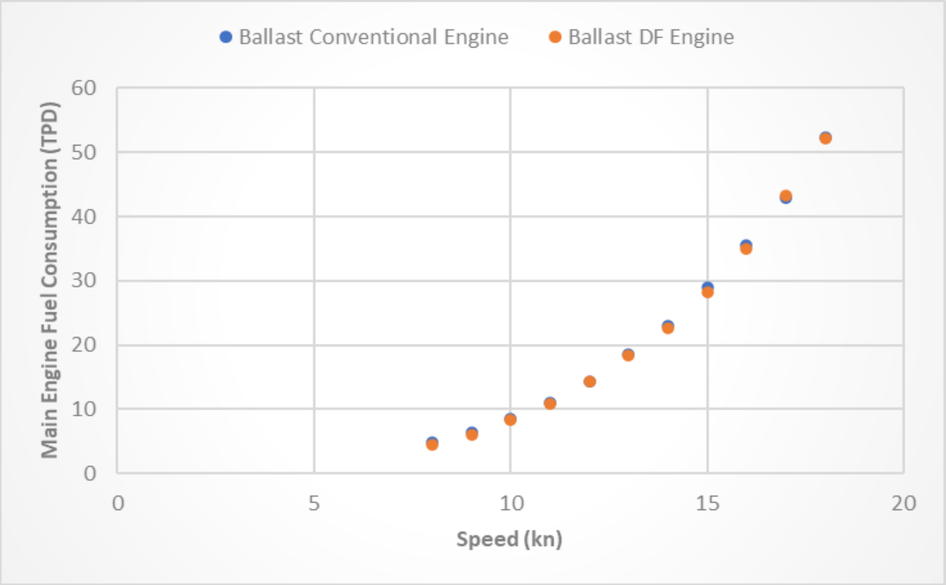

Figure 53: Fuel consumption per day - speed graph of the LPG carrier in ballast mode when the ship uses HFO for the Main Engine versus when the ship uses LPG with MDO as pilot for the Main Engine.

A balanced required CII reduction factor strategy is developed in this case study, the input of which is as follows.

Table 60: Input of required CII reduction factor scenario for the LPG carrier.

Reference lines

Ref CII	7.91183143
Rating year	2023
IMO reduction 2027-2030	IMO 2.5%
IMO reduction 2031-2035	IMO 3%
IMO reduction 2036-2040	IMO 3.5%
IMO reduction 2041-2045	IMO 3.5%
IMO reduction 2046-2050	zero 50
Rating year ref CII	7.516239858

For both scenarios the same measure will be applied, Auxiliary Engine Economizer (AEECO). The reduction in boiler from the application of AEECO is not applied from the tool, as the data provided for the AEECO are considered more realistic than the reduction that the tool offers. The results of the ship utilizing conventional fuel without any measures, as well as utilizing AEECO, are shown below.

Table 61: Calculated CII with and without application of decarbonization measures to the LPG carrier propelled by a conventional diesel engine.

attained CII [grCO2/(t*nm)]	**3.854913037**
Rating before measure	***A rating***
1st Measure	AEECO
1 - Measure CII	**3.839518072**

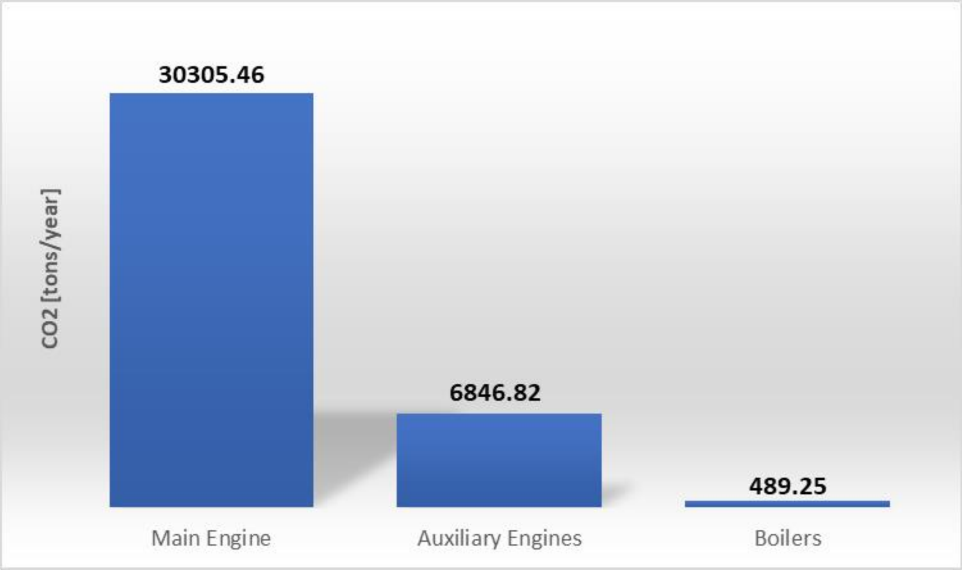

Figure 54: Total CO2 emissions in the case of a conventional diesel engine on the LPG carrier.

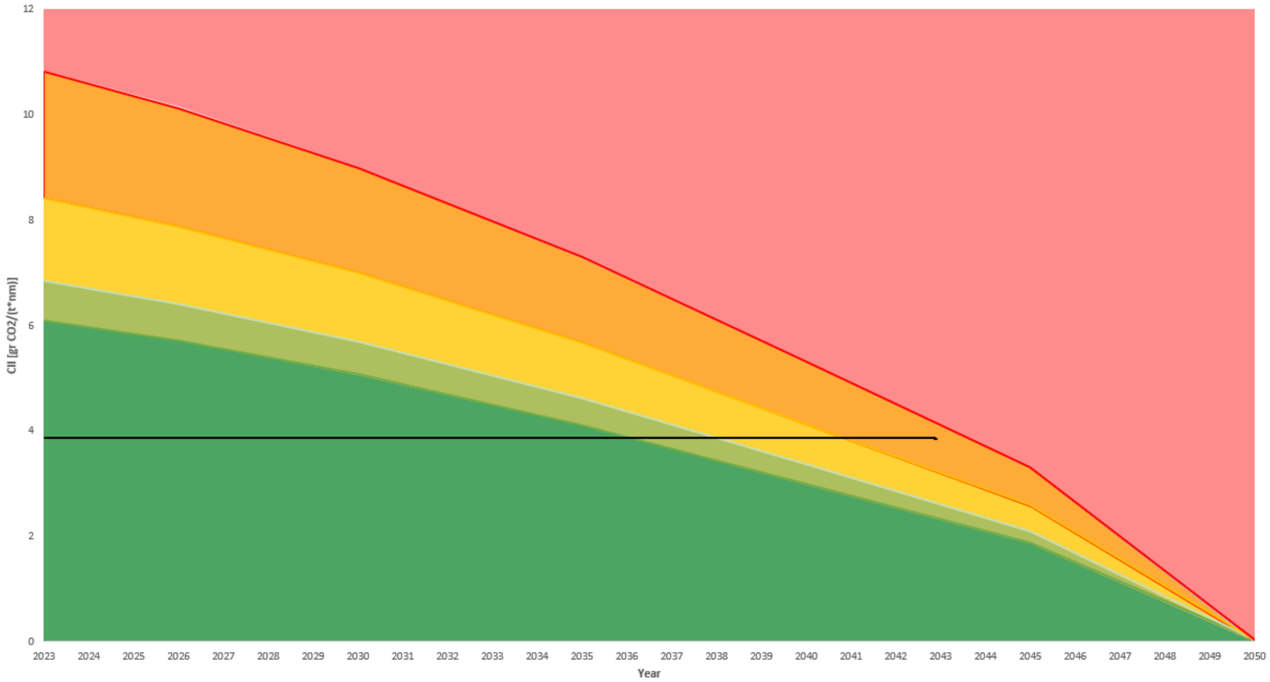

Figure 55: Graphical display of the LPG carrier’s performance when using HFO as fuel for propulsion.

Table 62: Projection years that the LPG carrier’s CII will hit every rating when using HFO as fuel for propulsion.

	Year of hit B rating	Year of hit C rating	Year of hit D rating	Year of hit D+2 rating	Year of hit E rating
No measure – Conventional fuel	2037	2038	2041	2043	2044
With AEECO	2037	2038	2041	2043	2044

The percentage drop of CII from the use of the AEECO for the case of which the LPG Carrier’s ME consumes conventional fuel, is shown in the following diagram.

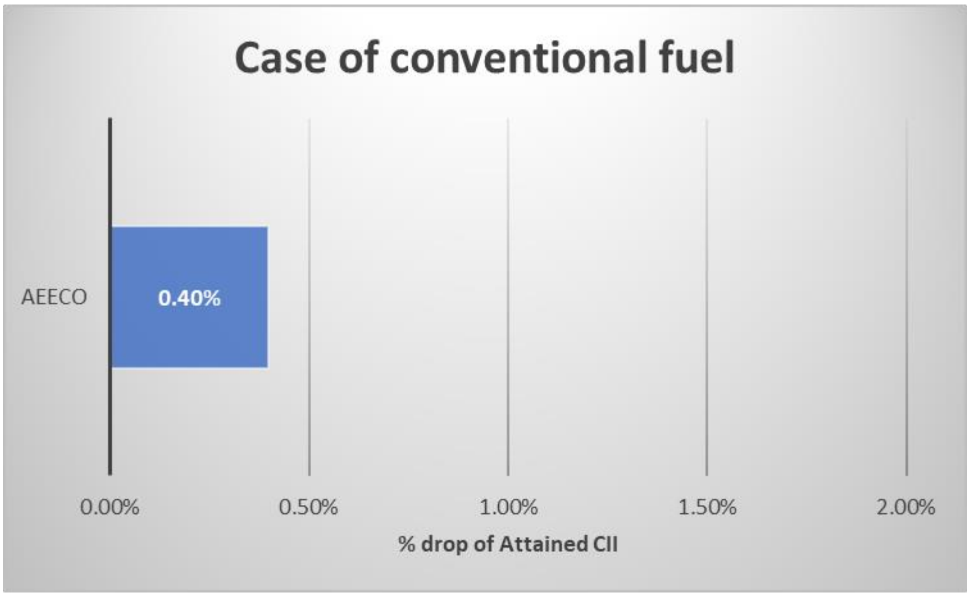

Figure 56: Percentage drop produced by AEECO -applied in the scenario where conventional fuel is used for the propulsion- to the attained CII of the LPG carrier.

The results of the ship utilizing LPG with diesel as its pilot fuel without any measures, as well as using AEECO, are shown below.

