National Technical University of Athens

School of Naval Architecture and Marine Engineering

Division of Ship Design and Maritime Transport

Carbon Intensity Indicator (CII) Impact Assessment on LNG Carriers

Diploma Thesis

of

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This work is dedicated to my parents, who have always been there for me.

Athens 2022,

Leonidas Alexandropoulos

Abstract

The decarbonization of shipping as part of a global strategy to mitigate climate change is the dominant issue in the shipping industry nowadays. In this context, the International Maritime Organization (IMO) recently adopted new regulations aimed at reducing emissions per transport work, including the Carbon Intensity Indicator regulation. This thesis intends to examine the impact of the CII regulation on the existing fleet of Liquefied Natural Gas Carriers. The study is based on the calculation of the Carbon Intensity Indicator for a share of the existing fleet of LNG Carriers using operational data from the MRV system for the year 2020. As the exact form of the regulation after 2026 is unknown, the compliance of vessels with the regulation until 2030 is examined by developing some trajectory scenarios. The study is conducted on a generalized fleet level as well as by categorizing the fleet based on size, age, and propulsion type. Furthermore, the CII between similar vessels and its comparison with technical efficiency indexes are evaluated. Finally, a case study is conducted between various types of LNG Carriers and Bulk Carriers that transport coal, the major CO_2 polluter and competitor of gas in the energy sector, to provide a more comprehensive perspective on the contribution of LNG in decarbonization and the role of shipping in the LNG supply chain. The aim is to compare the energy content of each cargo, as well as emissions during ship transportation and the entire lifecycle of cargo intended for power generation.

Keywords: GHG emission, LNG Carrier, CII, MRV, decarbonization, LNG, Coal.

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1. Introduction

1.1 Background of the study

Nowadays, tackling climate change and reducing greenhouse gas emissions are the most important and urgent challenges for all industries, as the effects of air pollution are more visible than ever and are expected to worsen in the coming years if effective measures are not implemented.

According to [1], shipping was responsible for 2.89% of total global anthropogenic CO_2 emissions in 2018, a relatively low percentage in comparison to other industries. In this context, the International Maritime Organization and the shipping industry in general have increased their efforts to reduce shipping's environmental footprint by focusing on better fleet management and energy efficiency. This effort began in 2013 with the implementation of the design energy efficiency index EEDI, which refers to the expected emissions per transport work. Following the same philosophy and taking more drastic measures, the IMO and the competent MEPC (Marine Environmental Protection Committee) decided in April 2018 to adopt a drastic strategy aimed at reducing emissions by 50% by 2030 compared to 2008 and reducing CO_2 emissions per transport project by 40% until 2030 and 70% until 2050, compared to 2008. New supplementary measures to reduce carbon emissions were adopted at the 76th MEPC meeting in June 2021, with the main measures being the energy efficiency index for existing ships, EEXI, which is basically the application of EEDI to existing ships, and the carbon intensity indicator, CII.

The CII is based on operational data expressing the actual CO_2 emissions per transport work and is expected to accompany the ships throughout their lifetime as it must be calculated on an annual basis. The process includes evaluating each ship and assigning a ranking label based on the CII value. However, the CII regulation has not yet been finalized and will be revised in the future, possibly with more ambitious goals for reducing emissions per transport work.

The effort to comply with the CII regulation, as expected, will create new challenges and changes in the shipping industry. Shipowners and operators will need to make continued efforts to improve the energy efficiency of their vessels, whether through operational or technical measures such as investing in energy-saving devices and alternative fuels.

The present thesis attempts to investigate the impact of the CII regulation on a specific type of ship, Liquefied Natural Gas Carriers. Because their cargo is also used as fuel during the voyage, LNG carriers have distinctive features. Moreover, such ships are large investments with high CAPEX, while the global fleet of LNG carriers is rapidly expanding.

Another reason for dealing with the subject is the value and importance of the cargo carried by such ships. Despite being a fossil fuel, LNG has significant air pollution advantages over other energy sources such as coal and is expected to play an important role in the effort to reduce GHGs. Shipping is becoming increasingly important in the LNG supply chain, and thus in the global energy transition and security, which is extremely crucial today, as well as in decarbonization efforts.

1.2 Literature review

This subsection aims at presenting a brief literature review, on research regarding generally IMO's short term measures to reduce GHG emissions such as Carbon Intensity Indicator and the energy efficiency of the LNG Carriers. Because the CII regulation is pretty recent, the literature, to the best of the author's knowledge, is limited.

Psaraftis [2] provided an analysis of the IMO MEPC 76 decisions (June 2021) and assessed the prospects for future shipping decarbonization in the aftermath of that meeting. Regarding the short-term CII measure, Psaraftis mentioned that the IMO has yet to agree on how to measure transport work, as both AER and EEOI options were left on the table, each with different supporters. Further about ratings and the consequences for non-compliant ships, Psaraftis noted that there will be no regulatory consequences, though the commercial implications of a ship rated D or E may be significant in terms of the ability of such a ship to attract charters. Wang et al. [3] proved in their research that, at least in theory, requiring a ship's attained annual CII to be less than a reference value, regardless of which CII option is used, may increase its carbon emissions. They revealed a paradox behind the CII by using some case studies, such as sailing an empty ship to reduce carbon intensity, which actually increases carbon emissions.

Before the implementation of CII, Psaraftis and Zis [4] described the impact assessment of a mandatory operational goal-based short-term measure proposed by Denmark to reduce greenhouse gas (GHG) emissions from ships in their paper. The paper developed a methodology for assessing the potential negative impacts of a goal-based measure in the base of AER on Least - developed countries and small island developing states. In another paper, Zis and Psaraftis [5] presented a methodology for assessing the impacts of various short-term measures on perishable products. One of the measures is a goal-based measure in the form of a carbon intensity indicator (CII) focusing on perishable cargoes transported by containerships.

Schroer et al. [6] investigated the relevant techno-economic implications of compliance with the IMO's short-term measures from the perspective of a shipowner and estimated the effect of six compliance options on six sample containerships in their study. The study is based on operational data from six representative containerships of various sizes and eras of technology. One conclusion of the paper is that scrapping might be a widely adopted solution since compliance with the operational CII will result in financial losses for shipowners/operators of older ships as the payback period of the necessary investments is probably longer than the lifetime of the ships.

Regarding LNG carriers and energy efficiency indicators, Attah and Bucknall [7] presented an analysis of LNG carrier powering options from the scope of Energy Efficiency Design Index (EEDI). The purpose of this paper was to investigate the effects of EEDI regulation on the design of future LNGCs. The study also included unburned methane emissions, as well as proposed and analyzed amendments to the EEDI baseline values for LNGCs and methods for implementing methane slip emissions into the EEDI calculations. One of the most important findings of the study was that when methane slip is taken into account and analyzed, the efficiency gains of DFDEs are eroded. In another paper, Attah and Bucknall [8] investigated the energy efficiency profile of steam propelled LNG carriers. One aspect of their work included estimating the vessel's efficiency using the EEOI, which was based on actual operational conditions.

1.3 Purpose and structure of the thesis

The purpose of this thesis is to assess the impact of the upcoming IMO short-term measure, Carbon Intensity Indicator regulation, on the current fleet of LNG Carriers until the end of the decade, as well as to highlight the role and contribution of LNG in the energy security and the global decarbonization efforts. More specifically, the following are the primary objectives of the thesis:

- The presentation of the regulatory framework for reducing GHG emissions in shipping, with an emphasis on the CII regulation.
- The estimation of CII for the current fleet of LNG Carriers based on operational data.
- The assessment of the LNG carrier fleet's compliance with the CII requirements until the end of the decade, based on different trajectory scenarios.
- The correlation of CII with characteristics such as age, size, and propulsion type.
- The calculation of greenhouse gas emissions arising from the transportation of an LNG cargo by an LNG Carrier and a coal cargo by a bulk carrier.
- The comparison of the energy content of two different ship cargoes, LNG and coal, as well as the GHG emissions in CO_2 equivalent over the cargo's entire lifecycle, from production to combustion for energy production.

The present study is structured as follows:

Climate change is mentioned in Chapter 2, along with a description of the major greenhouse gases and the contribution of shipping in climate change.

Chapter 3 examines the regulatory framework for reducing GHG emissions. More specifically, a brief analysis of the International Maritime Organization's strategy and energy efficiency measures, as well as emissions monitoring systems from both the IMO and the European Union, is conducted. Since the CII regulation is an important component of this work, special emphasis is placed on it.

In chapter 4, the main characteristics of LNG Carriers are presented, emphasizing the distinctive features of this type of ship. Characteristics such as cargo (LNG), size, cargo containment system, and type of propulsion, which is given more emphasis since it directly affects energy efficiency and thus emissions, are analyzed.

The methodology used for calculating the CII and the correlation with the fundamental characteristics of the ships are then presented in detail in chapter 5, which leads into the most practical section of the study. Specifically, the data collection and reliability of the MRV data are presented, as well as the study's main assumptions, the calculation of CII including methane slip in LNG engines, and the hypothetical trajectory scenarios for the future of the regulation.

Chapter 6 provides the results of the analysis conducted using the methodology of Chapter 5 regarding the impact of the CII regulation on the fleet studied. Furthermore, an evaluation of the CII is performed between similar vessels in order to estimate the operational factor, as well as a comparison with the technical efficiency indexes.

In Chapter 7, a case study is used to compare two ship cargoes and their contribution to decarbonization due to the increased role of shipping in the LNG supply chain and the global energy transition and security, particularly in the power sector. LNG and coal are the cargoes, and they are transported by LNG Carrier and Bulk Carrier, respectively.

Finally, the conclusions and recommendations for future research are presented in Chapter 8.

2. Air pollution and effects

2.1 Climate change

Climate change and air pollution are widely acknowledged to be the most important problems of our time, as the consequences of environmental pollution are more noticeable than ever. The results of numerous studies indicate that the planet's temperature is rising quickly over time. Climate change, as defined by the Intergovernmental Panel on Climate Change (IPCC) [9], is a shift in the state of the climate that can be determined (e.g., through the use of statistical tests) by changes in the mean and/or variability of its properties and that lasts for a considerable amount of time, usually decades or longer. Climate change can be brought on by internal natural processes or external forcings like variations in the sun's cycle, volcanic eruptions, and enduring anthropogenic changes in the atmosphere's composition or in how land is used.

The greenhouse effect is the primary cause of climate change [10]. Some gases in the Earth's atmosphere act like the glass in a greenhouse, trapping the sun's heat and preventing it from leaking back into space and causing global warming. While many of these greenhouse gases are produced naturally, human activity is raising the levels of some of them in the atmosphere. The main GHGs are Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), and Fluorinated Gases, according to [11].

- **Carbon dioxide (CO_2):** Carbon dioxide enters the atmosphere as a result of the combustion of fossil fuels (mainly coal, natural gas, and oil), solid waste, trees, and other biological materials, as well as certain chemical reactions (e.g., manufacture of cement). As part of the biological carbon cycle, carbon dioxide is absorbed by plants and subsequently removed from the atmosphere (or "sequestered").
- **Methane (CH_4):** Methane is emitted during the production and transportation of coal, natural gas, and oil. Land use, livestock, other agricultural practices, and the decomposition of organic waste in municipal solid waste landfills all contribute to methane emissions.
- **Nitrous oxide (N_2O):** Nitrous oxide is emitted during agricultural, land use, and industrial activities; combustion of fossil fuels and solid waste; as well as during treatment of wastewater.
- **Fluorinated gases** are powerful greenhouse gases emitted by a wide range of household, commercial, and industrial applications and processes. Fluorinated gases are sometimes used as substitutes for ozone-depleting substances in the stratosphere (e.g., chlorofluorocarbons, hydrochlorofluorocarbons, and halons) and are emitted in smaller quantities than other greenhouse gases, but they are potent greenhouse gases as they have a very strong warming effect.

As mentioned in [11] , each gas's effect on climate change depends on three main factors. The first is the amount in the atmosphere, the second is how long they stay in the atmosphere, and the third is how strongly they impact the atmosphere. A Global Warming Potential (GWP) was developed for each greenhouse gas to allow comparisons of the global warming impacts of different gases. It is a measure of how much energy one ton of a gas will absorb over a given period of time in comparison to one ton of carbon dioxide emissions (CO_2).

The impacts of climate change on different sectors of human society are numerous and interconnected. The biggest health threat to humanity, according to the World Health Organization, is climate change, and medical professionals are already taking action to mitigate its effects.

Some key facts as stated in [12] , are the following:

- The social and environmental determinants of health, such as clean air, safe drinking water, enough food, and adequate shelter, are impacted by climate change.
- Climate change is predicted to result in an additional 250,000 deaths per year between 2030 and 2050, mostly from malnutrition, malaria, diarrhea, and heat stress.
- By 2030, it is predicted that the direct costs to health will range between USD 2-4 billion/year (i.e., excluding costs in health-determining sectors like agriculture and water and sanitation).
- The areas least able to cope without assistance to prepare and respond will be those with weak health infrastructure, which is mostly in developing countries.
- Better food, transportation, and energy choices can reduce greenhouse gas emissions, which can improve health, especially by reducing air pollution.

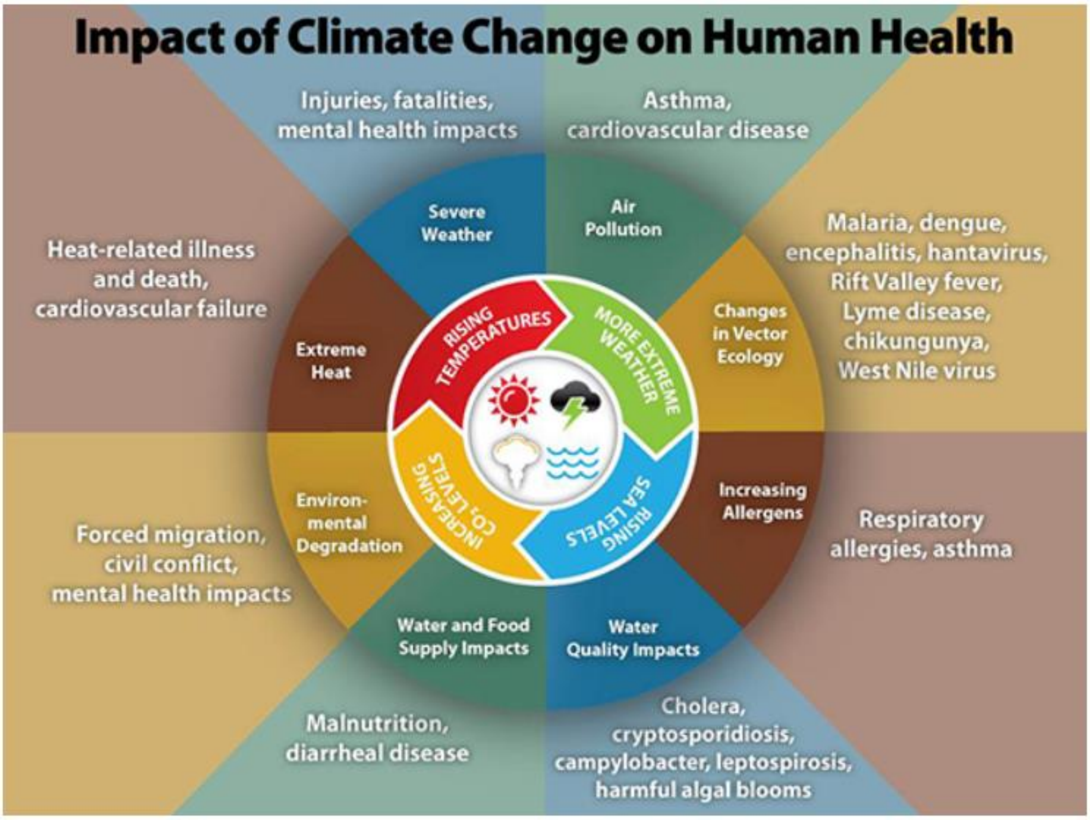


Figure 1: Impact of climate change on human health [13].

2.2 Shipping and Greenhouse Gases

The impact of shipping on global climate change is a major topic that is causing concern among those in charge of environmental policy. Merchant vessels emit a wide range of gaseous pollutants, including CO_2, CH_4, N_2O, SOx, NOx, PM, Black Carbon, and CO, which either pollute the air or cause climate change. Figure 2 conceptually summarizes the overall effects of emissions (of any kind) on the climate for the shipping industry.

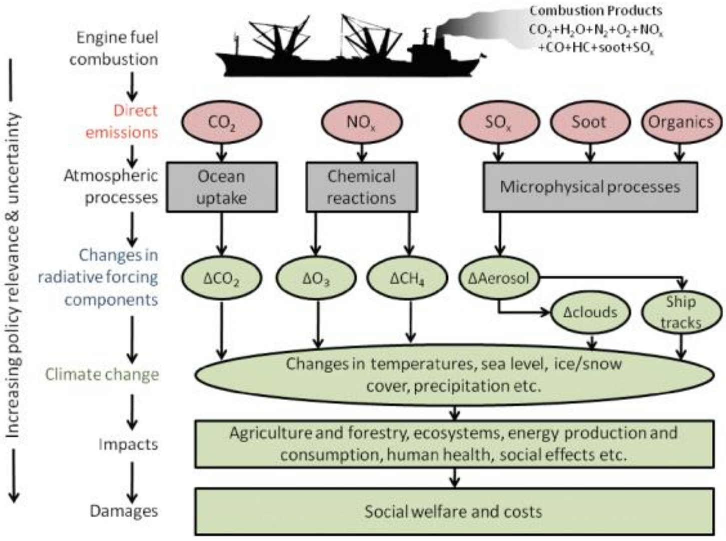
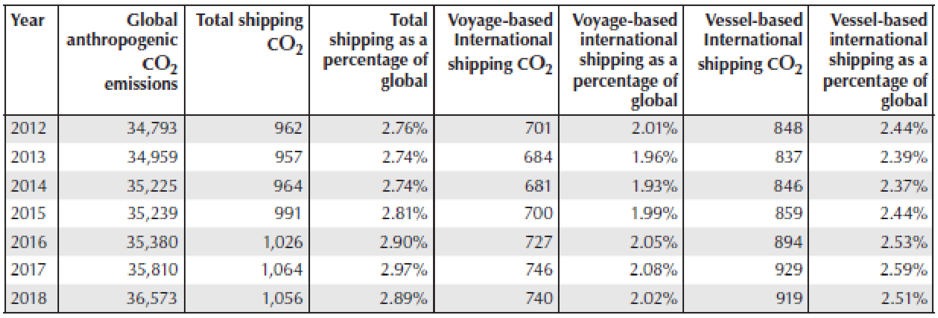


Figure 2: Overall impacts of emissions from the shipping sector on climate change [14] .

Although maritime transportation is one of the most energy-efficient modes of transportation, it is also a significant source of greenhouse gases. According to the IMO 4th study [1], total shipping CO_2 emissions increased by 9.3% between 2012 and 2018, while its share of global CO_2 emissions increased progressively from 2.76 to 2.89% during the same period. For a variety of plausible long-term economic and energy scenarios, these emissions are projected to rise from 90% to 130% of 2008 levels by 2050 [15]. The total shipping CO_2 emissions in million tonnes as a share of the global anthropogenic CO_2 emissions for the years 2012-2018 is shown in the next figure.



Year	Global anthropogenic CO_2 emissions	Total shipping CO_2	Total shipping as a percentage of global	Voyage-based International shipping CO_2	Voyage-based international shipping as a percentage of global	Vessel-based International shipping CO_2	Vessel-based international shipping as a percentage of global
2012	34,793	962	2.76%	701	2.01%	848	2.44%
2013	34,959	957	2.74%	684	1.96%	837	2.39%
2014	35,225	964	2.74%	681	1.93%	846	2.37%
2015	35,239	991	2.81%	700	1.99%	859	2.44%
2016	35,380	1,026	2.90%	727	2.05%	894	2.53%
2017	35,810	1,064	2.97%	746	2.08%	929	2.59%
2018	36,573	1,056	2.89%	740	2.02%	919	2.51%

Figure 3: Total shipping CO_2 emissions as a share of global anthropogenic CO_2 emissions [1] .

As mentioned in [16], by 2050, shipping could account for about 10% of global GHG emissions under a business-as-usual scenario and if other economic sectors reduce emissions to keep global temperature increases under 2 degrees Celsius.

3. Regulatory framework for reducing Greenhouse Gas emissions from shipping

3.1 Introduction

This chapter examines the regulatory framework for Greenhouse Gas emissions from shipping. The regulations that will be presented are from the International Maritime Organization (IMO) and the European Union. It should be noted that the regulatory framework presented focuses solely on greenhouse gases, with other regulations relating to pollutants such as sulphur oxides (SOx) and nitrogen oxides (NOx) omitted. The IMO's energy efficiency indicators and efforts to achieve its short-, medium-, and long-term goals are presented first. As a crucial component of this work, special emphasis is placed on the carbon intensity indicator (CII) and its calculation. The next section of the chapter discusses the IMO and EU's monitoring and recording systems for pollutants. Finally, a mention is made of the recent appearance and impending importance of the new European Union proposed regulations for the decarbonization of shipping.

3.1.1 IMO

The international effort to tackle climate change and its effects is aided by the International Maritime Organization. Therefore, as part of its international convention for the prevention of pollution from ships (MARPOL) the IMO has adopted mandatory measures to reduce GHG emissions from the global shipping sector. Under the authority of IMO, the Marine Environment Protection Committee (MEPC) handles environmental issues. Mandatory technical (EEDI) and operational (SEEMP) measures for ship energy efficiency were established by MEPC 62 (July 2011). Furthermore, the IMO adopted a mandatory Fuel Oil Data Collection System (DCS) for international shipping in 2016, requiring ships of 5,000 gross tonnage or greater to start collecting and reporting data to an IMO database beginning in 2019.

- IMO initial strategy

The IMO adopted an initial strategy in 2018 to contribute to global efforts by reducing GHG emissions from international shipping. The Initial Strategy, according to [17], is aimed at:

- Enhancing IMO's contribution to global efforts by addressing GHG emissions from international shipping. The Paris Agreement and its goals are the main international efforts to reduce GHG emissions.
- Identifying actions to be implemented by the international shipping sector, as appropriate, while addressing impacts on States and recognizing the critical role of international shipping in supporting the continued development of global trade and maritime transport services.
- Identifying actions and measures, as appropriate, to help achieve the above objectives, including incentives for research and development and monitoring of GHG emissions from international shipping.

According to [17], the levels of ambition directing the Initial Strategy are as follows:

- Carbon intensity of the ship to decline through implementation of further phases of the energy efficiency design index (EEDI) for new ships.

- Reduction of CO_2 emissions per transport work (carbon intensity), as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008.
- Reduction of the total annual GHG emissions from international shipping by at least 50% by 2050 compared to 2008, while, at the same time, pursuing efforts towards phasing them out as called for in the vision, for achieving CO_2 emissions reduction consistent with the Paris Agreement temperature goals.

The proposed measures that can lead to the achievement of the above ambitious goals are divided into three categories: short-term, mid-term, and long-term. The IMO GHG Strategy includes a wide range of potential short-, mid-, and long-term measures, such as improved EEDI and SEEMP, National Action Plans, enhanced technical cooperation, port activities, research and development, support for the effective use of alternative low-carbon and zero-carbon fuels, innovative emission reduction mechanisms, etc. [18]. Candidate measures outlined in this Initial Strategy should conform to the following timelines [17] :

- Short-term measures could be finalized and agreed upon by the Committee between 2018 and 2023.
- Mid-term measures could be finalized and agreed upon by the Committee between 2023 and 2030.
- Long-term measures could be finalized and agreed upon by the Committee after 2030.

The following figure shows the overall GHG reduction pathway to reach the ambitious goals of the IMO.

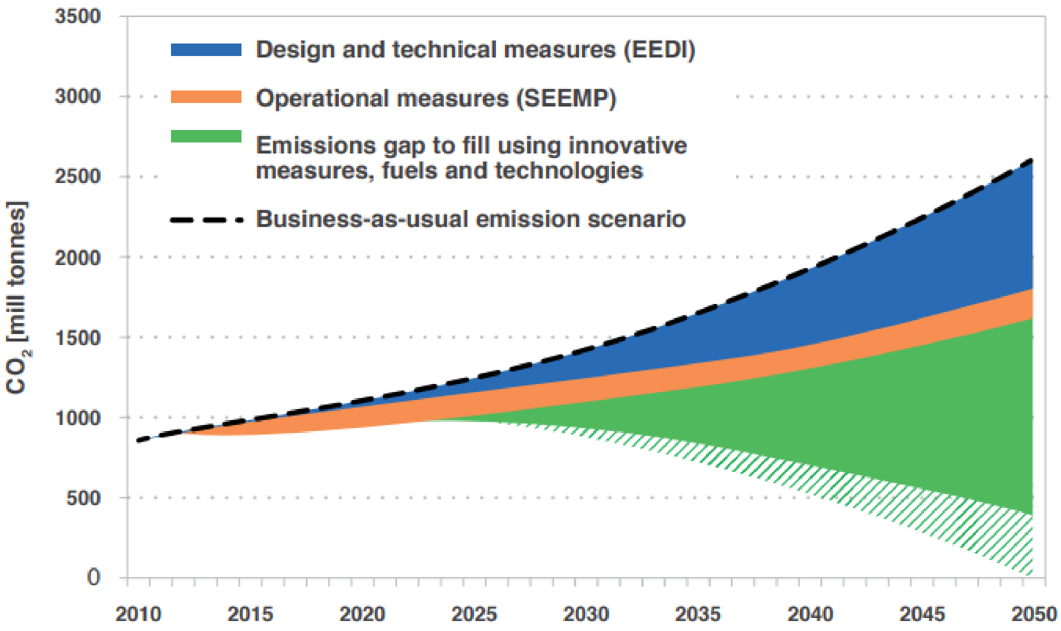


Figure 4: Overall GHG reduction pathway [18] .

3.1.2 European Union

The European Union cooperates with the IMO, but it also makes its own efforts to reduce GHG emissions from shipping in Europe by implementing regulations and legislation. In 2013, the Commission proposed a strategy to reduce GHG emissions from the shipping industry. According to [15] , the strategy consists of 3 consecutive steps:

- Monitoring, reporting, and verification of CO_2 emissions from large ships using EU ports.
- Greenhouse gas reduction targets for the maritime transport sector.
- Further measures, including market-based measures, in the medium to long term.

The first step in the strategy was the adoption of the EU MRV regulation (Regulation 2015/757), which came into force on July 1, 2015, and requires ship owners and operators to monitor, report, and verify CO_2 emissions for vessels calling at any EU port on an annual basis.

As part of its larger European Green Deal, which aims to make the EU carbon-neutral by 2050, the EU Commission published an extensive legislative proposal package in July 2021 titled "Fit For 55," outlining how it intends to reduce its net greenhouse gas emissions by at least 55 percent by 2030, compared to 1990 levels. To address the climate impact of maritime transportation, the EU has made several proposals [15] including:

- Extending the EU Emissions Trading System (ETS) to maritime transport.
- Boosting demand for marine renewable and low-carbon fuels (FUEL EU maritime regulation).
- Boosting alternative fuels infrastructures.
- Accelerating the supply of renewables in the EU, through a revision of the Renewable Energy Directive (RED).
- Revising the existing Energy Taxation Directive (ETD).

3.2 Energy efficiency measures

3.2.1 Energy efficiency design index (EEDI)

At MEPC 62 (July 2011), changes to MARPOL Annex VI were adopted, making the Energy Efficiency Design Index (EEDI) mandatory for new ships. Since the adoption of the Kyoto Protocol, this was the first legally binding agreement on climate change [19]. EEDI regulation applies to ships of 400 gross tonnage and above, engaged in international voyages. The EEDI for new ships is considered to be the most important technical measure and promotes the use of more environmentally friendly equipment and engines. For each new design, the EEDI is calculated and expresses the CO_2 production (in grams) per unit of carrying capacity - distance (in ton-miles). As a result, the lower the value, the more energy efficient the ship [20]. In its theoretical form, the EEDI expresses the impact on the environment to the benefit for society through cargo transportation.

$$EEDI = \frac{Impact\ to\ environment}{Benefit\ for\ society} = \frac{CO_2\ emission}{Transport\ work}\ (\frac{gC02}{t * nm})$$

A brief summary of the attained EEDI formula is given by the below form.

$$EEDI = \frac{P * SFOC * C_F}{Capacity * Speed}$$

Where,

- P is the power required from the engine.
- SFOC is the specific fuel oil consumption of the engine
- C_F is the conversion factor of fuel oil to $CO_{2,}$ depends on the fuel type.