Table 63: Calculated CII with and without application of decarbonization measures to the LPG carrier propelled by an LGIP engine.

attained CII [grCO2/(t*nm)]	**3.812379259**
Rating before measure	***A rating***
1st Measure	AEECO
1 - Meas. CII	**3.787694168**

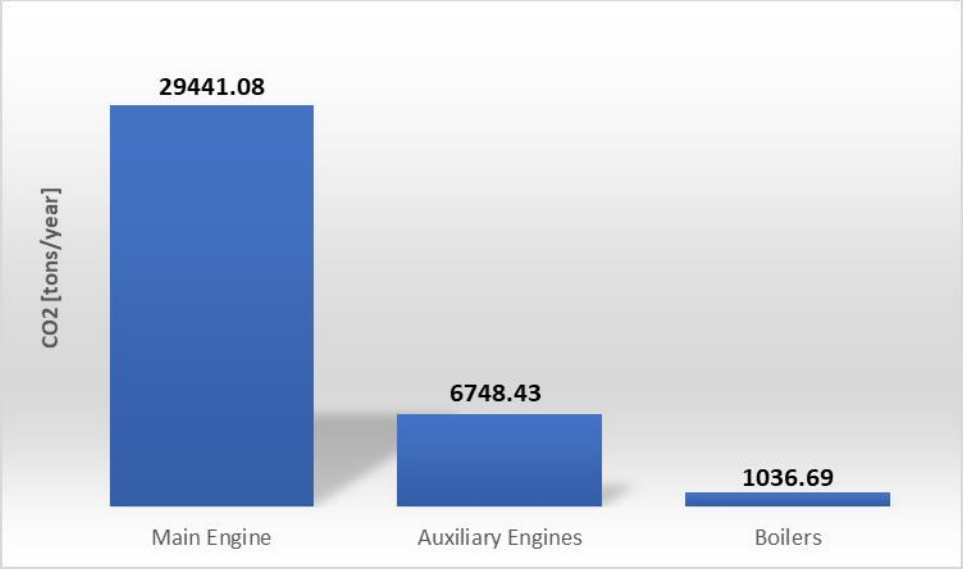

Figure 57: Total CO2 emissions in the case of a Dual Fuel engine on the LPG carrier.

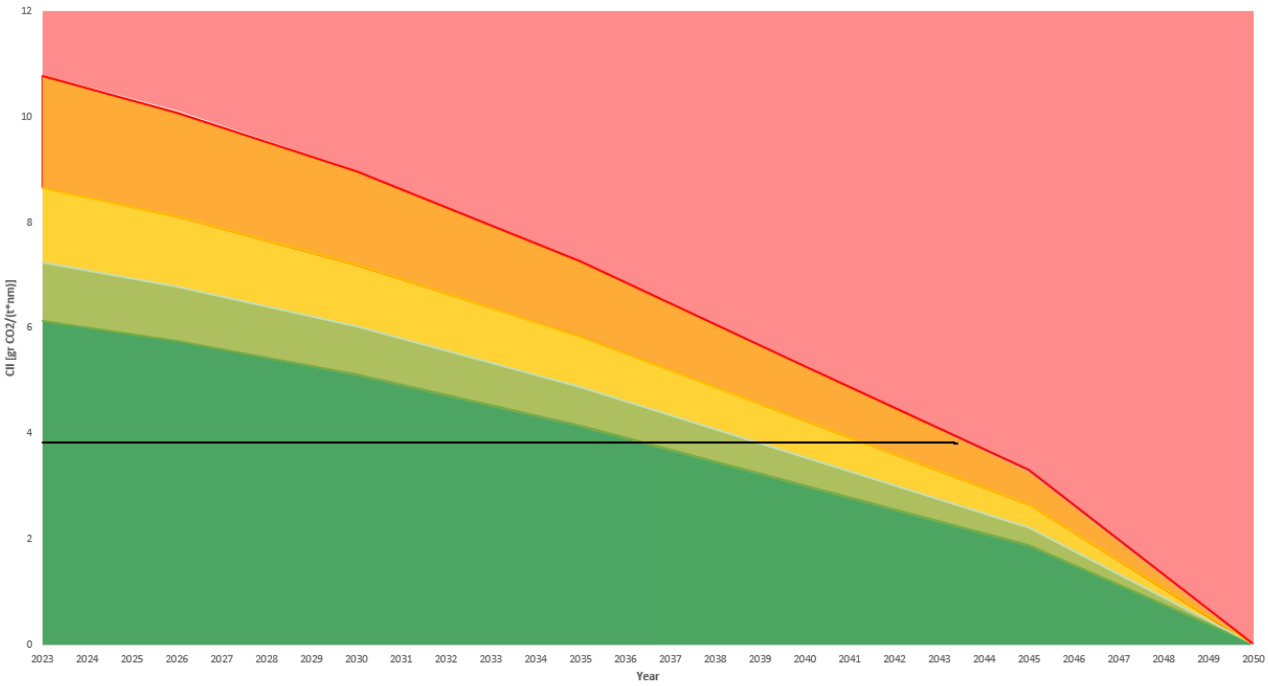

Figure 58: Graphical display of the LPG carrier's performance when using LPG with MDO as fuel for propulsion.

Table 64: Projection years that the LPG carrier's CII will hit every rating when using LPG with MDO as fuel for propulsion.

	Year of hit B rating	Year of hit C rating	Year of hit D rating	Year of hit D+2 rating	Year of hit E rating
No measure – Dual fuel	2037	2039	2042	2044	2044
With AEECO	2037	2039	2042	2044	2044

The percentage drop of CII from the use of the AEECO for the case of which the LPG Carrier's ME consumes dual fuel, is shown in the following diagram.

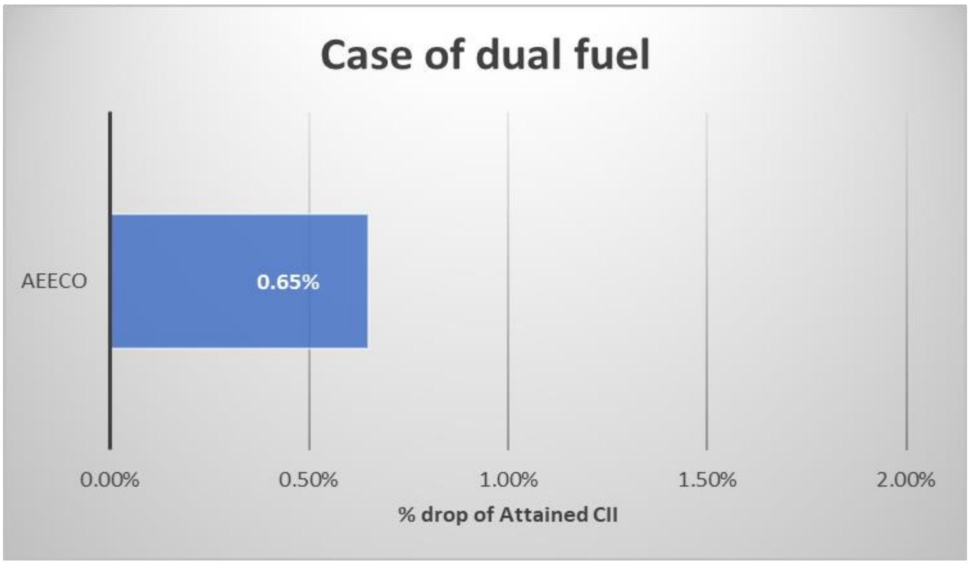

Figure 59: Percentage drop produced by AEECO -applied in the scenario where LPG with MDO as pilot are used for the propulsion- to the attained CII of the LPG carrier.

The difference, in relation to CII, between the use of conventional fuel and dual fuel for the same ship is demonstrated below.

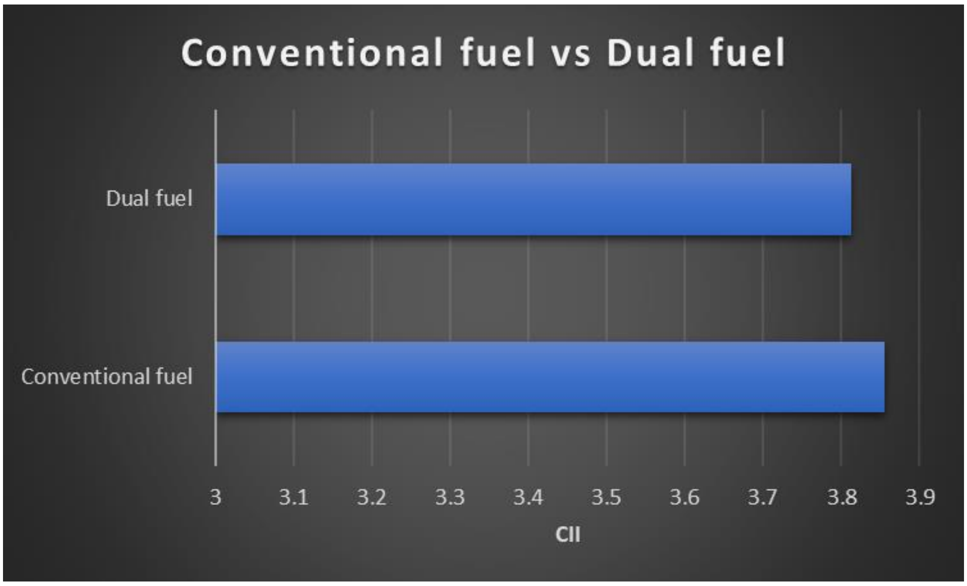

Figure 60: Attained CII of the LPG carrier propelled by a Dual Fuel engine using LPG as primary fuel versus when it is propelled by a conventional diesel engine.

In conclusion, although the fuel consumption – speed curves of DF and HFO are almost identical, there is a minor difference in CII when the ship is installed with a DF engine. In this case the ship can gain 1 year without punishment or development of a plan for corrective actions in comparison with the case that the conventional engine is installed. The difference maker is the usage of LPG fuel, since it has lower emission factor than HFO. Another interesting finding is the difference that AEECO makes when it is used in the case of a conventional engine shown in *Figure 56* versus the case of a DF engine showcased in *Figure 59*. That is because the exhaust gas heat recovery to the boilers from the LGIP engine is not as efficient as the heat recovery from the engine that burns HFO. This means that when no AEECO is applied, in the LGIP engine case, the ship consumes more boiler and therefore more CO_2 will be reduced from the application of AEECO in comparison with the conventional fuel scenario. Another explanation to the above observation is that the impact of the reduction of fuel consumption from the boiler is greater in the LGIP engine case, as LPG's emission factor is less than HFO's emission factor.

5.4 Bulk Carrier

For the 4th application case a Very Large Ore Carrier (VLOC) is selected. The DWT of the bulk carrier is 324963 tons. The ship sailed for approximately 264 days out of the entirety of the year, 138 days of which it was full loaded, and the rest 126 days was sailing at ballast condition. The ship was stationary in port for 40 days, as loading and unloading took 20 days each, during the year. Also, the VLOC had to wait a total of 60 days during the year outside of the port in anchorage either loaded or unloaded.

The vessel, when sailing fully loaded, was moving slower than when it was loaded only with ballast, as 12.15 knots was the laden mean speed, and 13.38 knots was the ballast mean speed. *Figure 62* portrays the ship's speeds under ballast and laden conditions throughout the year.

In this case study, only HFO was used during the year for all the operational modes. The fuel consumption was given separately for the 2 fuel consumers when the ship was sailing in ballast and laden conditions. It is important to note that when sailing the boilers were not working to produce steam, as the steam demand was covered by the Main Engine economizers. The ME fuel consumption - measured in tons per day- versus speed graph, for both sailing modes is in *Figure 63*.