The full EEDI formula, which includes a number of adjustments and factors designed to suit particular classes of vessels and alternative configurations and operating conditions, is detailed in MEPC.1/Circ.681.

For various ship types and size segments, the EEDI requires a minimum energy efficiency level per capacity mile. Reference lines have been developed for each ship category. The definition of a reference line is a curve that represents the average index value fitted on a group of individual index values for a specific group of ships [21]. The reference EEDI, also known as the baseline, is a function of ship size for each ship type.

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

$$Attaned\ EEDI\ \leq Required\ EEDI$$

The required EEDI is the reference value of EEDI multiplied by a reduction factor based on the vessel's year of construction and type.

$$Required\ EEDI = \left(1 - \frac{X}{100}\right) * Reference\ line\ value$$

Where X is the reduction factor.

The reduction factor X is determined according to year of built for new ships in phases. The IMO has established three phases to enhance continued innovation and technical development of all the components influencing a ship's fuel efficiency, with each phase progressively requiring less energy (and thus CO_2) to perform the same amount of transport work. According to the relevant time period, the corresponding phases as noted by [22], are listed below:

- 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.

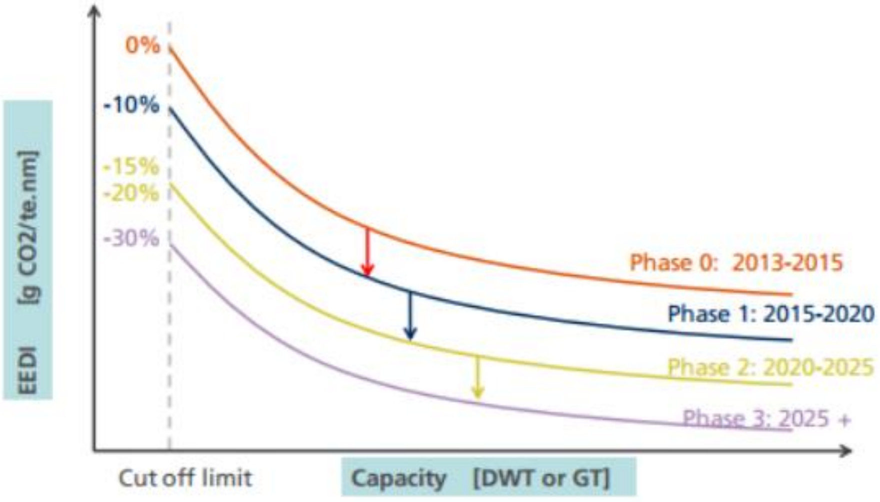


Figure 5: EEDI phases [23].

3.2.2 Ship Energy Efficiency Management Plan (SEEMP)

From January 1, 2013, all ships over 400 GT operating internationally must have a Ship energy Efficiency Management Plan (SEEMP) on board, in accordance with MARPOL Annex VI Regulation 22. According to [19] , the SEEMP is an operational measure that establishes a mechanism to improve the energy efficiency of a ship in a cost-effective manner. There are three parts to a SEEMP.

- ✓ Part I of the SEEMP

The SEEMP part I provide an approach for shipping companies to manage ship and fleet efficiency performance over time and reduce the carbon intensity of a ship's operation. The ship-owner, operator, or any other party involved, such as the charterer, should develop the SEEMP part I as a ship-specific plan. The SEEMP aims to improve a ship's energy efficiency in four steps [24] :

- Planning
- Implementation
- Monitoring
- Self-evaluation and improvement

The following are some key practices and measures proposed by the IMO that can be used to improve ship energy efficiency and carbon intensity:

- Improved voyage planning
- Weather routeing.
- Just in time arrival.
- Speed optimization.
- Optimized ship handling (optimum trim and optimum ballast).
- Optimized shaft power.
- Hull maintenance.

- Propulsion system maintenance.

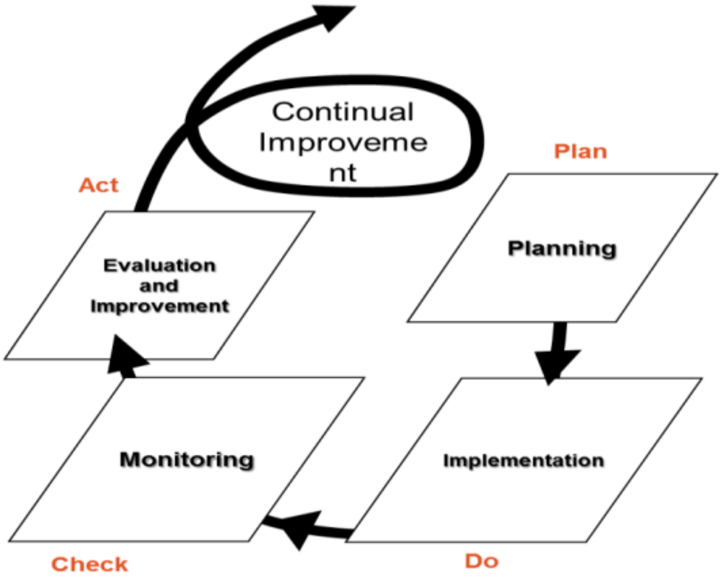


Figure 6: SEEMP continuous improvement concept [23] .

✓ Part II of the SEEMP

The SEEMP Part II is also referred to as the ship fuel oil data collection plan. This part outlines the methodologies to be used to gather the data needed to comply with MARPOL Annex VI regulation 27 as well as the procedures the ship should follow to report the data to its administration, or any other entity duly authorized by it. Part II of the SEEMP applies to any ship of 5,000 GT and above [24]. The following information must be included in the SEEMP Part II.

- Ships particulars.
- Record of revision of Fuel Oil Consumption Data Collection Plan.
- Ship engines and other fuel oil consumers and fuel oil types used.
- Emission factor of fuels used (Conversion factor C_F).
- Method to measure fuel oil consumption.
- Method to measure distance travelled.
- Method to measure hours underway.
- Processes that will be used to report the data to the Administration.
- Data quality.

✓ Part III of the SEEMP

The SEEMP Part III is also referred to as the ship operational carbon intensity plan. At the 76th meeting of the IMO's MEPC in 2021, additional amendments to MARPOL Annex VI were approved. The CII rating, which is based on the annual fuel consumption of each ship, will be implemented on January 1, 2023. The SEEMP Part III is designed to ensure the ship's efficient operation and achievement of the required CII. For specific categories of ships of 5,000 GT and above, on or before 1 January 2023, the SEEMP shall include the following, in accordance with Regulation 26.3.1 of MARPOL Annex VI [24] :

- 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 annual operational CIIs for the next three years.
- An implementation plan documenting how the required annual operational CIIs will be achieved during the next three years.
- A procedure for self-evaluation and improvement.

3.2.3 Energy Efficiency Operational Indicator (EEOI)

The Energy Efficiency Operational Indicator (EEOI), which was implemented by the IMO in 2010 as a voluntary method for monitoring and managing ship emissions, is used for existing ships. According to IMO guidelines, the goal of EEOI is to establish a uniform method for calculating a ship's energy efficiency for each voyage or over a specific amount of time. The EEOI is anticipated to help ship owners and operators assess the operational efficiency of their fleet. In fact, the EEOI is recommended as a monitoring tool in the SEEMP. Similar to EEDI, EEOI measures the CO_2 emissions from a ship per unit of cargo mile transported (in gCO_2/ton-mile). As opposed to the EEDI, which is defined for one operating point of a ship, the EEOI, which is determined by multiplying the total fuel consumption for each fuel type by the appropriate carbon factor for each fuel, represents the actual CO_2 emissions from combustion of all fuel types on board a ship during each voyage. The calculated amount of transport work is determined by multiplying the actual cargo weight (in tonnes, TEUs, cars, or passengers) by the actual distance traveled by the vessel [23] .

The basic expression for EEOI for a voyage is defined as [25] :

$$EEOI = \frac{\sum_j FC_j * C_{Fj}}{m_{cargo} * D}$$

The guidelines allow averaging EEOI throughout multiple voyages. When the average of the indicator is obtained over a period of time (e.g., a year) or over a number of voyages, the EEOI is calculated as follows:

$$EEOI = \frac{\sum_i \sum_j (FC_{ij} * C_{Fj})}{\sum_i m_{cargo,i} * D_i}$$

Where:

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

3.2.4 Energy Efficiency Existing Ship Index (EEXI)

At its 76th meeting in June 2021, the Marine Environment Protection Committee (MEPC) adopted amendments to MARPOL Annex VI that make the Energy Efficiency Existing Ship Index (EEXI) regulation mandatory. Similar to the concept of the EEDI, the EEXI is a measure to lower the greenhouse gas emissions of existing ships and is related to a ship's technical design. Ships have to attain EEXI approval once in a lifetime, by the first periodical survey in 2023 at the latest. The EEXI requirements shall apply to all vessels above 400 GT falling under MARPOL Annex VI. Similarly to the EEDI requirements, the attained EEXI shall be as follows:

$$Attained\ EEXI = \left(1 - \frac{y}{100}\right) * EEDI\ reference\ line\ value$$

Where y is the reduction factor specified on the Table 1 for the required EEXI compared to the EEDI reference value.

Table 1: Reduction factors for shup type and size [26] .

Type of ship	Size	Reduction factor (y)%
Bulk Carrier	200,000 DWT and above	15
	20,000-200,000 DWT	20
	10,000-20,000 DWT	0-20*
Gas carrier	15,000 DWT and above	30
	10,000-15,000 DWT	20
	2,000-10,000 DWT	0-20*
Tanker	200,000 DWT and above	15
	20,000-200,000 DWT	20
	4,000-20,000 DWT	0-20*
Containership	200,000 DWT and above	50
	120,000-200,000 DWT	45
	80,000-120,000 DWT	35
	40,000-80,000 DWT	30
	15,000-40,000 DWT	20
	10,000-15,000 DWT	0-20*
General cargo ship	15,000 DWT and above	30
	3,000-15,000 DWT	0-30*
Refrigerated cargo carrier	5,000 DWT and above	15
	3,000-5,000 DWT	0-15*

Combination carrier	20,000 DWT and above	20
	4,000-20,000 DWT	0-20*
Ro-ro cargo ship (vehicle carrier)	10,000 DWT and above	15
Ro-ro cargo ship	2,000 DWT and above	5
	1,000-2,000 DWT	0-5*
Ro-ro passenger ship	1,000 DWT and above	5
	250-1,000 DWT	0-5*
LNG carrier	10,000 DWT and above	30
Cruise passenger ship having non-conventional propulsion	85,000 GT and above	30
	25,000-85,000 GT	0-30*
***Reduction factor to be linearly interpolated between the two values dependent upon size.**		

The reference line values vary for vessels of various sizes and types, and shall be calculated as follows:

$$Reference\ line\ value\ =\ a * b^{-c}$$

where a, b and c are the parameters given in Table 2 as stated by [27] .

Table 2: Parameters for the reference line [27] .

Ship type defined in regulation 2	a	b	c
2.2.5 Bulk carrier	961.79	DWT of the ship where DWT<279,000 279,000 where DWT > 279,000	0.477
2.2.7 Combination carrier	1,219.00	DWT of the ship	0.488
2.2.9 Containership	174.22	DWT of the ship	0.201
2.2.11 Cruise passenger ship having non-conventional propulsion	170.84	GT of the ship	0.214
2.2.14 Gas carrier	1,120.00	DWT of the ship	0.456
2.2.15 General cargo ship	107.48	DWT of the ship	0.216
2.2.16 LNG carrier	2,253.7	DWT of the ship	0.474
2.2.22 Refrigerated cargo carrier	227.01	DWT of the ship	0.244
2.2.26 Ro-ro cargo ship	1405.15	DWT of the ship	
	1686.17*	DWT of the ship where DWT<17,000* 17,000 where DWT > 17,000*	0.498
2.2.27 Ro-ro cargo ship (vehicle carrier)	$(DWT/GT)^{-0.7}$. 780.36 where DWT/GT < 0.3 1,812.63 where DWT/GT ≥ 0.3	DWT of the ship	0.471
2.2.28 Ro-ro passenger ship	752.16	DWT of the ship	
	902.59*	DWT of the ship where DWT<10,000* 10,000 where DWT > 10,000*	0.381
2.2.29 Tanker	1,218.80	DWT of the ship	0.488

In accordance with [26], the concept formula of the attained EEXI is as follows:

$$EEXI\ \left(\frac{gco2}{ton * nm}\right) = \frac{CO_2 Conversion\ factor * SFC\ \left(\frac{g}{kW * h}\right) * Engine\ power\ (kW)}{Capacity\ (ton) * EEXI\ Speed\ (knots)}$$

Where SFC the fuel consumption at 75% MCR for the main engine and at 50% MCR for the auxiliary engines.

The EEXI formula is same to the EEDI formula, but some parameters have different definitions. The exact formula of the attained EEXI as well as the guidelines on the method of calculation and the parameters can be found on resolution MEPC 333(76).

The following EEXI guidelines were adopted at the IMO's MEPC 76 in June 2021:

- Guidelines on the method of calculation of the attained EEXI (MEPC.333(76)).
- Guidelines on survey and certification of the EEXI (MEPC.334(76)).
- Guidelines on the shaft / engine power limitation system to comply with the EEXI requirements and use of a power reserve (MEPC.335(76)).

As stated by [26], the EEXI requirements will start from 1st January 2023. The Figure 7 presents the exact timeline from regulation adoption to application.

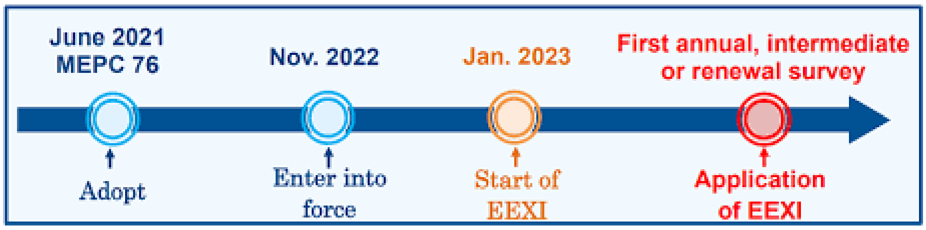


Figure 7: EEXI timeline [26].

The following chart provides a detailed description of the EEXI application process [26], [28].