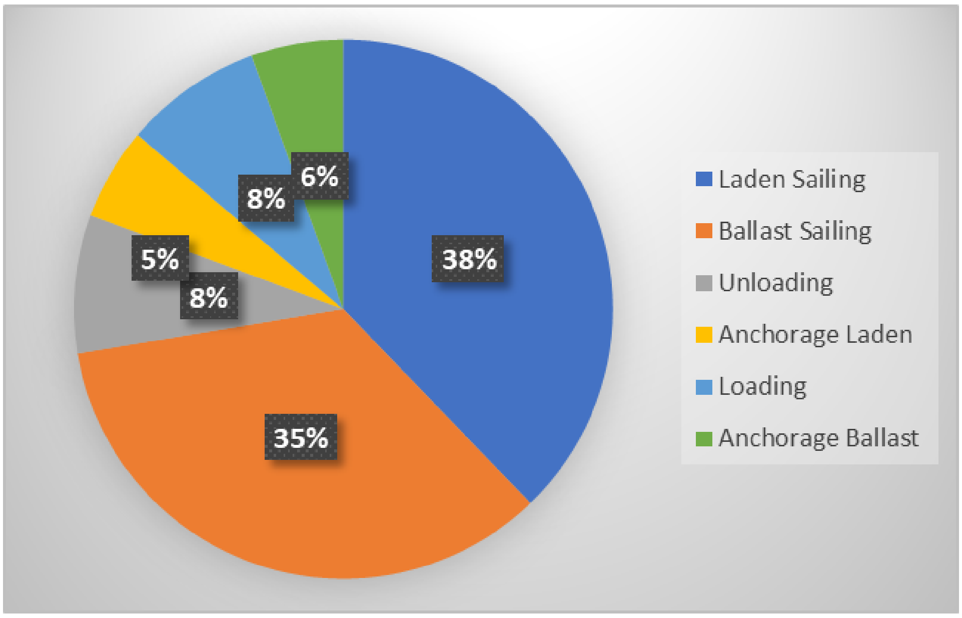

Figure 61: Operational profile of the VLOC throughout the year.

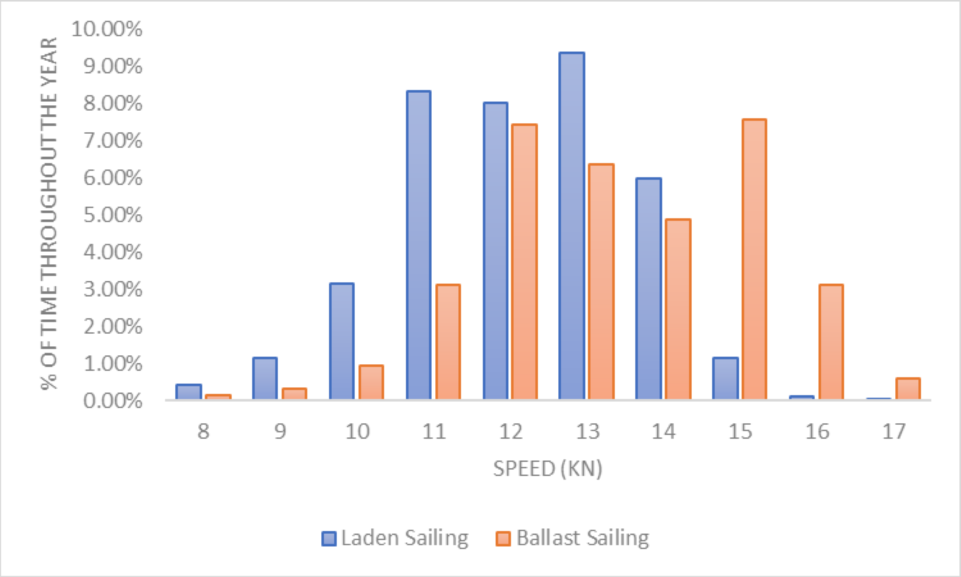

Figure 62: Speeds that the VLOC sailed during the year when in laden and ballast mode.

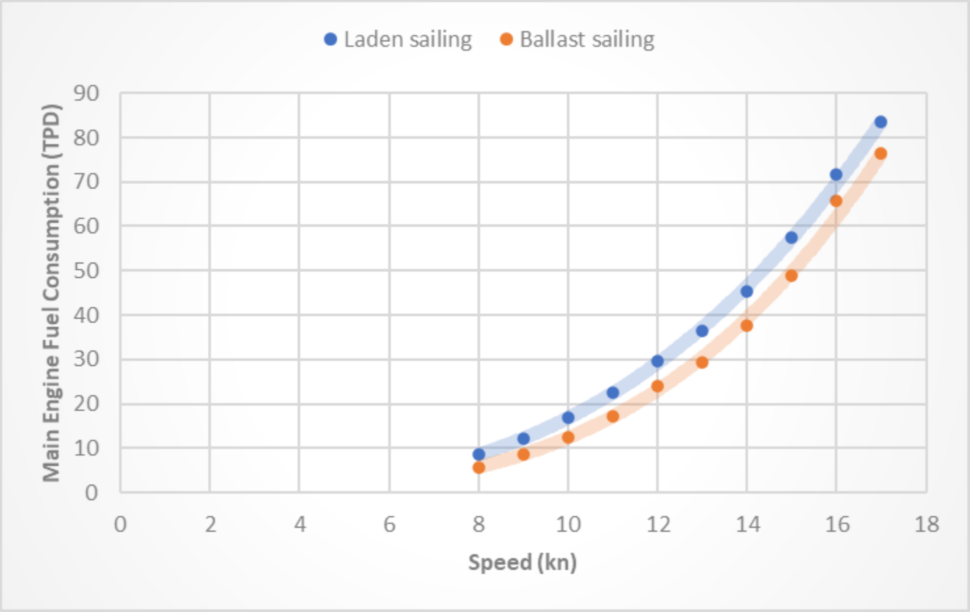

Figure 63: Fuel oil consumption at tons per day versus speed graph of the VLOC when in laden and ballast mode.

No correction factor is taken into consideration for the CII calculation. The attained CII, the rating for the year 2023, and the distribution of CO2 emissions from the 3 consumers are as follows.

Table 65: Results of the VLOC without measures applied.

Final Results

attained CII [grCO2/(t*nm)] =	**1.31909652**
Rating before measure	***A rating***

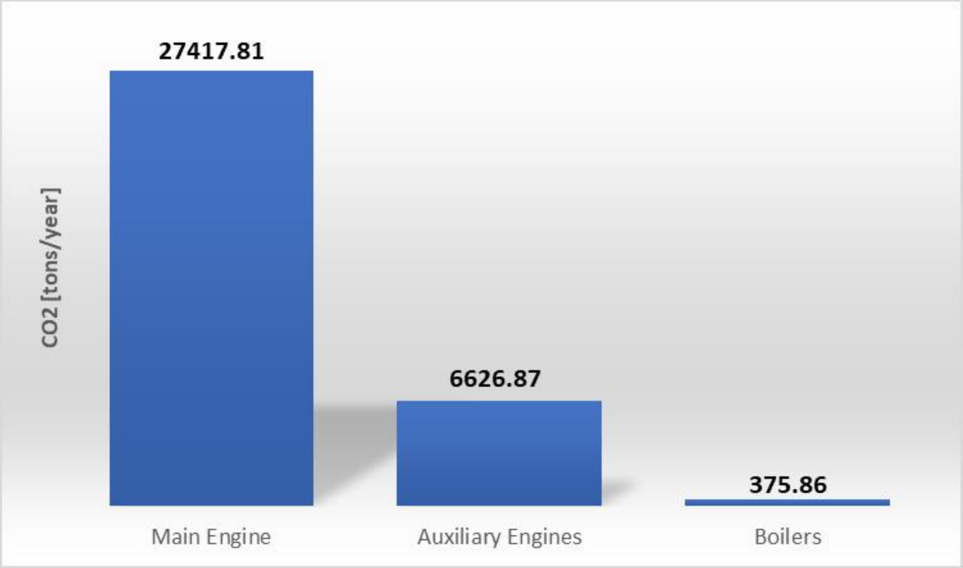

Figure 64: Tons of CO2 emitted by the VLOC's 3 fuel consumers for the year.

The chosen by IMO required CII reduction factor scenario is developed in this case study, the input of which is as follows:

Table 66: Input of required CII reduction factor scenario for the VLOC.

Reference lines	
Ref CII	1.945675464
Rating year	2023
IMO reduction 2027-2030	zero 50
IMO reduction 2031-2035	zero 50
IMO reduction 2036-2040	zero 50
IMO reduction 2041-2045	zero 50
IMO reduction 2046-2050	zero 50
Rating year ref CII	1.848391691

In this case study 6 decarbonization measures are selected and examined over their influence of the CII reduction. The decarbonization measures are the following:

- Propeller retrofitting.
- Engine de-rating.
- Optimizing turbocharging at lower engine loads (exhaust gas bypass (EGB)).
- Aerodynamic Optimization of Superstructures.
- Kite.
- Variable frequency drive (VFD) controlled pumps, fans, and motors.

The new CIIs by applying each of the measures are:

Table 67: Calculated CII with the measures applied to the VLOC.

1st Measure	Propeller retrofitting
1 - Meas. CII	**1.308589206**
2nd Measure	Engine de-rating
1+2 - Meas. CII	**1.256052634**
3rd Measure	Optimizing turbocharging at lower engine loads (exhaust gas bypass (EGB))
1+2+3 - Meas. CII	**1.235038005**
4th Measure	Aerodynamic Optimization of Superstructures
1+2+3+4 - M CII	**1.22453069**
4th Measure	Kite
1+2+3+4+5 - M CII	**1.203516061**
4th Measure	Variable frequency drive (VFD) controlled pumps, fans, and motors
1+2+3+4+5+6 - M CII	**1.19081801**

The projection years that the ship will hit each rating boundary without and with the application of the measures, the percentage drop of CII from the use of each of the measures, as well as graphical display of the tool's outputs are showcased in *Table 68*, Figure 65, *Figure 66*:

Table 68: Projection years that the VLOC's CII will hit every rating without and with decarbonization measures applied.

	Year of hit B rating	Year of hit C rating	Year of hit D rating	Year of hit D+2 rating	Year of hit E rating
0 - M	2029	2031	2033	2035	2035
1 - M	2029	2031	2033	2035	2035
1+2 - M	2030	2032	2034	2036	2036
1+2+3 - M	2031	2032	2034	2036	2036
1+2+3+4 - M	2031	2032	2034	2036	2036
1+2+3+4+5 - M	2031	2033	2035	2037	2036
1+2+3+4+5+6 - M	2031	2033	2035	2037	2037

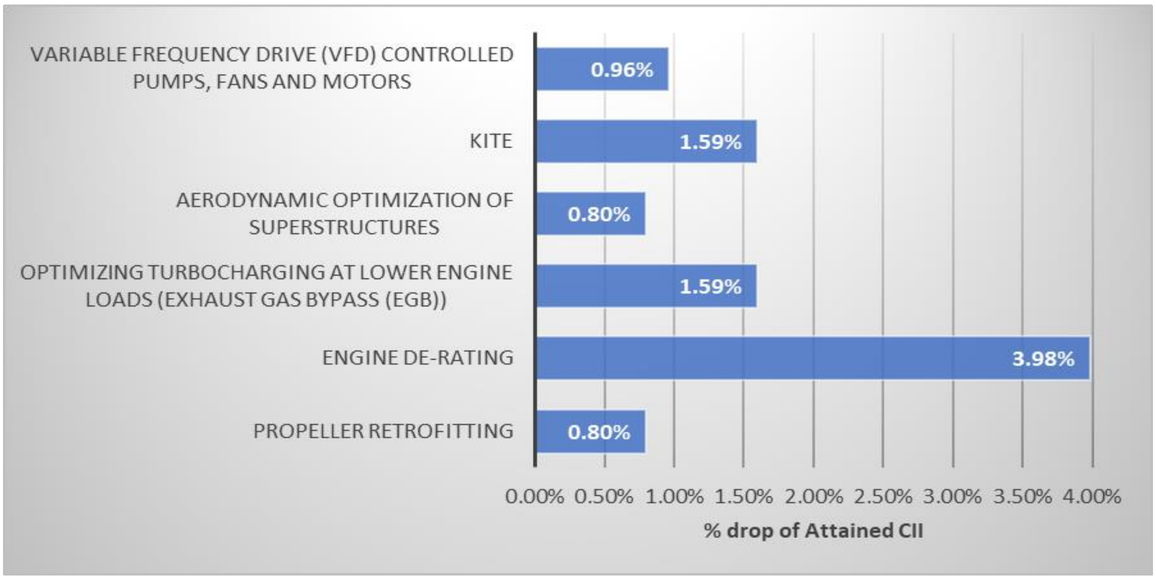

Figure 65: Percentage drop produced by each of the 6 decarbonization measures to the attained CII of the VLOC.