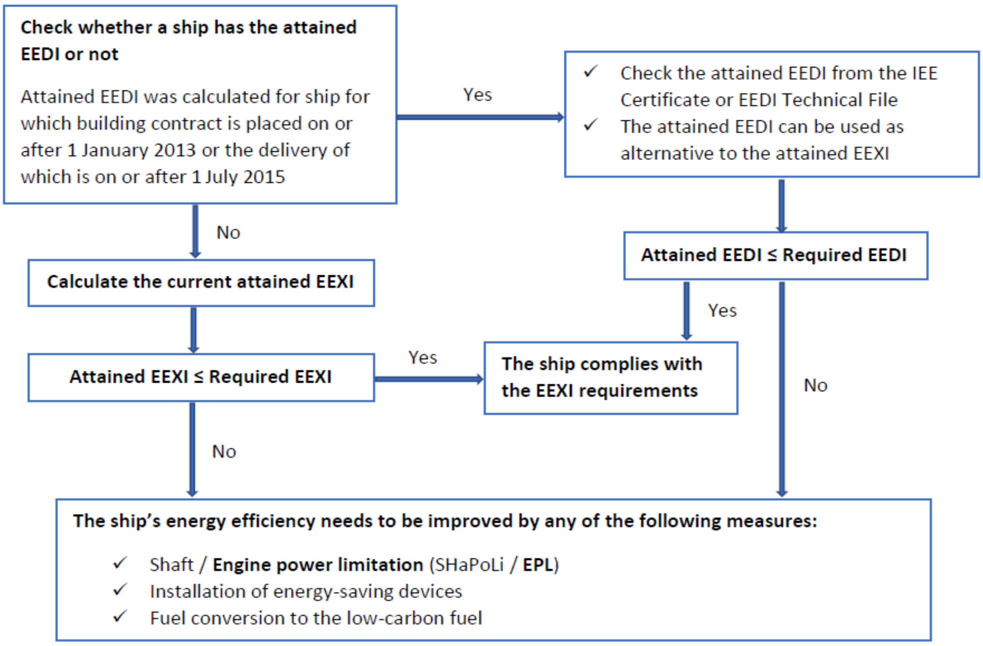


Figure 8: EEXI application procedure [26], [28] .

As stated in [27], the IMO must review the regulation by January 1, 2026, evaluating its effectiveness while taking into account any guidelines the Organization may have developed, and adopt further amendments if necessary.

3.2.5 Carbon Intensity Indicator (CII)

In addition to the EEXI regulation, the MEPC adopted the Carbon Intensity Indicator (CII) measure at its 76th session in June 2021 as a short-term measure to reduce carbon emissions from ships. CII is the operational Carbon Intensity Indicator expressed in grams of CO_2 per cargo carrying capacity and nautical mile and it is a measure of vessel efficiency of CO_2 emitted in transporting cargo or passengers. In contrast to other energy efficiency indexes like the design based EEDI and EEXI, the CII is based solely on an operational approach. The idea behind CII is that the ship will receive an annual rating ranging from A to E based on the CII it has achieved, with the rating thresholds getting tougher each year.

3.2.5.1 Application and reporting period

The CII is applicable to all ships with a gross tonnage (GT) of 5,000 or more, including bulk carriers, gas carriers, tankers, container ships, general cargo ships, refrigerated cargo ships, combination carriers, LNG carriers, vehicle carriers, Ro-Ro cargo vessels, Ro-Ro passenger vessels, and cruise ships. After the end of the calendar year 2023, and each subsequent calendar year, each ship of 5,000 gross tonnage or greater that falls into applicable categories shall calculate the attained annual operational CII over a 12-month period from 1 January to 31 December for the preceding calendar year, using data collected for the Data Collection System and taking into account the guidelines to be developed by the IMO. The ship must report the attained annual operational CII to its Administration, or any entity duly authorized by it, within three months of the end of each calendar year [27] .

The following CIII guidelines were adopted at the IMO's MEPC 76 in June 2021:

1. Guidelines on operational carbon intensity indicators and the calculation methods (CII guidelines, G1).
2. Guidelines on the reference lines for use with operational carbon intensity indicators (CII Reference line guidelines, G2).
3. Guidelines on the operational carbon intensity reduction factors relative to reference lines (CII Reduction factor guidelines, G3).
4. Guidelines on the operational carbon intensity rating of ships (CII Rating Guidelines, G4).

There are two definitions for operational CII metrics, according to [29] .

1. A specific CII calculated based on the actual or estimated mass or volume of the shipment carried on board a ship is generally referred to as demand-based CII.
2. A specific CII, in which calculation the capacity of a ship is taken as proxy of the actual mass or volume of the shipment carried on board, is generally referred to as supply-based CII.

The supply-based CII which uses DWT as the capacity of a ship is referred to as Annual Efficiency Ratio (AER) and the supply-based CII which uses GT as the capacity is referred to cgDIST. Actually, the demand-based CII and EEOI are identical.

3.2.5.2 Attained Carbon Intensity Indicator (CII)

In its most simple form, the attained annual operational CII of individual ship 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 [29] :

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

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:

$$M = FC_j * C_{Fj}$$

Where:

- j is the fuel oil type.
- FC_j is the total mass (in grams) of consumed fuel oil of type j in a year, as reported under IMO Data Collection System.
- C_{Fj} represents the fuel oil mass to CO_2 mass conversion factor for each fuel oil type j, in line with the resolution MEPC.308(73) for the method of calculation of the EEDI. If the fuel oil type is not covered by the guidelines, the conversion factor should be obtained from the fuel oil supplier and supported by documentation.

Table 3: Carbon factors [30].

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 data on actual transport work, supply-based transport work (W_s), which is calculated as the product of a ship's carrying capacity and the distance traveled in a given calendar year as follows [29] ,can be used as a proxy.

$$W_S = C * D_t$$

Where:

- C represents the ship's capacity.
  - For bulk carriers, tankers, container ships, gas carriers, LNG carriers, ro-ro cargo 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.
- D_t represents the total distance travelled (in nautical miles), as reported under IMO DCS.

At the 78th MEPC meeting in June 2022, some of the aforementioned guidelines from the 76th MEPC meeting were revoked and interim guidelines on correction factors and voyage adjustments for CII calculations were introduced. The following formula can be used to calculate the achieved annual operational CII using the voyage adjustments and correction factors.

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

Where:

- $FC_{voyage,j}$ is the mass (in grams) of fuel of 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 one of the following situations:
  1. scenarios specified in regulation 3.1 of MARPOL Annex VI, which may endanger safe navigation of a ship.

2. sailing in ice conditions, which means sailing of an ice-classed ship in a sea area within the ice edge.

If FC_{voyage} 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}) $\cdot FC_{S,j}$ represents the quantity of fuel j removed for STS or shuttle tanker operation, where $FC_{S,j}$= FC_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.
- AF_{Tanker} represents the correction factor to be applied to Shuttle tankers or STS voyages 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 formulas:

$$AF_{Tanker,STS} = 6.1742 \times DWT^{-0.246}$$

$$AF_{Tanker,Shuttle} = 5.6805 \times DWT^{-0.208}$$

When $AF_{Tanker,STS}$ is applied, $FC_{electrical}$, FC_{boiler} ,FC_{others} should not be used and when $AF_{Tanker,Shuttle}$ is applied, $FC_{electrical}$, FC_{boiler} ,FC_{others} and $AF_{Tanker,STS}$ should not be used.

- y_i is a consecutive numbering system starting at y_{2023} = 0, y_{2024} = 1, y_{2025} = 2, etc.
- $FC_{electrical,j}$ is the mass (in grams) of fuel type j, consumed for production of electrical power which is allowed to be deducted from the calculation of the attained CII for the following purposes:

1. Electrical consumption of refrigerated containers (on all ships where they are carried).
2. Electrical consumption of cargo cooling/reliquefaction systems on gas carriers and LNG Carriers.
3. Electrical consumption of discharge pumps on tankers.

The calculation methodology is specified in part A of appendix 1 in MEPC.355 78 guidelines [31].

- $FC_{boiler,j}$ is the mass (in grams) of fuel 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. The calculation methodology for $FC_{Boiler,j}$ is specified in Part B of Appendix 1 in MEPC.355 78 guidelines [31].
- $FC_{others,j}$ is the mass (in grams) of fuel type j, consumed by consumed by standalone engine driven cargo pumps during discharge operations on tankers which may be deducted from the calculation of the attained CII.
- f_i is the capacity correction factor for ice-classed ships as specified in the 2018 Guidelines on the method of calculation of the attained EEDI for new ships (resolution MEPC.308(73) as amended by resolution MEPC.322(74)).

- f_m is the factor for ice-classed ships having IA Super and IA as specified in the 2018 Guidelines on the method of calculation of the attained EEDI for new ships (resolution MEPC.308(73) as amended by resolution MEPC.322(74)).
- f_c represents the cubic capacity correction factors for chemical tankers as specified in paragraph 2.2.12 of the 2018 Guidelines on the method of calculation of the attained EEDI for new ships (resolution MEPC.308(73) as amended by resolution MEPC.322(74)).
- $f_{i,VSE}$ represents the correction factor for ship specific voluntary structural enhancement as specified in paragraph 2.2.11.2 of the 2018 Guidelines on the method of calculation of the attained EEDI for new ships (resolution MEPC.308(73) as amended by resolution MEPC.322(74)), to be applied only to self-unloading bulk carriers.
- $Capacity$ is deadweight or gross tonnes as defined for each specific ship type in the 2022 Guidelines on the Reference Lines for Use with Operational Carbon Intensity Indicators (CII Reference Lines Guidelines, G2) (resolution MEPC.353(78)).
- D_x represents distance travelled (in nautical miles) for voyage periods which may be deducted from CII calculation.

3.2.5.3 Reference lines

According to [32], an operational carbon intensity indicator (CII) reference line is a curve that represents the median attained operational carbon intensity performance of a defined group of ships in 2019 as a function of capacity. Given the limited data for the year 2008 that is available, the operational carbon intensity performance of ship types in the year 2019—which was the first reporting year with verified DCS data reported to IMO—is used as the reference. The following formula is used to calculate the reference line for a specified group of ships.

$$CII_{ref} = a \times Capacity^{-c}$$

The parameters a and c are estimated using median regression fits on the achieved CII and Capacity of individual ships from the IMO DCS in 2019. The following table lists the parameters for determining the ship type-specific reference lines [32]. Figure 9 illustrates the reference lines for some ship types that use DWT as capacity.

Table 4: Parameters for determing the 2019 ship specific reference lines [32].

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)	57,700 GT and above	57,700	3627	0.590
	30,000 GT and above, but less than 57,700 GT	GT	3627	0.590
	Less than 30,000 GT	GT	330	0.329
Ro-ro cargo ship		GT	1967	0.485
Ro-ro passenger ship	Ro-ro passenger ship	GT	2023	0.460
	High-speed craft designed to SOLAS chapter X	GT	4196	0.460
Cruise passenger ship		GT	930	0.383

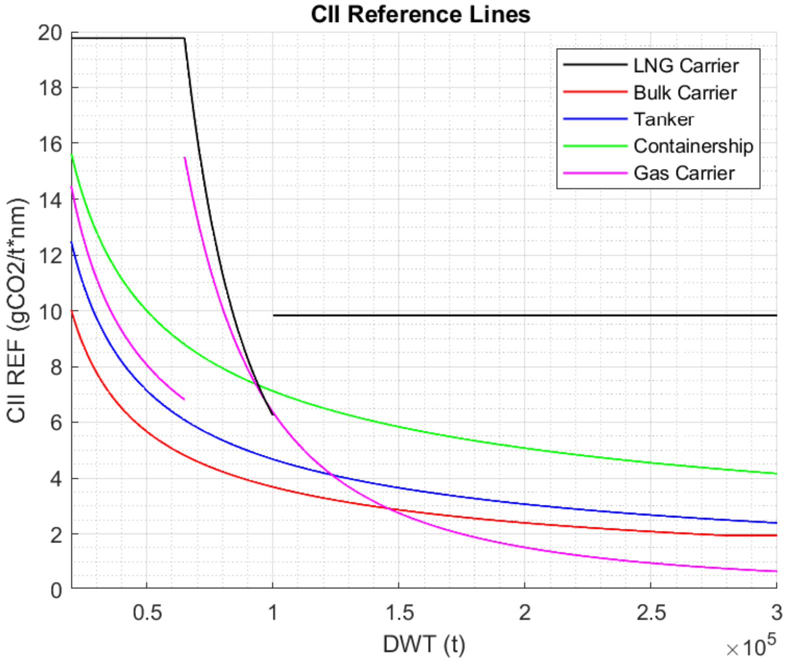


Figure 9: CII reference lines.

3.2.5.4 Required annual operational Carbon Intensity Indicator (CII)

As referred in the regulation 28 of MARPOL Annex VI the required annual operational CII for a ship is calculated as follows:

$$Required\ annual\ operational\ CII = \left(1 - \frac{Z}{100}\right) * CII_R$$

Where CII_R is the reference value in year 2019 as described above. The factor Z is a general reference to the reduction factors for the required CII of ship types from year 2023 to 2030. As stated in [33] , the reduction factors have been set at the appropriate levels to ensure that, when combined with other relevant MARPOL Annex VI requirements, the reduction in CO_2 emissions per transport work of at least 40% from 2008 to 2030 can be achieved as an average across international shipping. The reduction factor Z will be starting from 5% in 2023 and 2% will be added yearly. Z factors of 1%,2%,3% are set for the years of 2020 to 2022, similar as business as usual until the entry into force of the measure. After 2026, Z factors for the years of 2027 to 2030 will be further strengthened and developed taking into account the review of the short-term measure.

Table 5: Reduction factor (Z%) for the CII relative to the 2019 reference line [33].

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

3.2.5.5 Rating

As defined in [34], the operational carbon intensity rating is the process of assigning a ranking label to a ship based on the attained annual operational carbon intensity indicator, indicating a major superior, minor superior, moderate, minor inferior, or inferior performance level. The five grades are A, B, C, D, and E. For the five-grade rating mechanism, superior, lower, upper, and inferior boundaries are defined for each year from 2023 to 2030 in order to make the rating assignment simpler. As a result, a rating can be determined by comparing a ship's achieved annual operational CII with the boundary values. The boundaries are established using the 2019 distribution of CIIs for individual ships. According to the achieved annual operational CIIs, the middle 30% of individual ships across the fleet segment are to be assigned rating C, while the upper 20% and further upper 15% of individuals are to be assigned rating D and E, and the lower 20% and further lower 15% of individuals are to be assigned rating B and A, as shown in Figure 10.

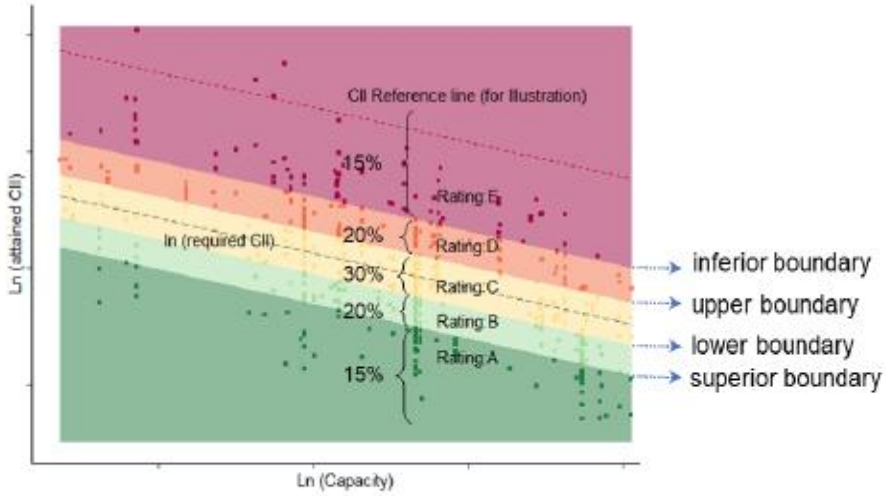


Figure 10: Operational energy efficiency performance rating scale [34].

The performance rating boundaries should be synchronized in accordance with the operational carbon intensity reduction factors over time, although the relative distance between the boundaries should not change. A ship's rating will be determined by the achieved CII and the predetermined rating boundaries. As shown in Figure 11, the boundaries can be established using the necessary annual operational CII along with the vectors, which show the direction and distance they deviate from the necessary value (referred to as dd vectors).

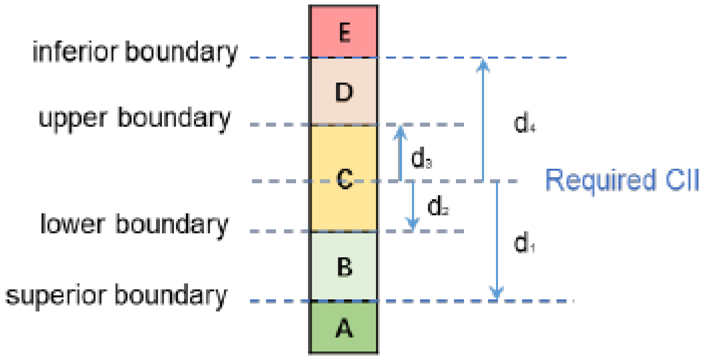


Figure 11: Rating boundaries [34].

Based on the required CII, the four boundaries can be determined as follows through an exponential transformation of each dd vector:

$$\underline{superior\ boundary = exp(d1) * required\ CII}$$

$$\underline{lower\ boundary = exp(d2) * required\ CII}$$

$$\underline{upper\ boundary = exp(d3) * required\ CII}$$

$$\underline{inferior\ boundary = exp(d4) * required\ CII}$$

The estimated dd vectors after exponential transformation for determining the rating boundaries of each ship type are listed in the table below.

Table 6: dd vectors for determining the rating boundaries of ship types [34].

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	1.06	1.19
General cargo ship		DWT	0.83	0.94	1.06	1.14
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	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		GT	0.76	0.89	1.08	1.30
Ro-ro passenger ship		GT	0.76	0.92	1.14	1.30
Cruise passenger ship		GT	0.87	0.95	1.06	1.16

By comparing the attained annual operational CII of a specific ship with the four boundaries, a rating can then be assigned.

3.2.5.6 Corrective actions

A ship that has been rated D for three consecutive years or E must develop a corrective action plan to achieve the required annual operational CII. The SEEMP shall be reviewed, taking into account the guidelines that the IMO will develop, to include the plan of corrective actions accordingly. The updated SEEMP must be submitted to the Administration, or any organization duly authorized by it, for verification no later than one month after reporting the achieved annual operational CII [27].

As stated in [27], the IMO must review the regulation by January 1, 2026, to assess:

1. The effectiveness of this regulation in reducing the carbon intensity of international shipping.
2. The need for reinforced corrective actions or other means of remedy.
3. The need for enhancement of the enforcement mechanism.
4. The need for enhancement of the data collection system.
5. The revision of the Z factor and CII_R values.

3.3 Monitoring of emissions

The need to reduce ship air emissions has resulted in the adoption of data collection regulations that are extremely useful for recording emissions and developing future strategies. Both the IMO and the European Union have developed their own emission monitoring systems. The IMO established the Data Collection System, while the European Union established the EU MRV regulation. Since 2017 (MRV) and 2018 (IMO DCS), the EU MRV and IMO DCS have been mandatory.

3.3.1 EU MRV

The European Union MRV Regulation (Regulation (EU) 2015/757) on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport entered into force on 1 July 2015. The MRV Regulation establishes requirements for the monitoring, reporting, and verification of carbon dioxide (CO_2) emissions from ships arriving, transiting, or departing EU and/or European Economic Area ports regardless of flag. This Regulation applies to ships with a gross tonnage of more than 5000 except warships, naval auxiliaries, fish-catching or fish-processing ships, wooden ships of a primitive build, ships not propelled by mechanical means, and government ships used for non-commercial purposes [35].

The MRV process consists of six steps, according to [36]. The development of the monitoring plan is the first step in the MRV process. Before beginning monitoring and reporting, companies must complete a monitoring plan explaining how they intend to monitor the relevant parameters required by the EU MRV Regulation. For the purpose of monitoring CO_2 emissions, companies have four options:

a) Bunker Fuel Delivery Note (BDN) and periodic stocktakes of fuel tanks.
b) Bunker fuel tank monitoring on board.
c) Flow meters for applicable combustion processes.
d) Direct CO_2 emissions measurements.

All monitoring plans must be evaluated by an accredited verifier. The second step of the MRV process consists of the monitoring and reporting of the relevant parameters. The data collected by the monitoring activity is reported on an annual basis. While the ship is at sea as well as when it is berthed, CO_2 emissions must be monitored and reported, along with other necessary data. Additionally, companies have the option to voluntarily submit data to make it easier to analyze their CO_2 emissions and energy efficiency indicators. The accuracy and completeness of the monitored and reported data are ultimately the responsibility of shipping companies. The monitoring data must be recorded, gathered, analyzed, and documented, including assumptions, references, emission factors, and activity data. This needs to be done in a transparent way that enables the verifier to repeat its analysis of the CO_2 emissions. The following key parameters must be monitored [35]:

- On a per voyage basis.
  - Port of departure and port of arrival including the date and hour of departure and arrival.
  - Amount and emission factor for each type of fuel consumed in total.
  - CO_2 emitted.
  - Distance travelled.
  - Time spent at sea.
  - Cargo carried.
  - Transport work.

- On an annual basis.
  - Amount and emission factor for each type of fuel consumed in total.
  - Total aggregated CO_2 emitted within the scope of this regulation.
  - Aggregated CO_2 emissions from all voyages between EU/EEA ports.
  - Aggregated CO_2 emissions from all voyages which departed from EU/EEA port.
  - Aggregated CO_2 emissions from all voyages to EU/EEA port.
  - CO_2 emissions which occurred within EU/EEA ports at berth.
  - Total distance travelled.

- Total time spent at sea.
- Total transport work.
- Average energy efficiency.

Companies must prepare an emission report in THETIS-MRV based on their monitoring activities in the third step of the MRV process. The THETIS-MRV system, created by European Maritime Safety Agency, enables companies in charge of operating ships in EU ports to report their CO_2 emissions in accordance with MRV regulation. All relevant parties covered by the Regulation can fulfill their monitoring and reporting obligations in a centralized and standardized manner through this web-based application [37] . In the fourth step of the MRV process, accredited independent verifiers must verify the emission reports submitted by companies by evaluating the accuracy, dependability, and credibility of the provided data and information in accordance with the procedure defined in the legislation. Verifiers issue a verification report classifying an emission report as satisfactory if it is free of errors and omissions and if it complies with all regulatory obligations. Companies must have their emission report verified as satisfactory in THETIS-MRV by 30 April of each year beginning in 2019 and submit it to the Commission and their flag State. If the emissions report satisfies the requirements of the MRV Regulation, the verifier issues a document of compliance and informs the Commission and the flag State in the fifth step of the process. The document of compliance must be carried on board by June 30 and is valid for 18 months after the end of the reporting period. Finally, according to the regulation, the Commission is required to publish CO_2 emissions and other relevant data by the 30th of June each year. The data is available at the individual ship level and is aggregated on an annual basis. This information is available in the public section of the THETIS-MRV website as a searchable database or as a downloadable data sheet [36] .

Figure 12: The different steps of the MRV process [36].

The following figure illustrates a representation of the EU MRV annual timeline as provided by [38] .

Figure 13: EU MRV annual timeline [38].

3.3.2 IMO Data Collection System (DCS)

A mandatory Fuel Oil Data Collection System (DCS) was adopted by the International Maritime Organization (IMO) for international shipping, requiring ships of 5,000 gross tons or more to begin collecting and reporting data to an IMO database from 2019. By resolution MEPC.278(70), IMO adopted mandatory MARPOL Annex VI requirements for ships to record and report their fuel oil consumption in October 2016. These amendments came into force on 1 March 2018. Ships of 5000 GT and above are required to submit annual reports to their administration on fuel consumption, distance traveled, and hours underway, in accordance with the methodology outlined in Part II of the Ship Energy Efficiency Monitoring Plan (SEEMP). Every ship of 5000 GT or above must prepare a fuel oil data report after the monitoring period ends using a standardized data reporting format provided by the International Maritime Organization (IMO). As noted in [39], the following elements must be included in the fuel oil data report:

- 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.

The aggregated data is reported to the flag State, which then issues a Statement of Compliance to the ship after concluding that the data has been reported in accordance with the requirements. This information must then be transferred by flag states to an IMO Ship Fuel Oil Consumption Database. Fuel oil consumption data can only be submitted by the Administration, or an organization authorized by the Administration to submit data on their behalf [40]. The following figure illustrates a representation of the IMO DCS annual timeline as provided by [38].

Figure 14: IMO DCS annual timeline [38].

3.3.3 Comparison of EU MRV and IMO DCS

Despite basic common principles such as the 5000 GT value, the common monitoring period of 12 months, the goal of reducing air pollution from greenhouse gases, and the required monitoring method, the IMO and EU systems differ significantly in many aspects. For example, the IMO DCS requires reporting of ships' fuel consumption data, whereas the EU MRV requires reporting of CO_2 emissions, cargo weight, and energy efficiency [41]. The following table, as noted in [41], [42], lists the crucial differences between the two systems in comparison to one another.

Table 7: EU MRV and IMO DCS comparison [41], [42].

	EU MRV	**IMO DCS**
Entry into force	1st July 2015	1st March 2018
Scope	Ships 5000 GT or above Voyages to/from EEA ports of call	Ships 5000 GT or above international voyages
1st monitoring period	2018	2019
Procedures	Monitoring Plan (37 sections)	Data Collection Plan (SEEMP Part II) (9 sections)
Compliance (procedures)	Assessment Report (no need to be on-board)	Confirmation of Compliance (must be on-board)
Reporting	-Fuel consumption (port/sea) -Carbon emissions -Transport work (actual cargo carried) -Distance sailed -Time at sea excluding anchorage	-Total fuel consumption -Distance travelled -Hours underway -Design deadweight used as a proxy
Verification	Independently accredited verifiers (ISO 14064)	Flag administrations or Authorized Organizations
Compliance (reporting)	Document of compliance (June 2019)	Statement of Compliance (May 2020)
Publication/ Disclosure	Annual reporting data including the individual ship information made publicly available	Anonymized data will be made available to IMO member states
A centralized database of fuel consumption	THETIS, MRV operated by EMSA.	IMO management Database of Fuel Consumption, (GISIS)
Data range for monitoring	Per voyage	Not specified
Data on cargo carried	The actual amount of cargo	Deadweight (design)

3.4 Upcoming regulations

The European Commission launched its Fit for 55 package of proposals on July 14, 2021, with the goal of reducing the EU's total GHG emissions by at least 55% by 2030 compared to 1990 levels and achieving climate neutrality by 2050. Shipping will be subject to new and stricter EU regulations as a result. The two most important proposals of the "fit for 55" package, the EU ETS, and the Fuel Eu regulation, are briefly described in this section of the chapter, while the remaining proposals related to shipping are mentioned in the chapter's introduction.

3.4.1 EU Emissions Trading System

As stated in [15] , the Commission is proposing to expand the scope of the EU's Emissions Trading System to cover CO_2 emissions from large ships, above 5000 gross tonnage, regardless of the flag they fly, in order to ensure that the maritime transport sector contributes to the EU's increased climate ambition. The extension will cover the below emissions from ships.

- 100% of CO_2 emissions for voyages between EU ports.
- 100% of CO_2 emissions at berth in a port under the jurisdiction of a Member State.
- 50% of CO_2 emissions for extra – EU voyages (starting or ending at EU ports).

The inclusion of EU ETS would be implemented through a phase-in period, during which the amount of emissions to surrender will gradually increase to reach 100% by the reported period 2026, in order to ensure a smooth transition. Shipping companies must surrender allowances in accordance with the schedule below [43].

- 20% of verified emissions reported for 2023.
- 45% of verified emissions reported for 2024.
- 70% of verified emissions reported for 2025.
- 100% of verified emissions reported for 2026 and each year thereafter.

3.4.2 Fuel EU regulation

The FuelEU Maritime regulation, which focuses on encouraging the EU maritime sector toward decarbonization along with four other measures, is one of the recommendations included in the "Fit for 55" package of legislative proposals. According to [44], this new regulation imposing life cycle GHG footprint requirements on the energy used on board ships will go into effect in 2025. In addition to CO_2, it will also cover methane and nitrous oxide from a well-to-wake perspective and will be applicable to the same ships as those covered by the EU MRV regulation. The GHG intensity of energy used, in grams of CO_2 equivalent per MJ, must be reduced by 2% in 2025 compared to 2020, increasing to 75% by 2050. Additionally, in order to promote consistent use of renewable and low-carbon fuels and alternative energy sources throughout the Union, the Regulation establishes uniform rules imposing the requirement to use on-shore power supply or zero-emission technology in ports under the jurisdiction of a Member State [45]. Similar to the ETS, non-compliance can result in penalties and a ban from EU waters [44].