Figure 66: Graphical display of the VLOC's performance.

6. Conclusions

The main aim of this thesis was to formulate a calculation model that is easy to use and test it, in order to find the attained and improved- with the application of decarbonization measures- Carbon Intensity Index of ships. Also, an overview of the decarbonization regulations in shipping industry is presented, with special emphasis given to CII and its importance, as it is the regulation that will be applied for the foreseeable future on a yearly basis. The model is a supporting tool for the decision makers. The tool provides flexibility with different required CII reduction factor scenarios that might be adopted eventually by the IMO, so that the users can create their desired strategies for the future. It also offers adaptability with a plethora of technologies to abide by the standards of required CII, allowing the ship to adapt to every reduction factor scenario that is created. To assess the reduction of the attained CII that each type of ship gets from the use of the decarbonization technologies, an assessment for the majority of decarbonization alternatives, that are available in shipping industry, was necessary. Finally, application cases were run, to test the tool operability and examine the results that came up.

Application cases were carried out based on operational data of the following four commercial ships.

- One Very Large Crude Carrier.
- One Aframax Tanker.
- One Liquefied Petroleum Gas Carrier.
- One Bulk Carrier.

There have been applied multiple decarbonization measures on the ships and calculations were executed in pursuance of realizing the gain for each measure when it comes to CII. The following are the main conclusion derived from this thesis:

- Main Engine efficiency is of enormous importance as the Main Engine emitted CO_2 yearly of the ship amount for 60-80 % of the total emitted CO_2 annually. This also means, that the decarbonization technologies that affect the Main Engine, such as the hydrodynamic measures, are those that reduce the CII of the ship more than the technologies that affect the other two fuel consumers.
- The operating profile of the ship is the attribute that affects CII the most as a reduction of up to 20% was marked in the application cases. The longer the ship waits in anchorage, the worse the CII rating gets since the vessel consumes fuel without covering distance. This means that proper planning regarding the vessel's operations is essential.
- Lower speeds seem to contribute to the deduction of CII, meaning that slow steaming for a desired period, depending on the operator's interests, should be considered before proceeding with the application of a decarbonization technology.
- Concerning innovative fuels, no massive difference was detected between a Dual Fuel engine that burns LPG (LGIP engine) and a conventional Diesel engine that burns HFO, since the fuel consumption per day – speed curve is identical. The minor difference in the emission factors of LPG and HFO was the reason that in the DF engine case the CII was less. However, the margin in CII might be larger for other more innovative fuels such as hydrogen, ammonia, methanol, or even LNG, as their respective emission factor is lesser.
- An interesting discovery in the LGIP versus Diesel engine case is that the CII drop percentage is bigger in the LGIP case, when a measure is applied for the boiler(s), compared to the Diesel engine case. This is due to the fact that in the LGIP case the steam produced from the main engine economizer

was less compared to steam production in the Diesel engine case, meaning that more boiler fuel consumption could be saved.

- From the utilization of decarbonization technologies, a vessel might gain 6 or more years without punishment or development for a plan of corrective actions.
- Last but not least, in the present thesis the Very Large Ore Carrier has better CII rating than the Very Large Crude Carrier, where both ships have similar fuel consumption and operational profile. However, the impact of the applied measures is bigger for the tanker since the value of CII is also higher. Finally, bulk carriers generally are closer to zero by 2050 scenario since their CII is lesser than all the commercial ships.

Based on the present thesis and the above conclusions, an extension of the developed tool could be the examination of specific measures and the implementation of the gained reduction for each consumer for each speed and draft, as one limitation of the tool is that for all measures, the same deduction in fuel is applied for each speed and draft, which is unrealistic. Also, the step of speed could be lowered to 0.5 or even 0.1 knots so the modelling of CII and decarbonization measures is improved even more. Moreover, a techno-economic analysis of several decarbonization technologies and their evaluation depending on their impact on CII and cost could be feasible. Another suggestion for further research is the impact of EEXI compliance in the CII. Lastly, in the condition that the tool is used for CII calculation of several ships, the developed database could be used for research purposes.

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APPENDIX A - VLCC

In this chapter the input and results for the application case of the VLCC are presented.

Table 69: Imput for the application case of the VLCC.

Ship's Main Particulars

Name of ship	
IMO Number	
Length [m]	
Breadth [m]	
Draught [m]	
Ship type	Tanker
DWT [t]	299430
GT [t]	

Operational Profile

Operational Mode	Days
Laden Sailing	141.62
Ballast Sailing	118.625
Unloading	9.125
Anchorage Laden	24.455
Maneuvering Laden	9.855
Loading	12.045
Anchorage Ballast	35.04
Maneuvering Ballast	13.505
Total	364.27

Laden Sailing

Speed	% of time
8	0.35%
9	1.05%
10	2.45%
11	5.90%
12	13.80%
13	12.15%
14	2.70%
15	0.35%
16	0.05%
17	0.00%
Mean Speed	12.09

Ballast Sailing

Speed	% of time
8	1.55%
9	3.85%
10	6.40%
11	5.30%
12	5.55%
13	4.45%

14	2.85%
15	1.80%
16	0.60%
17	0.15%
Mean Speed	11.47

Maneuvering Laden

Speed	4

Maneuvering Ballast

Speed	4

Laden Sailing Fuel Consumption

FC Curve

Speed	ME FC[tn/d]	AE FC[tn/d]	Boiler FC[tn/d]
8	26.15006	6.4	3.3
9	27.34611	6.4	3.3
10	36.98402	6.4	3.3
11	44.15013	6.4	3.3
12	52.80297	6.4	3.3
13	58.06454	6.4	3.3
14	63.2997	6.4	3.3
15	72.09803	6.4	3.3
16	78.19614	6.4	3.3
17	87.47892206	6.4	3.3
1st Fuel	HFO		
1st fuel %	62.51%		
2nd Fuel	LFO		
2nd fuel %	34.89%		
3rd Fuel	Diesel/Gas Oil		
3rd fuel %	2.60%		

Ballast Sailing Fuel Consumption

FC Curve

Speed	ME FC[tn/d]	AE FC[tn/d]	Boiler FC[tn/d]
8	18.16556	6.4	3.3
9	17.57904	6.4	3.3
10	21.88196	6.4	3.3
11	28.4664	6.4	3.3
12	37.57198	6.4	3.3
13	43.23517	6.4	3.3
14	51.69824	6.4	3.3
15	69.63622	6.4	3.3
16	77.40518	6.4	3.3
17	89.67404943	6.4	3.3
1st Fuel	HFO		
1st fuel %	62.51%		
2nd Fuel	LFO		
2nd fuel %	34.89%		

3rd Fuel	Diesel/Gas Oil
3rd fuel %	2.60%

Non-sailing and Maneuvering Modes Fuel Consumption

Unloading

AE FC [tns/day]	11.52839
Boiler FC [tns/day]	23.712
1st Fuel	HFO
1st fuel %	62.51%
2nd Fuel	LFO
2nd fuel %	34.89%
3rd Fuel	Diesel/Gas Oil
3rd fuel %	2.60%

Anchorage Laden

AE FC [tns/day]	4
Boiler FC [tns/day]	1.506333
1st Fuel	HFO
1st fuel %	62.51%
2nd Fuel	LFO
2nd fuel %	34.89%
3rd Fuel	Diesel/Gas Oil
3rd fuel %	2.60%

Maneuvering Laden

ME FC [tns/day]	14.15091
AE FC [tns/day]	6.4
Boiler FC [tns/day]	3.3
1st Fuel	HFO
1st fuel %	62.51%
2nd Fuel	LFO
2nd fuel %	34.89%
3rd Fuel	Diesel/Gas Oil
3rd fuel %	2.60%

Loading

AE FC [tns/day]	10.64930083
Boiler FC [tns/day]	2.254169175
1st Fuel	HFO
1st fuel %	62.51%
2nd Fuel	LFO
2nd fuel %	34.89%
3rd Fuel	Diesel/Gas Oil
3rd fuel %	2.60%

Anchorage Ballast	
AE FC [tns/day]	3.1016106
Boiler FC [tns/day]	1.5977994
1st Fuel	HFO
1st fuel %	62.51%
2nd Fuel	LFO
2nd fuel %	34.89%
3rd Fuel	Diesel/Gas Oil
3rd fuel %	2.60%

Maneuvering Ballast	
ME FC [tns/day]	10.24691
AE FC [tns/day]	6
Boiler FC [tns/day]	3
1st Fuel	HFO
1st fuel %	62.51%
2nd Fuel	LFO
2nd fuel %	34.89%
3rd Fuel	Diesel/Gas Oil
3rd fuel %	2.60%

Correction Factors

Ice class applicable	NO
Type of Ice Class	
Length [m]	
Breadth [m]	
Depth [m]	
Volume of displacement [m3]	
Cubic Correction Factor applicable	NO
Cubic Capacity [m3]	
Structural Enhancement Correction Factor applicable	NO
LWTenhanced - if applicable	
LWTref - if applicable	
Correction relating Voyage Adjustment	NO
FCvoyage[tns/yr] =	
Fuel	
Corrections to Shuttle Tankers or STS voyages on tankers	NO
Correction for Shuttle Tanker or STS voyage?	
$FC_{shuttle/STS}$[tns/yr] =	
Fuel	
Corrections relating electrical power,boiler,other	YES
Year of calculation	**2023**

FCelectical[tns/yr] =	
Fuel	
FCboiler[tns/yr] =	250.00
Fuel	HFO
FCother[tns/yr] =	
Fuel	
Distance travelled for voyage periods which may be deducted from CII calculation	NO
Dx[nm/yr] =	

Table 70: Results of VLCC without any measures included.

Final Results

attained CII[grCO2/(t*nm)] =	**2.07440111**
Rating before measure	***B rating***
Preferred Rating	B rating

Table 71: Strict required CII reduction factor scenario.

Reference lines

Ref CII	2.395360727
Rating year	2023
IMO reduction 2027-2030	IMO 3.5%
IMO reduction 2031-2035	IMO 3.5%
IMO reduction 2036-2040	IMO 4%
IMO reduction 2041-2045	zero 50
IMO reduction 2046-2050	zero 50
Rating year ref CII	2.275592691

Table 72: Lenient required CII reduction factor scenario.

Reference lines

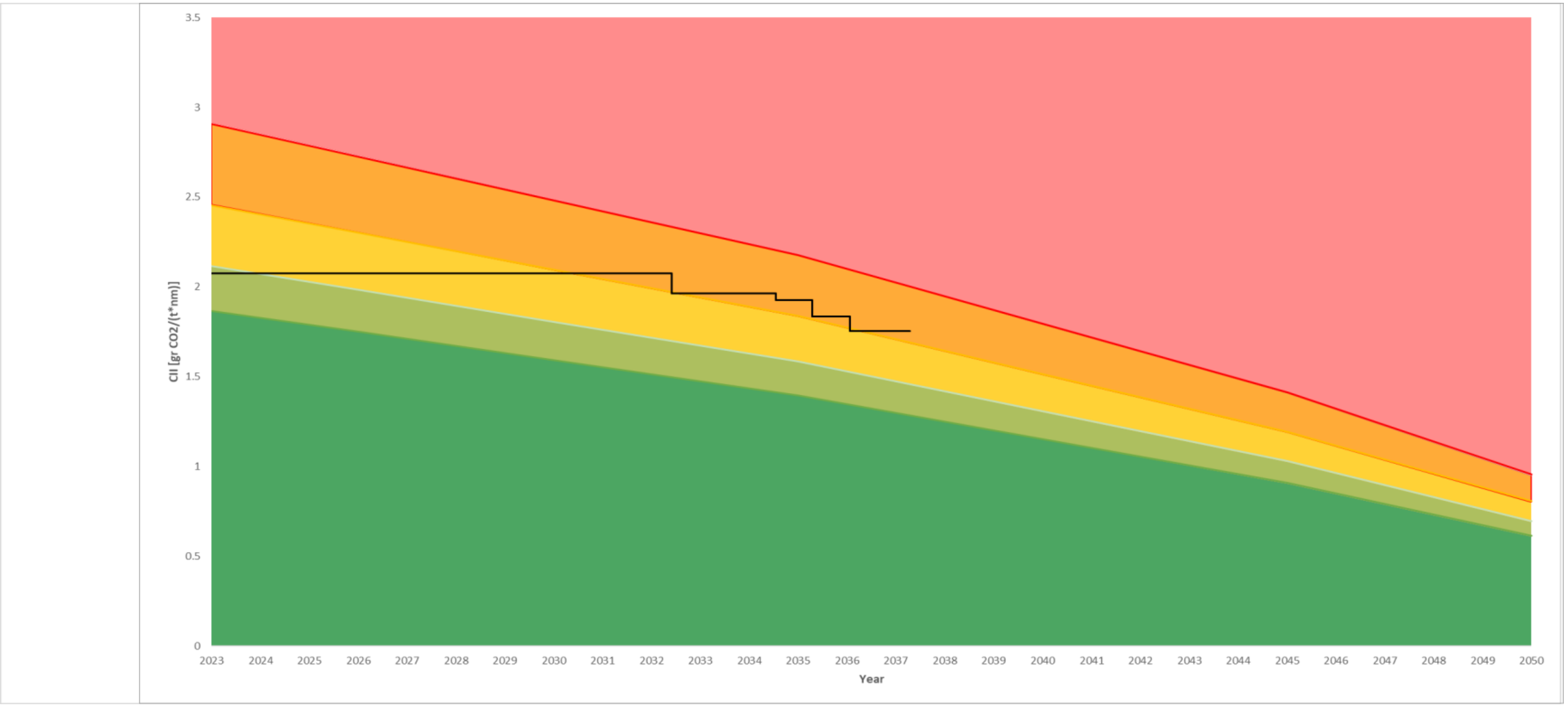
Ref CII	2.395360727
Rating year	2023
IMO reduction 2027-2030	IMO 2%
IMO reduction 2031-2035	IMO 2%
IMO reduction 2036-2040	IMO 2.5%
IMO reduction 2041-2045	IMO 2.5%
IMO reduction 2046-2050	IMO 3%
Rating year ref CII	2.275592691

Table 73: Results of four decarbonization measures applied, choosing a strict required CII factor scenario for the VLCC.

1st Measure	Pre-Swirl Duct	2nd Measure	Engine performance testing and tuning	3rd Measure	Hard sails or wings	4th Measure	Weather routing
1-M attained CII[grCO2/(t*nm)] =	**1.96395549**	**2-M attained CII[grCO2/(t*nm)] =**	**1.925443466**	**3-M attained CII[grCO2/(t*nm)] =**	**1.833066**	**4-M attained CII[grCO2/(t*nm)] =**	**1.754176483**
1-M Year until D+2 or E rating	***2031.7381***	**2-M Year until D+2 or E rating**	***2032.163441***	**3-M Year until D+2 or E rating**	***2033.18***	**4-M Year until D+2 or E rating**	***2034.054961***
1-M Year until preferred rating	***2026.23964***	**2-M Year until preferred rating**	***2026.733581***	**3-M Year until preferred rating**	***2027.92***	**4-M Year until preferred rating**	***2028.930185***

Table 74: Results of four decarbonization measures applied, choosing a lenient required CII factor scenario for the VLCC.

1st Measure	Pre-Swirl Duct	2nd Measure	Engine performance testing and tuning	3rd Measure	Hard sails or wings	4th Measure	Weather routing
1-M attained CII[grCO2/(t*nm)] =	1.96395549	2-M attained CII[grCO2/(t*nm)] =	1.925443466	3-M attained CII[grCO2/(t*nm)] =	1.833066	4-M attained CII[grCO2/(t*nm)] =	1.754176483
1-M Year until D+2 or E rating	*2034.54168*	2-M Year until D+2 or E rating	*2035.286022*	3-M Year until D+2 or E rating	*2036.06*	4-M Year until D+2 or E rating	*2037.276946*
1-M Year until preferred rating	*2026.41937*	2-M Year until preferred rating	*2027.283768*	3-M Year until preferred rating	*2029.36*	4-M Year until preferred rating	*2031.127824*



APPENDIX B – Aframax Tanker

In this chapter the input and results for the application case of the Aframax tanker are presented.

Table 75: Input for the application case of Aframax tanker.

Ship's Main Particulars

Name of ship	
IMO Number	
Length [m]	
Breadth [m]	
Draught [m]	
Ship type	Tanker
DWT [t]	115000
GT [t]	

Operational Profile

Operational Mode	Days
Laden Sailing	121.8503382
Ballast Sailing	71.15605963
Unloading	24
Anchorage Laden	44.99399828
Maneuvering Laden	0
Loading	24
Anchorage Ballast	78.99960385
Maneuvering Ballast	0
Total	365

Laden Sailing

Speed	% of time
8	
9	
10	3.92%
11	5.98%
12	13.50%
13	8.37%
14	1.32%
15	0.28%
16	0.02%
Mean Speed	11.94

Ballast Sailing

Speed	% of time
8	
9	
10	5.42%
11	3.71%
12	4.72%
13	3.32%

14	1.60%
15	0.66%
16	0.06%
Mean Speed	11.70

Laden Sailing Fuel Consumption

FC Curve			
Speed	ME FC[tn/d]	AE FC[tn/d]	Boiler FC[tn/d]
8			
9			
10	13.56038	4.6324606	1.448800459
11	17.83681	4.6324606	0.889766227
12	22.94935	4.6324606	0.487311099
13	28.724669	4.6324606	0.538801867
14	35.30263	4.6324606	0.492614665
15	43.767612	4.6324606	0.109558032
16	55.04879	4.6324606	0.000377246
1st Fuel	HFO		
1st fuel %	100.00%		
2nd Fuel			
2nd fuel %			
3rd Fuel			
3rd fuel %			

Ballast Sailing Fuel Consumption

FC Curve			
Speed	ME FC[tn/d]	AE FC[tn/d]	Boiler FC[tn/d]
8			
9			
10	10.388786	4.6324606	1.757850538
11	14.072511	4.6324606	1.421437221
12	18.589447	4.6324606	0.664658094
13	24.1058	4.6324606	0.499235332
14	30.081324	4.6324606	0.538998198
15	37.522854	4.6324606	0.4397502
16	47.817284	4.6324606	0.000377246
1st Fuel	HFO		
1st fuel %	100.00%		
2nd Fuel			
2nd fuel %			
3rd Fuel			
3rd fuel %			

Non-sailing and Maneuvering Modes Fuel Consumption

Unloading	
AE FC [tns/day]	5.074087
Boiler FC [tns/day]	33.59550562
1st Fuel	HFO
1st fuel %	100.00%

2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Anchorage Laden

AE FC [tns/day]	3.0803578
Boiler FC [tns/day]	1.961616418
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Loading

AE FC [tns/day]	9.267203
Boiler FC [tns/day]	1.961616418
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Anchorage Ballast

AE FC [tns/day]	3.0803578
Boiler FC [tns/day]	1.961616418
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Correction Factors

Ice class applicable	NO
Type of Ice Class	
Length [m]	
Breadth [m]	
Depth [m]	
Volume of displacement [m3]	
Cubic Correction Factor applicable	NO
Cubic Capacity [m3]	
Structural Enhancement Correction Factor applicable	NO
LWTenhanced - if applicable	
LWTref - if applicable	

Correction relating Voyage Adjustment	NO
FCvoyage[tns/yr] =	
Fuel	
Corrections to Shuttle Tankers or STS voyages on tankers	NO
Correction for Shuttle Tanker or STS voyage?	
FC$_{shuttle/STS}$[tns/yr] =	
Fuel	
Corrections relating electrical power,boiler,other	NO
Year of calculation	
FCelectical[tns/yr] =	
Fuel	
FCboiler[tns/yr] =	
Fuel	
FCother[tns/yr] =	
Fuel	
Distance travelled for voyage periods which may be deducted from CII calculation	NO
D$_x$[nm/yr] =	

Reference lines

Ref CII	4.29423079
Rating year	2023
IMO reduction 2027-2030	IMO 2.5%
IMO reduction 2031-2035	IMO 3%
IMO reduction 2036-2040	IMO 3.5%
IMO reduction 2041-2045	IMO 3.5%
IMO reduction 2046-2050	zero 50
Rating year ref CII	4.079519251

Table 76: Results of Aframax tanker without any measures included.

Final Results

attained CII[grCO2/(t*nm)] =	**3.43773655**
Rating before measure	***B rating***
Preferred Rating	C rating

Table 77: Results of the first scenario of selected decarbonization measures for the Aframax tanker.

1st Measure	Waste heat recovery	2nd Measure	Shaft Generator - PTO	3rd Measure	Rotor sails	4th Measure	Bulbous bow Retrofit
1-M attained CII[grCO2/(t*nm)] =	**3.2172939**	**2-M attained CII[grCO2/(t*nm)] =**	**2.99685125**	**3-M attained CII[grCO2/(t*nm)] =**	**2.799287406**	**4-M attained CII[grCO2/(t*nm)] =**	**2.647807886**
1-M Year until D+2 or E rating	***2035.20947***	**2-M Year until D+2 or E rating**	***2036.7939***	**3-M Year until D+2 or E rating**	***2037.326146***	**4-M Year until D+2 or E rating**	***2038.259351***
1-M Year until preferred rating	***2033.20947***	**2-M Year until preferred rating**	***2034.7939***	**3-M Year until preferred rating**	***2035.326146***	**4-M Year until preferred rating**	***2036.259351***