4. LNC Carriers characteristics

4.1 LNG as cargo

4.1.1 Features of LNG

Liquefied natural gas (LNG) is natural gas that has been stored and transported in the form of a cryogenic liquid. A cryogenic liquid is a gas that has been intensely cooled below its boiling point. LNG takes up about 1/600th of the volume of natural gas in its gaseous state. Liquefied natural gas is a liquid made up of a mixture of light hydrocarbons, primarily methane (CH_4, 85–98% by volume), with minor amounts of ethane (C_2H_6), propane (C_3H_8), higher hydrocarbons (C4+), and nitrogen as an inert substance. The characteristics of the natural gas source and the treatment of gas at the liquefaction facility, namely the pre-liquefaction and liquefaction processes, determine the precise composition of LNG [46]. LNG is lighter than water, odorless, colorless, non-toxic, and non-corrosive. Some typical thermophysical properties of LNG are presented in Table 8.

Table 8: Thermophysical properties of LNG [46].

Parameter	Value
Boiling point	-162 °C
Molecular weight	16-19 g/mol
Density	425-485 kg/m^3
Specific heat capacity	2,2-3,7 kJ/kg/°C
Viscosity	0,11-0,18 mPa*s
Higher heat value	38-44 MJ/m^3

Several factors, including density, heat value, methane, or nitrogen content, etc., can be used to classify LNG. Density is the factor that is most frequently used to classify it, which is highly dependent on temperature, pressure, and composition. Table 9 illustrates the typical composition and density of three typical LNG qualities and classifies them as heavy, medium, and light LNG according to [47].

Table 9: Classification of LNG by density [47].

Composition (%)	LNG Light	LNG Medium	LNG Heavy
Methane	98.00	92.00	87.00
Ethane	1.40	6.00	9.50
Propane	0.40	1.00	2.50
Butane	0.1	0.00	0.50
Nitrogen	0.10	1.00	0.50
Density (kg/m^3)	427.74	445.69	464.83

As a result, the exact composition of each cargo of an LNG carrier is dependent on a variety of factors and can differ.

4.1.2 Boil Off Gas

As mentioned above, LNG carriers are designed to carry their cargo at a temperature below its boiling point. Even though the insulation in the tanks is intended to limit the entry of outside heat, even a small amount of it will cause a slight evaporation of the cargo, known as boil-off gas (BOG). So, due to heat leakage into LNG and its cryogenic nature, LNG continuously evaporates during storage, shipping, and loading/unloading modes. The design and operational parameters of a ship's cargo tanks determine the amount of BOG. The pressure in the LNG operating tank rises as BOG in the ship's tanks rises. BOG should be continuously removed to keep the operating tank pressure within the safe range.

The BOG can be reliquefied, burned in a combustion unit, or burned as fuel depending on the vessel's characteristics. It is used as a fuel in the propulsion system of vessels without a reliquefaction plant, and any excess is burned in the gas combustion unit (GCU) or in the boilers, depending on the system in use [48]. On those ships that do have a reliquefaction plant, the produced BOG is reliquefied, returning it to the interior of the cargo spaces in a liquid state [48]. The rates of evaporation of more volatile components, such as nitrogen and methane, are higher than those of heavier components, such as ethane, propane, and other higher hydrocarbons, because the boiling points of different components of LNG widely vary, ranging from -196°C to +36°C [47]. Therefore, throughout the voyage, the BOG quantity and quality (composition and heating value) change [49].

BOG is produced throughout an LNG carrier's operation, particularly during the loading, shipping, and unloading modes. However, the majority of BOG is generated during the LNG carrier's voyage. The following are the primary reasons:

- The entry of heat into cargo tanks as a result of the temperature difference between the environment and the cargo tanks [46].
- Due to the periodic spraying of LNG in the upper part of the tank used to cool a ship's tanks during ballast voyages. During ballast voyages, cooling of a ship's tanks is used to lower the rising temperatures in cargo tanks. The cooling is accomplished by intermittently pumping LNG from the tank's bottom into the top part of the tank. BOG is produced when LNG comes into contact with the warm sides of the tank and evaporates [46].
- Because of the sloshing of cargo in partially filled tanks caused by the action of waves, friction on the inner wall of the tank creates an additional thermal effect [46]. As a result, the amount of BOG produced during bad weather is greatly increased.

The main cause of BOG generation on ships is heat ingress. The amount of evaporated cargo in LNG maritime transportation is typically expressed as a loss as a percentage of the total volume of liquid cargo during a single day [46], known as the Boil-Off Rate (BOR). The following equation can be used to determine this value.

$$BOR = \frac{V_{BOG} * 24}{V_{LNG}} = \frac{Q * 3600 * 24}{\Delta H * V_{LNG} * \rho} * 100$$

Where,

- BOR is in %/day
- V_{BOG} : volume of BOG in m^3/s
- V_{LNG}: the volume of LNG in cargo tanks in m^3
- ρ : the density of LNG kg/m^3
- Q : the heat exchange in W
- ΔH : the latent heat of vaporization in J/kg

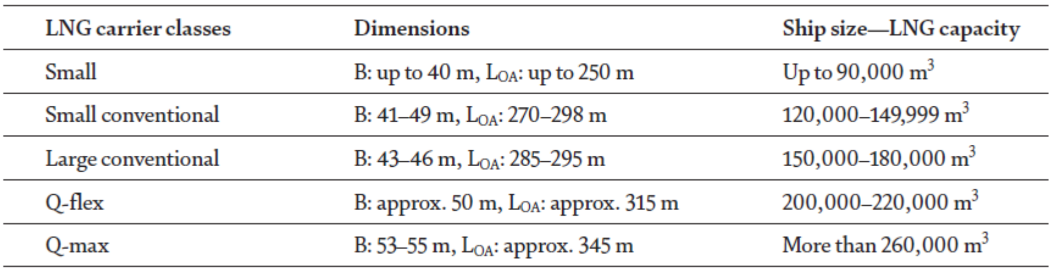
For different types of tanks, which will be examined in more detail in the next section of the chapter, typical nominal BOR values range from 0.1 % to 0.15 % for laden voyage. However, due to various operation conditions and parameters, the real BOR during a voyage constantly varies from its average nominal value.

4.2 Size

A ship's deadweight is its carrying capacity in metric tons (1,000 kg), which includes the weight of bunkers and other supplies required for propulsion. The maximum possible deadweight tonnage of a tanker, for example, is typically used to determine tanker size. However, the size of an LNG carrier is typically not determined by its deadweight tonnage but rather by its obtainable volumetric capacity of liquid natural gas in m^3.

The three main categories of merchant ships—tankers, bulk carriers, and container ships—are divided into various main groups or classes, such as handymax, panamax, etc., depending on the size and specifics of the ship. For LNG carriers, there isn't a similar general division into classes or groups based solely on dimensions. The reason is that, since 1962, LNG carriers have typically been built in large numbers of comparable vessels for specific uses, routes, and LNG terminals (with the resulting limitations to the ship dimensions) [50]. The table below shows a typical size categorization.

Table 10: LNG carriers classes [51].



LNG carrier classes	Dimensions	Ship size—LNG capacity
Small	B: up to 40 m, L_{OA}: up to 250 m	Up to 90,000 m^3
Small conventional	B: 41–49 m, L_{OA}: 270–298 m	120,000–149,999 m^3
Large conventional	B: 43–46 m, L_{OA}: 285–295 m	150,000–180,000 m^3
Q-flex	B: approx. 50 m, L_{OA}: approx. 315 m	200,000–220,000 m^3
Q-max	B: 53–55 m, L_{OA}: approx. 345 m	More than 260,000 m^3

Some examples of special LNG carriers sub-classes are the Med-max (Mediterranean maximum size) with a capacity of about 75,000 m^3 and the Atlantic-max (Atlantic sea maximum size) with a capacity of about 165,000 m^3.

The largest available capacities are provided by the two LNG carriers that make up the Qatari Q-Class (45 ships), the Q-Flex (210,000-217,000 m^3) and Q-Max (261,700-266,000 m^3). The first ships were delivered in 2007. The dimensions of a Q-max LNG carrier are the largest that can approach Qatar's loading and unloading facilities (Ras Laffan terminal).

The conventional class contains most of the LNG carriers that have been built, with the large conventional class being the dominant size in recent years. According to [52], the average size of the conventional carrier newbuilds that were delivered in 2018 was 171,500 m^3, and none of the 48 vessels had a capacity that was less than 150,200 m^3.

Ships with smaller sizes that do not belong in the above categories are not involved in large trades and are mainly used for coastal trades and bunkering purposes.

4.3 Cargo Containment System

The cargo containment system is a key feature that fully defines a liquified natural gas carrier. Natural Gas has strict requirements for liquefied transportation. As a result, special systems have been developed and tested in extreme conditions so that they can be used commercially safely. The condition of an LNG transport vessel is primarily determined by the tank system and has a direct impact on the vessel's efficiency and profitability The specifications that must be met by an LNG storage system are known, but it is crucial to closely monitor the cargo handling and loading. The basic requirements for LNG carriers and cargo containment systems are listed below.

- Cargo storage at 162 °C (LNG boiling point) at atmospheric pressure or slightly higher.
- Sufficient load insulation to reduce boil-off gas.
- Exhaust gas management system to prevent release into the atmosphere.
- Resistance to dynamic load effects due to free surfaces at any filling level in the tank at sea-going condition (Sloshing loads).
- Resistance to extreme thermal contraction and expansion.
- Resistance to load leakage

Integral tanks and independent tanks are the two main categories for cargo tanks according to the International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC code). Additionally, the independent tanks can be further divided into three subcategories known as Type A, Type B, and Type C, and the integral tanks are primarily of the membrane type.

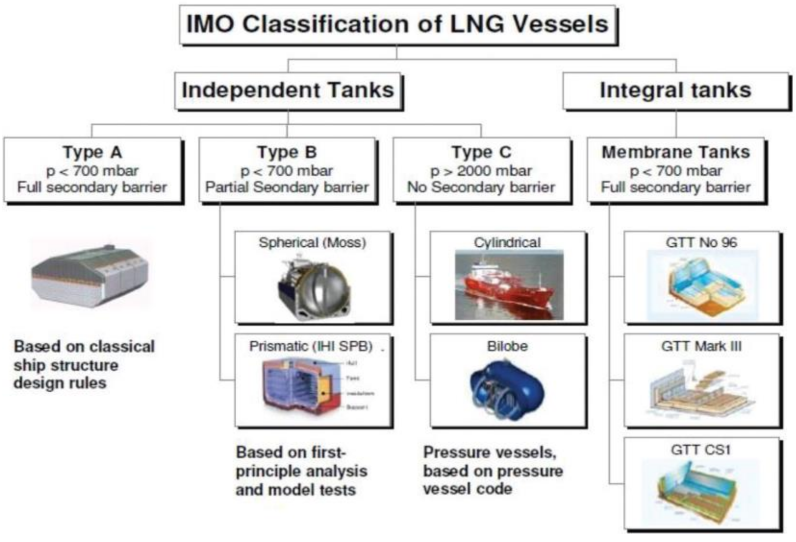


Figure 15: Categorization of containment systems in LNG Carriers [51].

Type B and membrane tanks are mainly used on large scale LNG Carriers. The Moss Rosenberg design and the membrane-tank system were the first two designs developed for LNG containment on ships.

The Moss Rosenberg system, which has been in use for nearly 50 years, was introduced in 1973 and is well known for its independent spherical tanks that often have the top half exposed on LNG carriers. The several independently supported spherical tanks are made of aluminum, each of which holds LNG that is insulated by polyurethane foam that has been flushed with nitrogen. The tank's spherical shape enhances durability and eliminates the need for a full secondary barrier by enabling accurate stress and fatigue prediction. Additionally, independent self-supporting spherical tanks enable partial loading during the voyage. However, the Moss Rosenberg system requires a heavier containment unit because of its spherical shape, which makes it less space-efficient than membrane storage [53].

One of the most significant disadvantages of these systems over membrane systems is their reduced capacity. As a result, improved space utilization and increased overall capacity are emphasized in the new designs of this type. The Sayaringo and Sayendo designs are newer designs that are improved versions of the Moss type system produced by Mitsubishi. The main characteristics of these systems are that all tanks are covered by a lightweight prismatic hull integrated with the main hull and that the tanks are stretched spherical rather than perfectly spherical. This structure provides numerous benefits to the ship's overall performance, including a more aerodynamic shape and increased total capacity.

The membrane-tank system is supported solely by the insulated hull structure and uses thin, flexible membranes. Specifically, the construction of the membrane containment tanks consists of a thin layer of metal (the primary barrier), insulation, a secondary membrane barrier, and additional insulation. According to [54], the following are some of the main characteristics of this system.

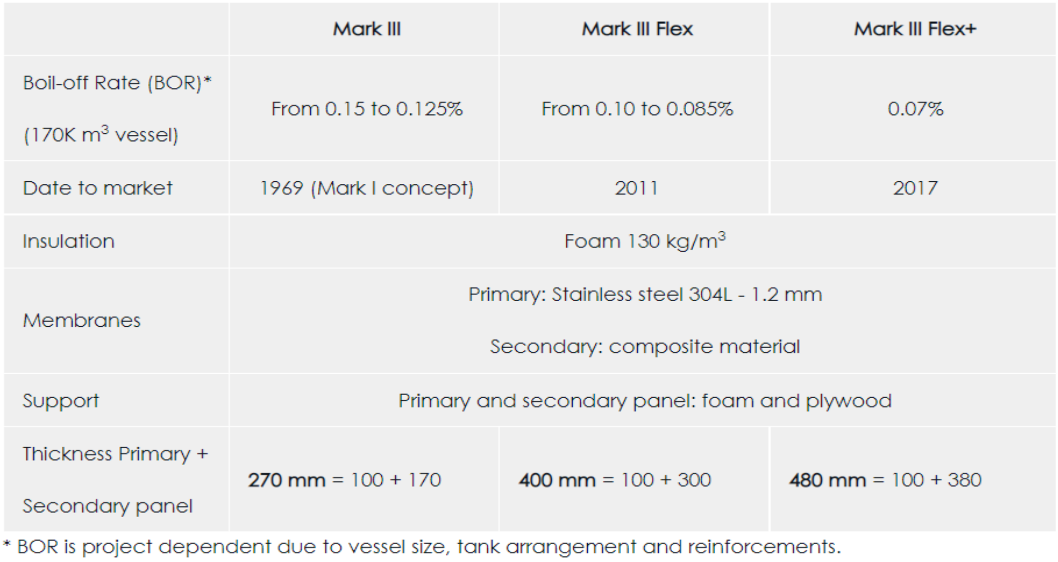
i. Non self-supporting.
ii. The load imposed by the cargo is carried by the ship's structure.
iii. Sloshing loads are a significant matter. Sloshing analysis and permissible filling limits are necessary.
iv. LNG transportation requires a full secondary barrier.
v. Thermal and other expansion and contraction of the membrane are compensated for without stressing the membrane.