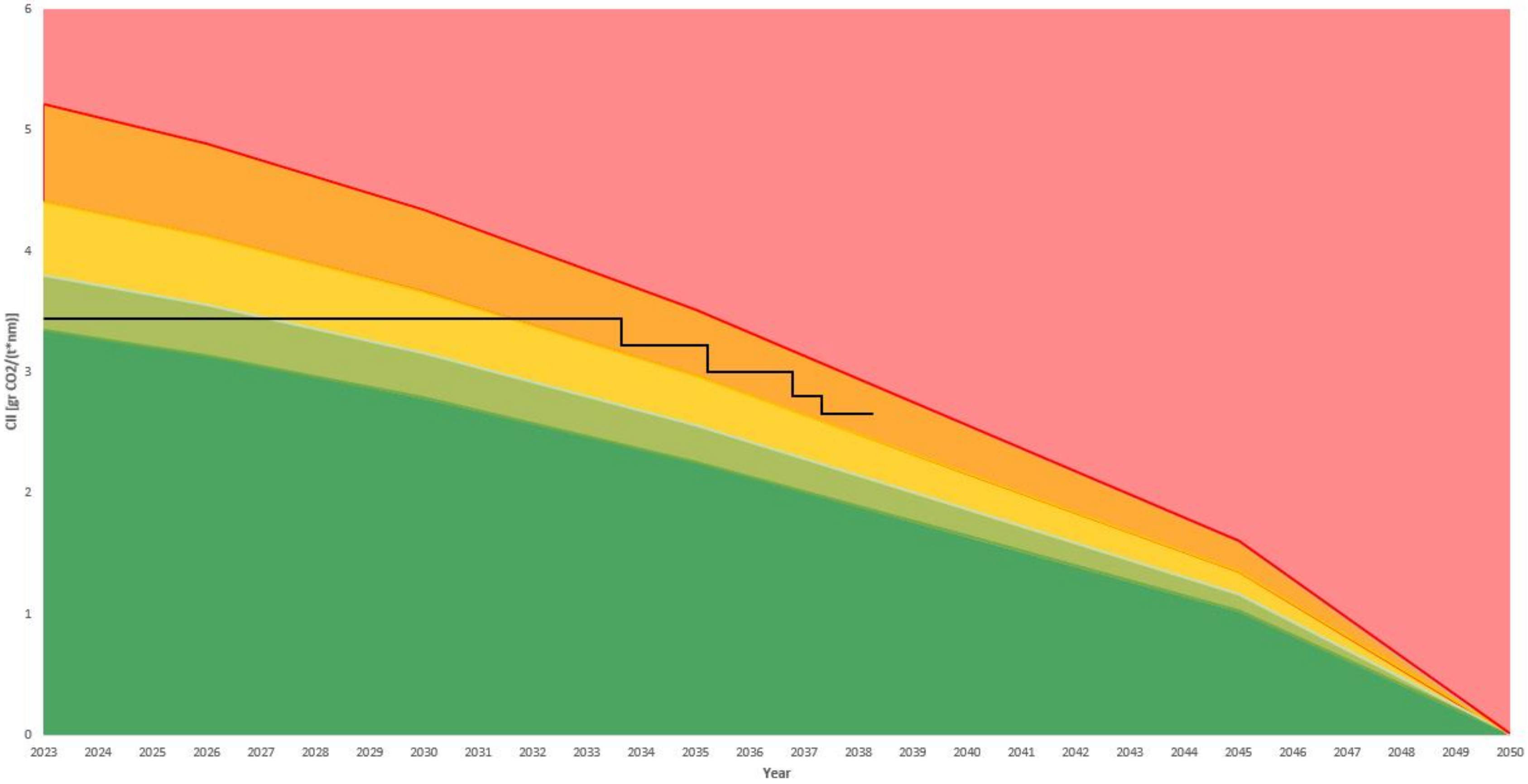
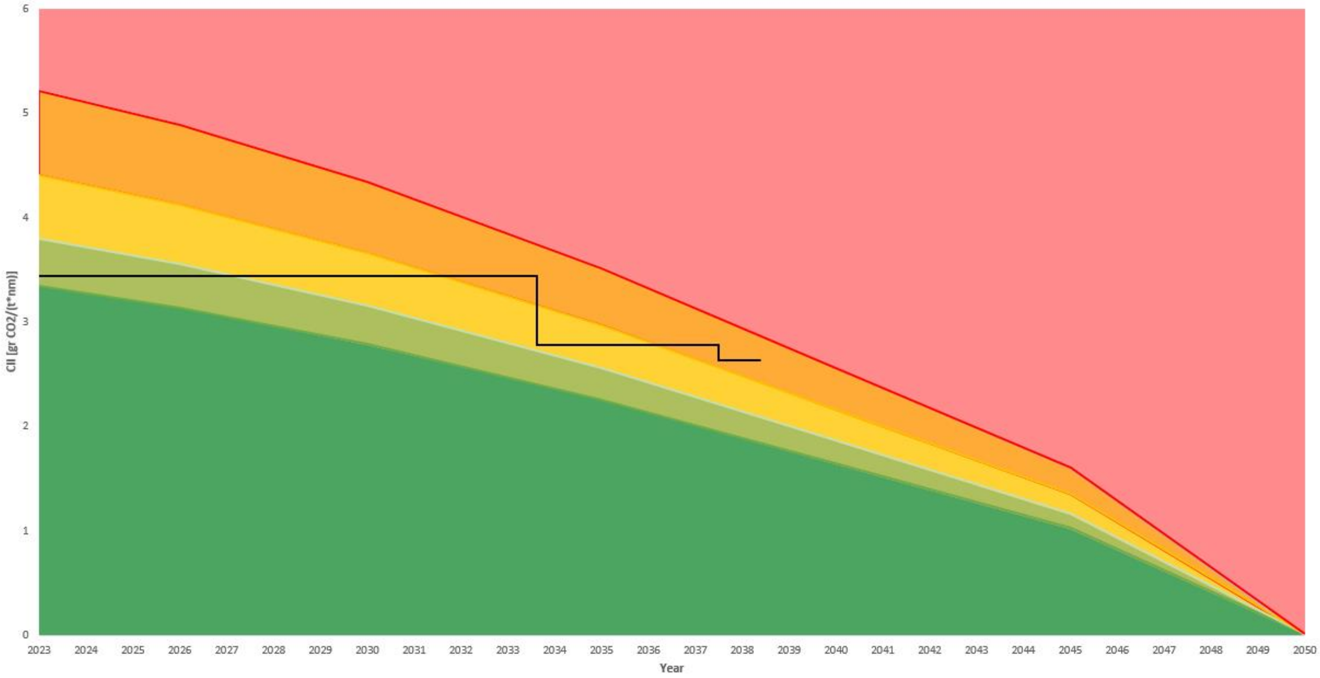


Table 78: Results with improved operational profile and foils on bow installed on the Aframax tanker.

Operational Profile

Operational Mode	Days
Laden Sailing	145.8503382
Ballast Sailing	115.1560596
Unloading	20
Anchorage Laden	24.99399828
Maneuvering Laden	0
Loading	20
Anchorage Ballast	38.99960385
Maneuvering Ballast	0
Total	365

1st Measure	Change of operational profile	**2nd Measure**	Foils on bow
1-M attained CII[grCO2/(t*nm)] =	**2.772248324**	**2-M attained CII[grCO2/(t*nm)] =**	**2.629185764**
1-M Year until D+2 or E rating	***2037.492723***	**2-M Year until D+2 or E rating**	***2038.374074***
1-M Year until preferred rating	***2035.492723***	**2-M Year until preferred rating**	***2036.374074***



Appendix C – LPG Carrier

In this chapter the input and results for the application case of the LPG carrier are presented.

Table 79: Input of the scenario that HFO is used as fuel for the LPG carrier without AEECO applied.

Ship's Main Particulars

Name of ship	
IMO Number	
Length [m]	
Breadth [m]	
Draught [m]	
Ship type	Gas Carrier
DWT [t]	90000
GT [t]	

Reference lines

Ref CII	7.91183143
Rating year	2023
IMO reduction 2027-2030	IMO 2.5%
IMO reduction 2031-2035	IMO 3%
IMO reduction 2036-2040	IMO 3.5%
IMO reduction 2041-2045	IMO 3.5%
IMO reduction 2046-2050	zero 50
Rating year ref CII	7.516239858

Operational Profile

Operational Mode	Days
Laden Sailing	160.130426
Ballast Sailing	135.546327
Unloading	22.85678063
Anchorage Laden	5.714195158
Maneuvering Laden	0
Loading	31.36162227
Anchorage Ballast	7.840405568
Maneuvering Ballast	0
Total	363.4497567

Laden Sailing

Speed	% of time
8	
9	
10	
11	0.49%
12	0.36%
13	0.73%
14	2.43%
15	10.07%
16	20.57%
17	9.16%
18	0.06%

Mean Speed	15.73

Ballast Sailing

Speed	% of time
8	
9	
10	
11	0.12%
12	0.79%
13	3.16%
14	10.50%
15	11.71%
16	6.19%
17	4.00%
18	0.67%
Mean Speed	14.91

Laden Sailing Fuel Consumption

FC Curve

Speed	ME FC[tn/d]	AE FC[tn/d]	Boiler FC[tn/d]
8	6.0029907	5.6060147	2.598370924
9	7.749049	5.6060147	2.598471651
10	9.757929	5.6060147	2.598567371
11	12.9189415	5.6060147	1.002252445
12	16.14024	5.6060147	1.185641775
13	20.572989	5.6060147	0.69508345
14	25.851381	5.6060147	0.000384364
15	31.212543	5.6060147	0.000384364
16	37.558384	5.6060147	0.000384364
17	45.724186	5.6060147	0.000384364
18	58.15535	5.6060147	0.000384364
1st Fuel	HFO		
1st fuel %	100.00%		
2nd Fuel			
2nd fuel %			
3rd Fuel			
3rd fuel %			

Ballast Sailing Fuel Consumption

FC Curve

Speed	ME FC[tn/d]	AE FC[tn/d]	Boiler FC[tn/d]
8	4.874596	4.996122	2.59851651
9	6.4593906	4.996122	2.598641283
10	8.586771	4.996122	2.598772114
11	11.038948	4.996122	2.598860545
12	14.381308	4.996122	1.20165356
13	18.495678	4.996122	0.975962883
14	23.05589	4.996122	0.318309707
15	28.965475	4.996122	0.000381364

16	35.494972	4.996122	0.000381364
17	42.805195	4.996122	0.000381364
18	52.31005	4.996122	0.000381364
1st Fuel	HFO		
1st fuel %	100.00%		
2nd Fuel			
2nd fuel %			
3rd Fuel			
3rd fuel %			

Non-sailing and Maneuvering Modes Fuel Consumption

Unloading

AE FC [tns/day]	15.258858
Boiler FC [tns/day]	1.841100607
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Anchorage Laden

AE FC [tns/day]	5.531103
Boiler FC [tns/day]	1.817509787
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Loading

AE FC [tns/day]	6.593156
Boiler FC [tns/day]	1.817509787
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Anchorage Ballast

AE FC [tns/day]	5.531103
Boiler FC [tns/day]	1.842948358
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Correction Factors

Ice class applicable	NO
Type of Ice Class	
Length [m]	
Breadth [m]	
Depth [m]	
Volume of displacement [m3]	
Cubic Correction Factor applicable	NO
Cubic Capacity [m3]	
Structural Enhancement Correction Factor applicable	NO
LWTenhanced - if applicable	
LWTref - if applicable	
Correction relating Voyage Adjustment	NO
FCvoyage[tns/yr] =	
Fuel	
Corrections to Shuttle Tankers or STS voyages on tankers	NO
Correction for Shuttle Tanker or STS voyage?	
FC$_{shuttle/STS}$[tns/yr] =	
Fuel	
Corrections relating electrical power,boiler,other	NO
Year of calculation	
FCelectical[tns/yr] =	
Fuel	
FCboiler[tns/yr] =	
Fuel	
FCother[tns/yr] =	
Fuel	
Distance travelled for voyage periods which may be deducted from CII calculation	NO
D$_x$[nm/yr] =	

Table 80: Fuel consumption input of the scenario that HFO is used as fuel for the LPG carrier with AEECO applied.