The French companies Gaztransport and Technigaz, subsequently merged to create Gaztransport & Technigaz (GTT), designed the most popular membrane-tank systems. The two dominant membrane type LNG containment systems are the Mark III and NO96 [53].

Mark III

The Mark III membrane system is directly supported by the hull structure of the ship. It is made up of a primary corrugated stainless steel membrane that is above the prefabricated insulation panels and a complete secondary membrane made of composite material [55]. Design evolutions with lower Boil-Off-Rates that improve thermal and structural efficiency, such as the Mark III Flex and Mark III Flex+, have entered the market.

Table 11: Mark III design [55].



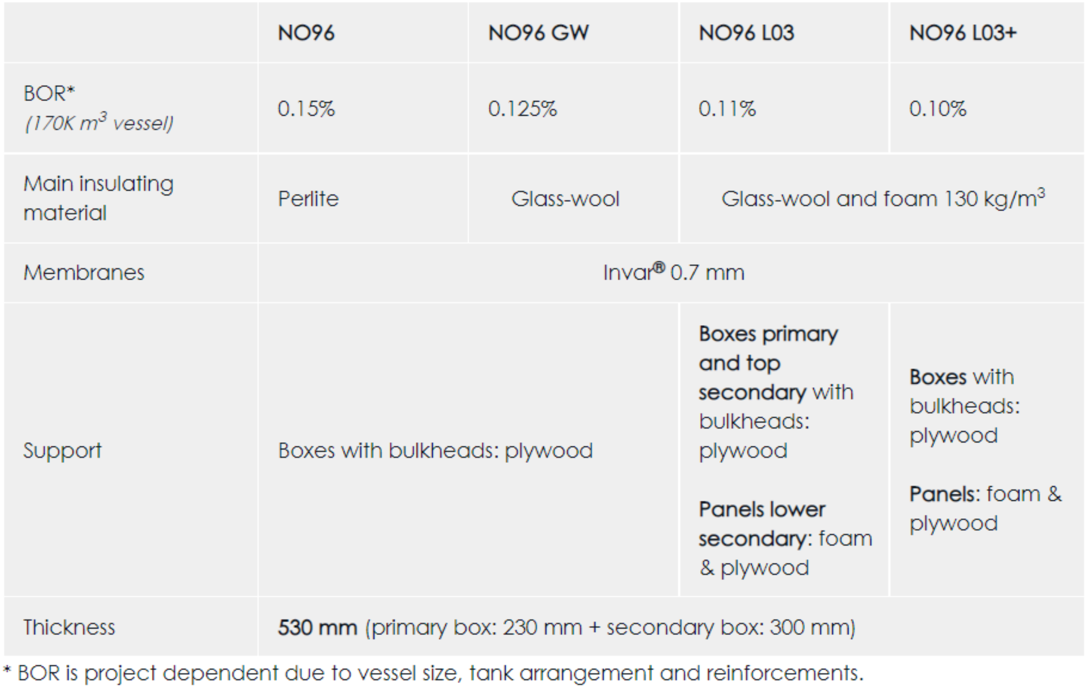
	Mark III	Mark III Flex	Mark III Flex+
Boil-off Rate (BOR)* (170K m^3 vessel)	From 0.15 to 0.125%	From 0.10 to 0.085%	0.07%
Date to market	1969 (Mark I concept)	2011	2017
Insulation	Foam 130 kg/m^3		
Membranes	Primary: Stainless steel 304L - 1.2 mm Secondary: composite material		
Support	Primary and secondary panel: foam and plywood		
Thickness Primary + Secondary panel	**270 mm** = 100 + 170	**400 mm** = 100 + 300	**480 mm** = 100 + 380

* BOR is project dependent due to vessel size, tank arrangement and reinforcements.

No 96

The primary and secondary membranes are constructed from 0.7mm-thick Invar, a 36 percent nickel-steel alloy. The primary membrane holds the LNG cargo, and the secondary membrane, which is an exact duplicate of the primary, ensures complete redundancy in the event of a leak. The primary and secondary insulation layers evenly support each of the 500mm wide Invar strakes as they are spread out along the tank walls. The insulating material is perlite. In more recent designs, glass-wool in NO96 GW evolution or foam in NO96 L03 have replaced the perlite [56]

Table 12: NO 96 [56].



	NO96	NO96 GW	NO96 L03	NO96 L03+
BOR* *(170K m^3 vessel)*	0.15%	0.125%	0.11%	0.10%
Main insulating material	Perlite	Glass-wool	Glass-wool and foam 130 kg/m^3	
Membranes	Invar® 0.7 mm			
Support	Boxes with bulkheads: plywood		**Boxes primary and top secondary** with bulkheads: plywood **Panels lower secondary**: foam & plywood	**Boxes** with bulkheads: plywood **Panels**: foam & plywood
Thickness	**530 mm** (primary box: 230 mm + secondary box: 300 mm)			

* BOR is project dependent due to vessel size, tank arrangement and reinforcements.

The IHI SPB design, designed by Ishikawajima-Harima Heavy Industries, a third containment type that resembles the membrane tank concept in shape but is another self-supporting and robust tank type (Type B), and the KC1 design, a new membrane system designed by KOGAS, are two other systems with a few applications.

4.4 Propulsion types

4.4.1 Introduction

Before the vessel is built, one of the most important decisions made by the owner is the type of propulsion. Different propulsion types have different building and operational costs, as well as different freight rates, and thus have a strong relationship with the overall feasibility, profitability, and competitiveness of a ship. Influencing factors such as current trends, the environmental footprint that is directly related to the regulatory framework, the technological process, and safety issues all have a significant impact on the choice of the propulsion system.

Liquefied natural gas carriers have special propulsion requirements as they have the ability to use cargo as fuel. This need arises from the nature of LNG, and the so-called Boil Off Gas which we will refer to in detail below. There are several proposed propulsion systems being used and considered by the industry that are closely related to the treatment and consumption of BOG. So, one approach of classifying LNG vessel propulsion systems is based on the purpose of the BOG produced [48].

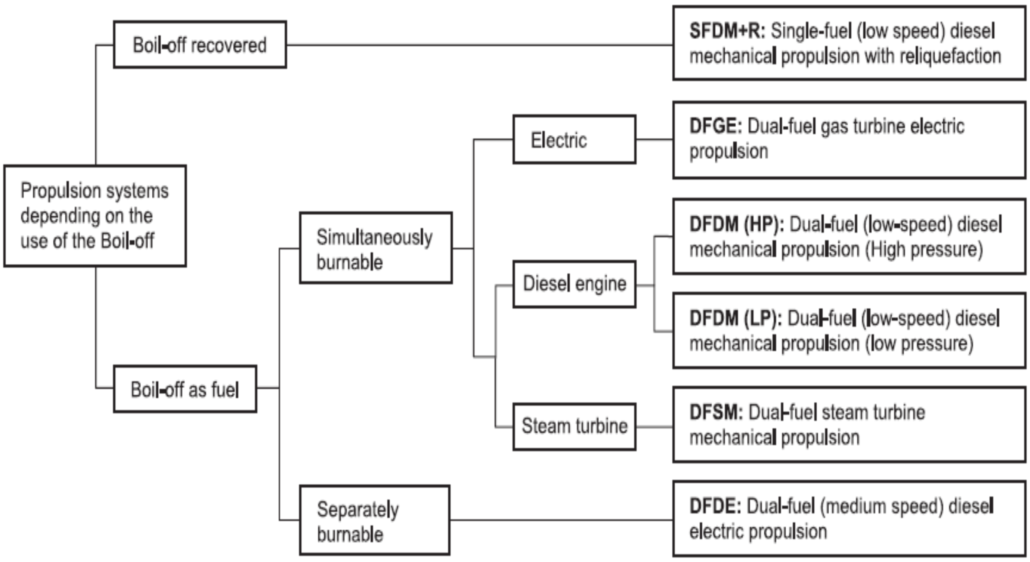


Figure 16: Classification of propulsion systems based on the purpose of the Boil-off [48].

Over the last several decades, the LNG shipping industry has been extremely cautious when choosing a propulsion system, and the steam turbine has essentially been the only option for LNG carriers [51]. These systems are simple, have low maintenance requirements, can consume both LNG that is evaporated in the tanks due to heat exchange with the environment (BOG) and heavy fuel oil. Their main disadvantage, which made it imperative to replace them, is their low thermal efficiency, which translates to high fuel consumption and high production of greenhouse gases and other polluters. Thus, since the beginning of the 21st century and specifically around the year 2003, the industry has been proposing new and more efficient solutions and steam turbines are being replaced by internal combustion engines, which allow for the burning of both heavy fuel oil and BOG from the cargo [48].

The first phase of the shift to internal combustion engines was the electric propulsion system with 4 stroke middle speed dual fuel or tri-fuel diesel electric engines, where the generators can consume natural gas produced by gasification (Boil Off Gas - BOG) and produce electricity that can be used for propulsion with gearboxes and electric motors, or for power consumption in the ship's various requirements.

The newest systems that have appeared on the market from 2010 and after are two-stroke dual-fuel engines, which operate on either high or low fuel gas pressure, depending on the thermodynamic operating cycle on which they are based - Diesel or Otto. Two-stroke dual fuel engines can be more efficient from both DFDEs and steam turbines as the thermal efficiency is very high and close to 50%, while the installation consists of compressors that raise the pressure to the desired value and, usually, a reliquefaction system, where the amount of gas that is not consumed, is partially liquefied, and returns to the tanks, increasing the overall energy and cargo savings of the system. As a result, at the present they have become a popular propulsion system option for LNG carriers [51]. Other types of propulsion have appeared from time to time, such as gas turbine, combined gas and steam turbine (COGES), steam turbine and gas engine (STaGE), which now have limited or no applications, have failed to establish themselves in the market. Another approach of classifying LNG vessel propulsion systems is based on fuel or combination of fuels used.

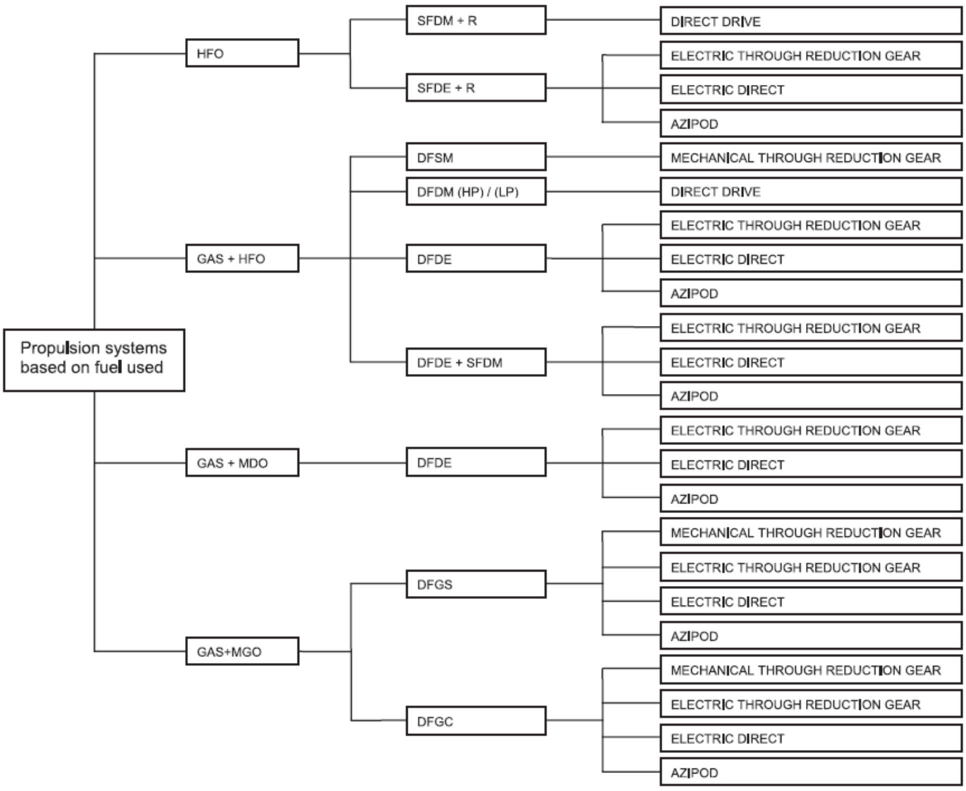


Figure 17: Propulsion systems based on fuel used [57].

Therefore, the selection of a LNG carrier's propulsion system is a complex problem that is mainly influenced by market trends and technological developments as well as the reduction of emissions in the shipping sector.

4.4.2 Steam Turbines

Since 1960 and the beginning of the offshore LNG trade, the steam turbine has proven to be the most popular choice as a propulsion system for LNG carriers, even though diesel engines quickly replaced it in other areas of commercial shipping. The need for a high-power output, proven reliability, low maintenance cost and the ability of the associated boiler plant to burn low-grade fuel as well as cargo boil-off gas prompted the original choice of steam turbines for LNG tankers [58]. The main disadvantage, which also directly contributed to the search for alternative LNG propulsion systems, is the steam turbines' low overall efficiency, which results in high fuel consumption for a given power output, and thus increased carbon dioxide emissions. Nowadays, the conventional form of the steam turbine is not the preferred choice for newbuilding vessels, but it still holds a significant share of the existing fleet.