Laden Sailing Fuel Consumption

FC Curve			
Speed	ME FC[tn/d]	AE FC[tn/d]	Boiler FC[tn/d]
8	6.0029907	5.6060147	2.1282015
9	7.749049	5.6060147	2.128284
10	9.757929	5.6060147	2.1283624
11	12.9189415	5.6060147	0.8208971
12	16.14024	5.6060147	0.97110254

13	20.572989	5.6060147	0.56930965
14	25.851381	5.6060147	0.000314814
15	31.212543	5.6060147	0.000314814
16	37.558384	5.6060147	0.000314814
17	45.724186	5.6060147	0.000314814
18	58.15535	5.6060147	0.000314814
1st Fuel	HFO		
1st fuel %	100.00%		
2nd Fuel			
2nd fuel %			
3rd Fuel			
3rd fuel %			

Ballast Sailing Fuel Consumption

FC Curve

Speed	ME FC[tn/d]	AE FC[tn/d]	Boiler FC[tn/d]
8	4.874596	4.996122	2.1450667
9	6.4593906	4.996122	2.1451697
10	8.586771	4.996122	2.1452777
11	11.038948	4.996122	2.1453507
12	14.381308	4.996122	0.991961
13	18.495678	4.996122	0.8056541
14	23.05589	4.996122	0.2627636
15	28.965475	4.996122	0.000314814
16	35.494972	4.996122	0.000314814
17	42.805195	4.996122	0.000314814
18	52.31005	4.996122	0.000314814
1st Fuel	HFO		
1st fuel %	100.00%		
2nd Fuel			
2nd fuel %			
3rd Fuel			
3rd fuel %			

Non-sailing and Maneuvering Modes Fuel Consumption

Unloading

AE FC [tns/day]	15.258858
Boiler FC [tns/day]	0.93454033
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Anchorage Laden

AE FC [tns/day]	5.531103
Boiler FC [tns/day]	1.3519807

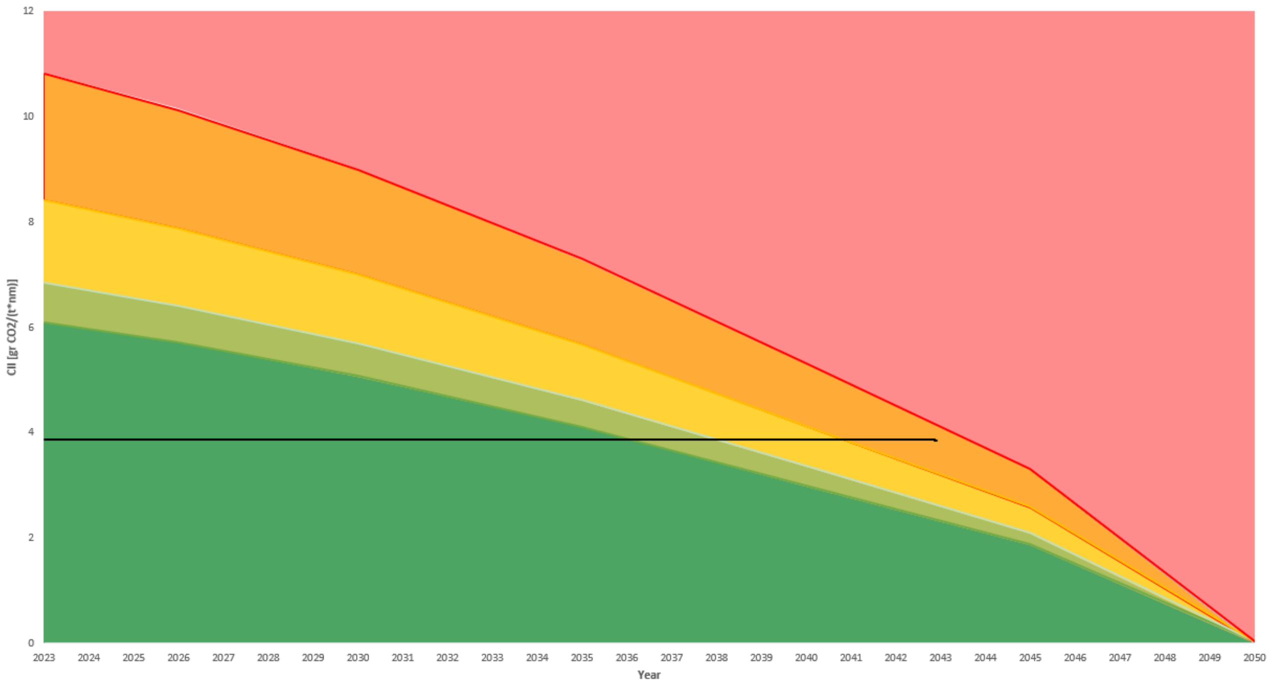
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Loading	
AE FC [tns/day]	6.593156
Boiler FC [tns/day]	1.3323022
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Anchorage Ballast	
AE FC [tns/day]	5.531103
Boiler FC [tns/day]	1.3519807
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Table 81: Results of the case that HFO is used for the propulsion of the LPG carrier.

attained CII [grCO2/(t*nm)]	**3.854913037**
Rating before measure	***A rating***
1st Measure	AEECO
1 - Measure CII	**3.839518072**



	Year of hit B rating	Year of hit C rating	Year of hit D rating	Year of hit D+2 rating	Year of hit E rating
0-Measure	2036.099331	2037.273659	2040.856276	2042.856276	2043.6184
1-Measure	2036.167966	2037.334752	2040.905914	2042.905914	2043.657

Table 82: Fuel consumption input of the scenario that LPG with MDO as pilot fuel are used for the propulsion of the LPG carrier without AEECO applied.

Laden Sailing Fuel Consumption

FC Curve			
Speed	ME FC[tn/d]	AE FC[tn/d]	Boiler FC[tn/d]
8	5.6040053	5.6060147	2.598733294
9	7.435929	5.6060147	2.598714981
10	9.5739	5.6060147	2.598696056
11	12.851751	5.6060147	1.21139581
12	16.04512	5.6060147	0.628451741
13	20.26917	5.6060147	0.694600465
14	25.269068	5.6060147	0.814358933
15	30.458395	5.6060147	0.885697643
16	37.414036	5.6060147	0.836631627
17	46.258476	5.6060147	0.000384364
18	57.552555	5.6060147	0.000384364
1st Fuel	LPG(Butane)		
1st fuel %	80.89%		
2nd Fuel	Diesel/Gas Oil		
2nd fuel %	4.36%		
3rd Fuel	HFO		
3rd fuel %	14.75%		

Ballast Sailing Fuel Consumption

FC Curve

Speed	ME FC[tn/d]	AE FC[tn/d]	Boiler FC[tn/d]
8	4.497643	4.996122	2.598974658
9	6.072229	4.996122	2.598971145
10	8.352499	4.996122	2.598948977
11	10.931656	4.996122	2.598928747
12	14.32135	4.996122	1.028177934
13	18.299799	4.996122	0.629775776
14	22.613218	4.996122	0.778623623
15	28.271408	4.996122	0.883236766
16	34.933334	4.996122	0.893035594
17	43.207367	4.996122	0.474620891
18	52.1815	4.996122	0.000381364
1st Fuel	LPG(Butane)		
1st fuel %	78.24%		
2nd Fuel	Diesel/Gas Oil		
2nd fuel %	4.97%		
3rd Fuel	HFO		
3rd fuel %	16.80%		

Non-sailing and Maneuvering Modes Fuel Consumption

Unloading

AE FC [tns/day]	15.258858
Boiler FC [tns/day]	1.842477226
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Anchorage Laden

AE FC [tns/day]	5.531103
Boiler FC [tns/day]	1.818452432
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Loading

AE FC [tns/day]	6.593156
Boiler FC [tns/day]	1.843918038
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	

3rd Fuel	
3rd fuel %	

Anchorage Ballast	
AE FC [tns/day]	5.531103
Boiler FC [tns/day]	1.818452432
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Table 83: Fuel consumption input of the scenario that LPG with MDO as pilot fuel are used for the propulsion of the LPG carrier with AEECO applied.

Laden Sailing Fuel Consumption

FC Curve

Speed	ME FC[tn/d]	AE FC[tn/d]	Boiler FC[tn/d]
8	5.6040053	5.60598	2.1284983
9	7.435929	5.60598	2.1284833
10	9.5739	5.60598	2.1284678
11	12.851751	5.60598	0.99219644
12	16.04512	5.60598	0.5147348
13	20.26917	5.60598	0.56891406
14	25.269068	5.60598	0.6670025
15	30.458395	5.60598	0.72543263
16	37.414036	5.60598	0.685245
17	46.258476	5.60598	0.000314814
18	57.552555	5.60598	0.000314814
19			
20			
21			
22			
23			
1st Fuel	LPG(Butane)		
1st fuel %	81.12%		
2nd Fuel	Diesel/Gas Oil		
2nd fuel %	4.37%		
3rd Fuel	HFO		
3rd fuel %	14.50%		

Ballast Sailing Fuel Consumption

FC Curve

Speed	ME FC[tn/d]	AE FC[tn/d]	Boiler FC[tn/d]
8	4.497643	4.9960914	2.1454449
9	6.072229	4.9960914	2.145442

10	8.352499	4.9960914	2.1454237
11	10.931656	4.9960914	2.145407
12	14.32135	4.9960914	0.84875745
13	18.299799	4.9960914	0.5198778
14	22.613218	4.9960914	0.6427512
15	28.271408	4.9960914	0.729109
16	34.933334	4.9960914	0.7371979
17	43.207367	4.9960914	0.39179796
18	52.1815	4.9960914	0.000314814
19			
20			
21			
22			
23			
1st Fuel	LPG(Butane)		
1st fuel %	78.55%		
2nd Fuel	Diesel/Gas Oil		
2nd fuel %	4.98%		
3rd Fuel	HFO		
3rd fuel %	16.47%		

Non-sailing and Maneuvering Modes Fuel Consumption

Unloading	
AE FC [tns/day]	15.410554
Boiler FC [tns/day]	0.9352391
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Anchorage Laden	
AE FC [tns/day]	5.5310693
Boiler FC [tns/day]	1.3526819
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

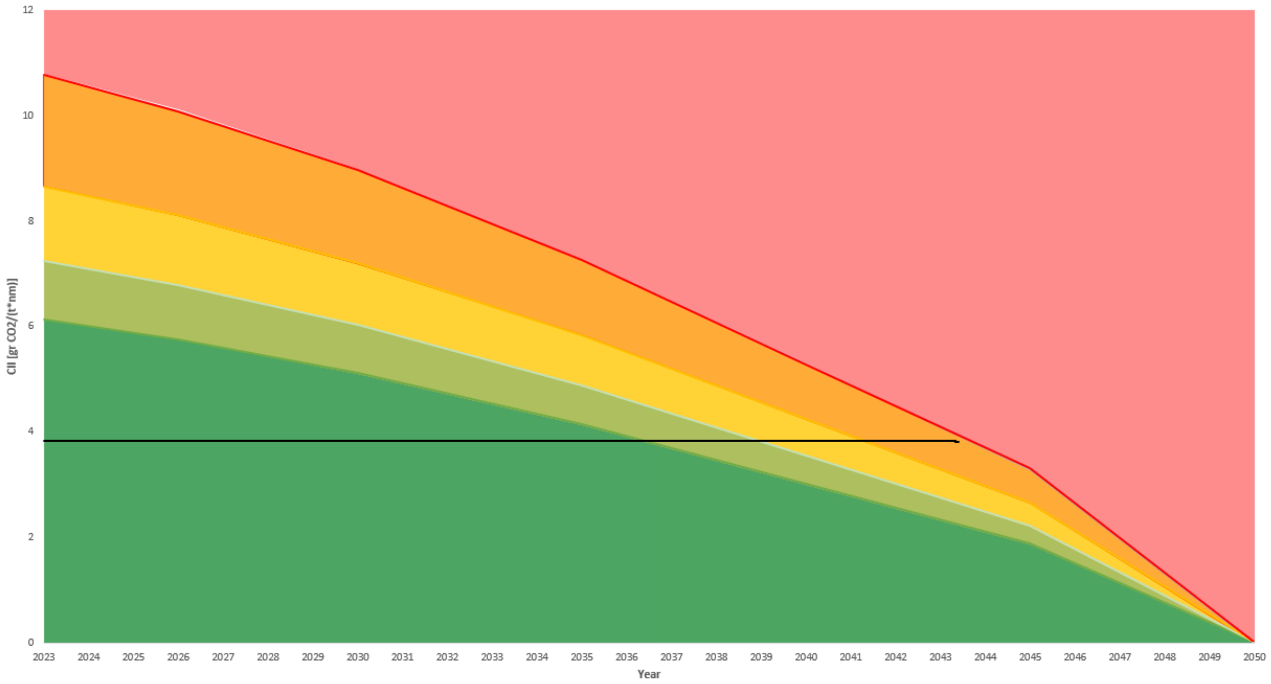
Loading	
AE FC [tns/day]	6.593115
Boiler FC [tns/day]	1.3330032
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	

2nd fuel %	
3rd Fuel	
3rd fuel %	

Anchorage Ballast	
AE FC [tns/day]	5.5310693
Boiler FC [tns/day]	1.3526819
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Table 84: Results of the case that LPG with MDO as pilot fuel are used for the propulsion of the LPG carrier.

attained CII [grCO2/(t*nm)]	**3.812379259**
Rating before measure	***A rating***
1st Measure	AEECO
1 - Meas. CII	**3.787694168**



	Year of hit B rating	Year of hit C rating	Year of hit D rating	Year of hit D+2 rating	Year of hit E rating
0-Measure	2036.420762	2038.272882	2041.32693	2043.32693	2043.6838
1-Measure	2036.529963	2038.365465	2041.404363	2043.404363	2043.7459

Appendix D – Bulk Carrier (VLOC)

In this chapter the input and results for the application case of the Bulk carrier are presented.

Table 85: Imput for the application case of the VLOC.

Ship's Main Particulars

Name of ship	
IMO Number	
Length [m]	
Breadth [m]	
Draught [m]	
Ship type	Bulk Carrier
DWT [t]	324963
GT [t]	

Reference lines

Ref CII	1.945675464
Rating year	2023
IMO reduction 2027-2030	zero 50
IMO reduction 2031-2035	zero 50
IMO reduction 2036-2040	zero 50
IMO reduction 2041-2045	zero 50
IMO reduction 2046-2050	zero 50
Rating year ref CII	1.848391691

Operational Profile

Operational Mode	Days
Laden Sailing	137.5443917
Ballast Sailing	125.8539427
Unloading	30.17499793
Anchorage Laden	20.11666529
Maneuvering Laden	
Loading	30.17499793
Anchorage Ballast	20.11666529
Maneuvering Ballast	
Total	363.9816608

Laden Sailing

Speed	% of time
8	0.42%
9	1.15%
10	3.14%
11	8.32%
12	8.03%
13	9.36%
14	5.97%
15	1.15%
16	0.12%
17	0.01%
Mean Speed	12.15

Ballast Sailing

Speed	% of time
8	0.16%
9	0.31%
10	0.93%
11	3.13%
12	7.43%
13	6.37%
14	4.87%
15	7.58%
16	3.12%
17	0.58%
Mean Speed	13.38

Maneuvering Laden

Speed	

Maneuvering Ballast

Speed	

Laden Sailing Fuel Consumption

FC Curve

Speed	ME FC[tn/d]
8	8.600303451
9	12.271014694
10	16.864217539
11	22.484328583
12	29.492067000
13	36.500366000
14	45.278020000
15	57.431070000
16	71.595140000
17	83.638980134
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Ballast Sailing Fuel Consumption

FC Curve

Speed	ME FC[tn/d]
8	5.775696723
9	8.644625175
10	12.399832941
11	17.184653784
12	23.912153000

13	29.378983000
14	37.677704000
15	48.753452000
16	65.804020000
17	76.287413731
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Non-sailing and Maneuvering Modes Fuel Consumption

Unloading	
AE FC [tns/day]	9.334938
Boiler FC [tns/day]	1.2
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Anchorage Laden	
AE FC [tns/day]	3.258792
Boiler FC [tns/day]	1.2
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Loading	
AE FC [tns/day]	9.334938
Boiler FC [tns/day]	1.2
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	
2nd fuel %	
3rd Fuel	
3rd fuel %	

Anchorage Ballast	
AE FC [tns/day]	3.258792
Boiler FC [tns/day]	1.2
1st Fuel	HFO
1st fuel %	100.00%
2nd Fuel	

2nd fuel %	
3rd Fuel	
3rd fuel %	

Correction Factors

Ice class applicable	NO
Type of Ice Class	
Length [m]	
Breadth [m]	
Depth [m]	
Volume of displacement [m3]	
Cubic Correction Factor applicable	NO
Cubic Capacity [m3]	
Structural Enhancement Correction Factor applicable	NO
LWTenhanced - if applicable	
LWTref - if applicable	
Correction relating Voyage Adjustment	NO
FCvoyage[tns/yr] =	
Fuel	
Corrections to Shuttle Tankers or STS voyages on tankers	NO
Correction for Shuttle Tanker or STS voyage?	
$FC_{shuttle/STS}$[tns/yr] =	
Fuel	
Corrections relating electrical power,boiler,other	NO
Year of calculation	
FCelectical[tns/yr] =	
Fuel	
FCboiler[tns/yr] =	
Fuel	
FCother[tns/yr] =	
Fuel	
Distance travelled for voyage periods which may be deducted from CII calculation	NO
D_x[nm/yr] =	

Table 86: Results of VLOC without any measures included.

Final Results

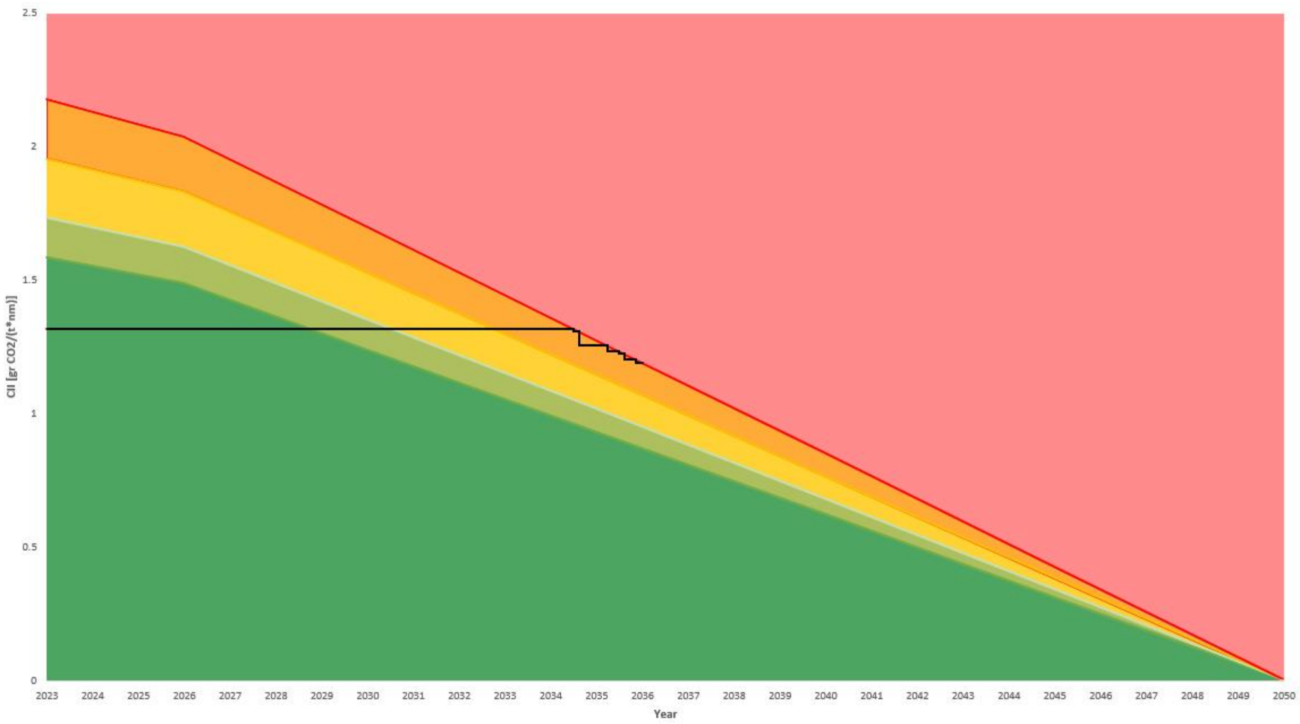
attained CII[grCO2/(t*nm)] =	**1.31909652**
Rating before measure	***A rating***
Preferred Rating	A rating

Table 87: Results of the six decarbonization measures applied for the VLOC.

1st Measure	Propeller retrofitting	2nd Measure	Engine de-rating
1-M attained CII[grCO2/(t*nm)] =	**1.30858921**	**2-M attained CII[grCO2/(t*nm)] =**	**1.25605263**
1-M Year until D+2 or E rating	***2034.63006***	**2-M Year until D+2 or E rating**	***2035.2471***
1-M Year until preferred rating	***2028.91101***	**2-M Year until preferred rating**	***2029.7577***

3rd Measure	Optimizing turbocharging at lower engine loads (exhaust gas bypass (EGB))	4th Measure	Aerodynamic Optimization of Superstructures
3-M attained CII[grCO2/(t*nm)] =	**1.235038005**	**4-M attained CII[grCO2/(t*nm)] =**	**1.22453069**
3-M Year until D+2 or E rating	***2035.493951***	**4-M Year until D+2 or E rating**	***2035.617364***
3-M Year until preferred rating	***2030.096351***	**4-M Year until preferred rating**	***2030.265685***

5th Measure	Kite	6th Measure	Variable frequency drive (VFD) controlled pumps, fans and motors
5-M attained CII[grCO2/(t*nm)] =	**1.2035161**	**6-M attained CII[grCO2/(t*nm)] =**	**1.19081801**
5-M Year until D+2 or E rating	***2035.8642***	**6-M Year until D+2 or E rating**	***2036.013333***
5-M Year until preferred rating	***2030.6044***	**6-M Year until preferred rating**	***2030.808992***



	Year of hit B rating	Year of hit C rating	Year of hit D rating	Year of hit D+2 rating	Year of hit E rating
0-Measure	2028.741679	2030.550898	2032.752683	2034.752683	2034.506648
1-Measure	2028.911013	2030.705821	2032.890067	2034.890067	2034.63006
2-Measure	2029.757683	2031.480433	2033.576988	2035.576988	2035.247125
3-Measure	2030.096351	2031.790279	2033.851757	2035.851757	2035.493951
4-Measure	2030.265685	2031.945201	2033.989141	2035.989141	2035.617364
5-Measure	2030.604353	2032.255046	2034.263909	2036.263909	2035.864189
6-Measure	2030.808992	2032.44227	2034.429937	2036.429937	2036.013333