The steam turbine installations used on liquefied natural gas carriers today are not significantly different from those used in the past. A steam turbine-based propulsion system typically consists of two gas/HFO-fueled boilers with a generating capacity of 80-90 t/h [48] supplying overheated high-pressure steam, typically at a pressure of 60–70 bar at 520°C, to the high- and low-pressure turbines driving a single propeller via a reduction gearbox [51]. Once expanded in both turbines, the steam is condensed in the main condenser and returned to the boiler via pumps after passing through a number of heaters that increase the thermal efficiency of the cycle by utilizing residual heat. Once inside the boiler, the cycle is completed by the corresponding change in state occurring once more through the input of heat, returning to the steam phase [48]. Also, the steam is used to feed turbo generators which provide the necessary electric energy onboard. Additionally, two auxiliary diesel engines with smaller power capacity are installed in order to meet the power demand of the vessel in any given situation. In such a propulsion system the boilers can operate on three modes and burn only heavy fuel oil (HFO)/ marine diesel oil (MDO), only boil off gas (BOG) or both HFO/MDO and BOG at any liquid/gas ratio. Excess BOG in cases where the ship is at anchor or in port and the steam turbine is not operating or operating at low loads is also burned in the boilers producing steam which is sent directly to the condenser to dissipate the energy to the sea. The main benefit that emerges through all this process that is done to control the pressure in the cargo tanks, is the reduction in the necessity for a gas combustion unit (GCU).

Some of the main advantages and disadvantages of the steam turbine propulsion system are analyzed below [51], [57], [58].

Advantages

i. Very easy and reliable method to utilize the BOG. The power requirements of a vessel in service, exceed the energy available from the BOG, enabling complete utilization.
ii. High reliability.
iii. The ability of the associated boiler plant to burn low-grade fuel as well as cargo boil-off gas.
iv. Low maintenance.
v. Low vibration levels.
vi. Very low lubricating oil consumption.
vii. Low percentage of methane slip.

Disadvantages

i. Low efficiency of the turbine plant, approximately 35% at full load and the efficiency becomes lower as the turbine load goes down, with the inevitable high fuel consumption.
ii. The need to continue developing experienced crew, familiar with the operation and maintenance of a steam plant.
iii. Long delivery time for turbines and reduction gears and very limited production versus demand. Hence in case of failure, major delays and 'off-hire' may be countered, unless depot spares of the major components are maintained which increases considerably the ship's capital cost, this becomes more pronounced as the number of sister ships in the fleet is reducing.
iv. The comparative inefficiency of steam plant and hence fuel consumption translates directly to high carbon dioxide emissions due to high exhaust gas volumes.
v. Larger engine room space requirements than for a motor ship, so in the case of Q-Flex/Q-Max ships with twin screw designs, it is very difficult to arrange side by side steam turbine.
vi. The layout offers limited propulsion redundancy.
vii. At low speeds or at anchor, the power generated by continuing to burn the BOG is much lower than the energy available from the BOG. The excess steam is "dumped" into the main condenser resulting in the loss of economic value of the boil off.
viii. Poor maneuvering characteristics.

A typical configuration of the above-described steam turbine-based propulsion system is shown in the next figure.

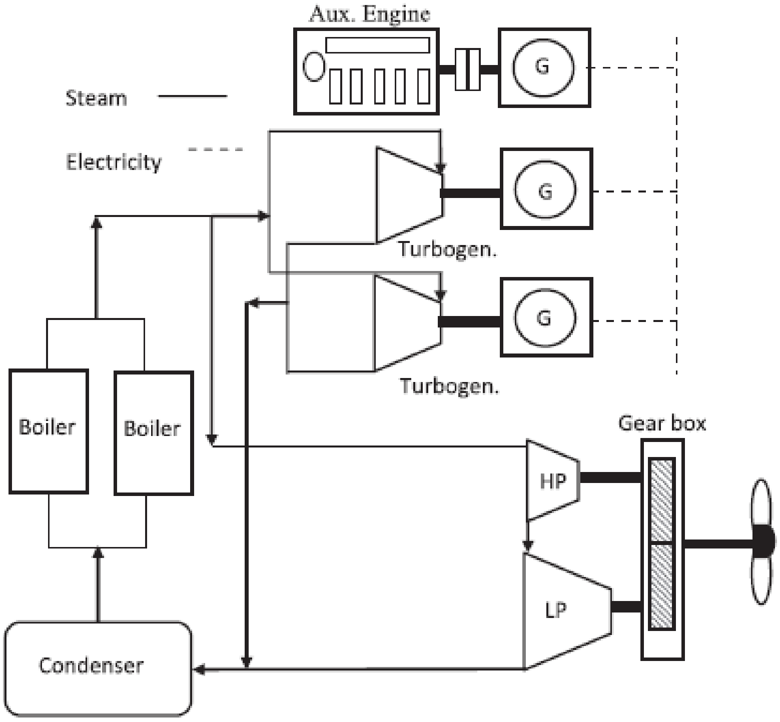


Figure 18: Configuration of a basic system through an ST [48].

The newest and most advanced steam turbine systems known as Ultra Steam Turbines (UST) are able to offer up to 15% increase in efficiency which however remains lower than other solutions such as diesel engines [59]. The following are the primary advantages of a UST system over a traditional ST system [48].

i. Despite the increased number of elements, the space required in the engine room remains constant.
ii. Increase in performance of around 15%.
iii. Highly reliable, comparable to the conventional system.
iv. Low emissions, reduced by around 15% of NOx, SOx and CO_2.

4.4.3 Four stroke medium speed diesel engine (Diesel electric)

The next type of propulsion developed in the early 2000s to replace steam turbines and has a significant market share today is diesel-electric propulsion with four-stroke dual-fuel and tri-fuel engines. The ability of these engines to use gas in conjunction with increased efficiency over steam turbines played a significant role in this shift.

The DFDE propulsion system uses multiple engines of the same type, typically four or five, coupled to electrical generators to provide energy to the entire ship, including propulsion, which is powered by electric motors [51]. A typical configuration of a diesel-electric propulsion system through 4S DF engines is shown in Figure 4 and consists of the equipment listed below.

- Main generator prime movers operating with dual fuel.
- Generators.
- Electric propulsion Motors.
- Frequency Converters.
- Propulsion Transformers.
- High Voltage Switchboards.
- Reduction Gear.
- Propeller.

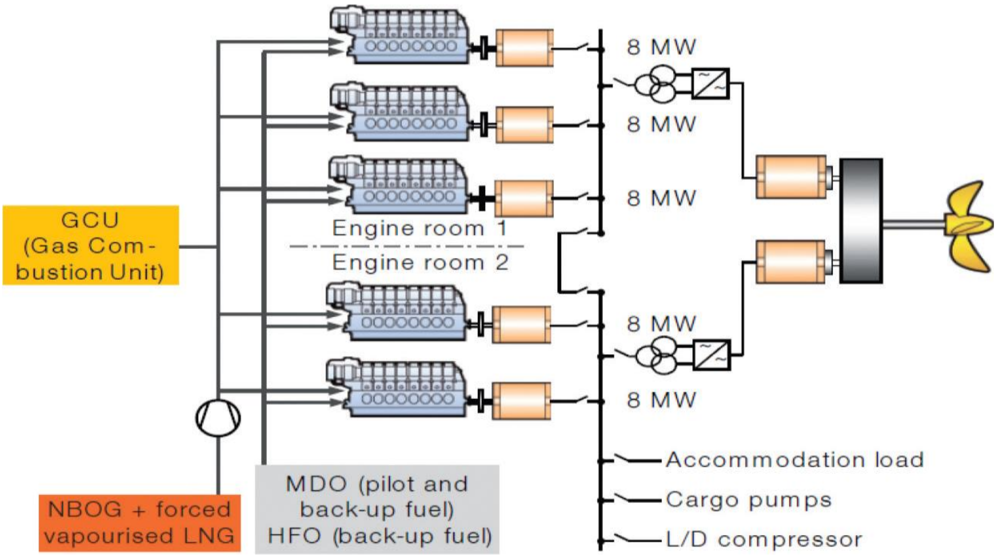
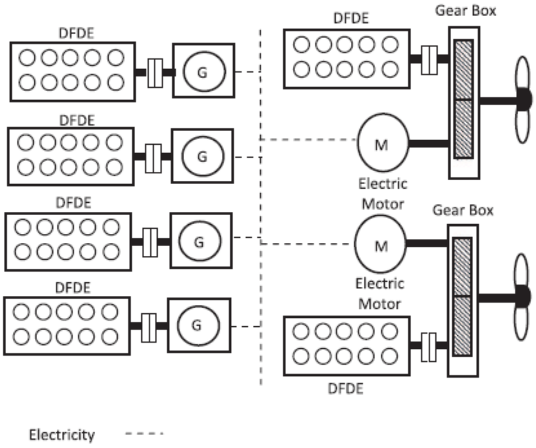


Figure 19: Basic schematic machinery of a four stroke DFDE plant [51].

However, there are several variations on the layout of such a system. The main differences in configuration through DF engines are found in the propulsion. The next figure shows two similar configurations in terms of power generation with four DF engines. The difference is in the arrangement of the propulsion system: the left option is composed of two electric engines and two dual fuel engines coupled to independent reducers while the right option is based entirely on the electric propulsion [48].



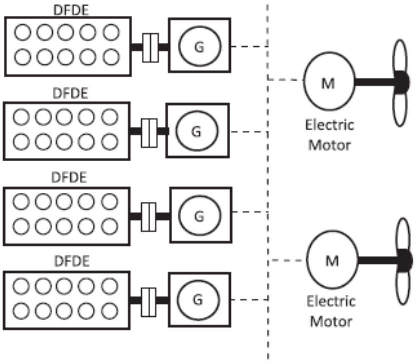


Figure 20: Configurations of diesel-electric propulsion using Dual-Fuel engines (4S) [48].

BOG, MDO, or HFO can be used in dual fuel engines. Depending on the fuel used, dual fuel engines operate in different modes. When using gas as fuel (gas mode), the engine employs the lean Otto cycle concept. In contrast, when MDO or HFO are used, the engine operates at the diesel cycle (diesel mode). In Gas Mode, the BOG is injected through a gas admission valve into the air intake before each cylinder, where it is mixed with the charged air before entering the combustion chamber. The mechanism allows the BOG to be compressed and injected at a relatively low pressure, around 5-6 bar, reducing the complexity of the fuel gas supply system and thus the risks associated with using methane at high pressure in the engine room. When operating on gas, a small amount (approx. 1%) of MDO is also required as a pilot fuel, providing a high-energy ignition source for the main fuel gas charge in the combustion chamber. In diesel mode, the DF-engine operates similarly to any other diesel engine, with a conventional jerk pump fuel injection system. Switching between the two operating modes is possible without disrupting the power supply. While the Gas mode has advantages in terms of fuel cost and exhaust emissions, the Diesel mode performs better in terms of thermal efficiency and dynamic response [51].

The combustion control system is one of the most important characteristics to consider in Dual Fuel engines because, depending on the operating mode, the engine's cycle varies between Otto and Diesel. When the engine is in Diesel mode, combustion is regulated by controlling exhaust temperatures to ensure process optimization. In contrast, regulating the combustion in gas mode is much more complicated because the control is adapted to different variables depending on the engine load [48], [51]. In general, the operating window between misfiring and knocking narrows as engine load and mean effective pressure increase [59]. Therefore, to achieve the optimum results in terms of efficiency, safety and emissions in all conditions, a system that controls the combustion process of each cylinder individually and precisely is required.

Another issue of great importance in dual fuel engines is the handling and preparation of the boil off gas. Dual fuel engines are designed to use methane as fuel, so it is necessary to separate methane from other hydrocarbons in a system called oil mist separator. If there is more BOG available than the power required for the propulsion or electric load, then the excess BOG is sent to the gas combustion unit (GCU). The installed capacity of GCU is typically sized to handle the total BOG capacity on a normal laden journey [51]. The addition of a reliquefaction plant is one possible alternative that could reduce the use of GCU and the BOG inefficient treatment.

Some of the main advantages and disadvantages of the dual fuel diesel electric propulsion system are analyzed below [51], [57], [58].

Advantages

i. Higher efficiency than steam propulsion (but lower compared to slow speed diesel options).
ii. High redundancy of the propulsion system, especially with a twin motor twin skeg configuration.
iii. High flexibility with relation to the fuel available and engine load.
iv. Increased cargo carrying capacity for a given ship size (in comparison to the steam propulsion option).
v. Reduced emissions and compliance with the IMO TIER II gas mission regulations when operating in gas mode.
vi. The propulsion engines meet the demand for auxiliary electric power, so no additional auxiliary generator sets are required.

Disadvantages

i. High investment cost.
ii. High maintenance cost due to more moving parts, higher speed and more cylinders.
iii. Limitations on engine operation due to gas composition.
iv. The handling of gas in the engine room adds complication, but low-pressure gas is supplied into the engine room similarly to the existing steam turbine design.
v. The power requirement is much lower at low speeds or while at anchor than the energy supplied by the BOG. Thus, the economic value of the boil off is lost when the excess BOG is sent to the GCU.
vi. The electric power generation process has a small efficiency loss (about 3-4%).
vii. Higher methane slip than other propulsion types.

4.4.4 Two-stroke slow speed diesel engine with re-liquefaction plant

In the mid-2000s, another propulsion system was introduced to the LNG shipping industry, primarily in tandem with the Qatari megatrain projects [60]. Two-stroke slow speed diesel engines are the most common propulsion plant in almost all sectors of merchant shipping, due to the high efficiency, ability to burn low-quality low-cost fuels, and low maintenance costs. The efficiency of such an installation reaches 50% compared to 30% in a conventional steam turbine installation as shown in the below figure.

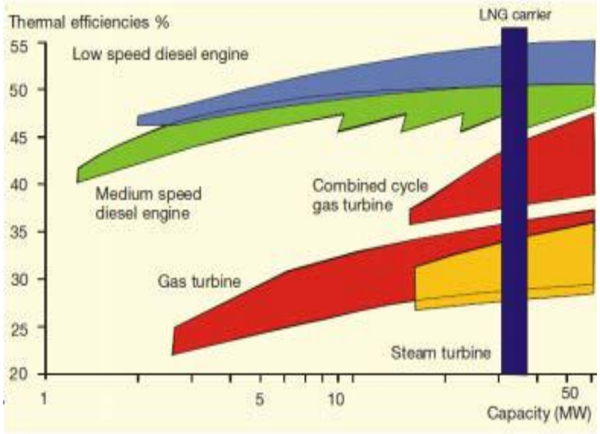


Figure 21: Typical thermal efficiencies of prime movers [50], [58].

However, in the past, the slow speed diesel has not been a viable propulsion option for LNG carriers due to the need to find an acceptable way to dispose of BOG. This situation has changed, though, with the passage of time and technological advancements in onboard reliquefaction plants [57]. Because the two-stroke slow speed engine is a single fuelled (HFO) propulsion plant without the ability to burn BOG, natural BOG from cargo tanks must be liquefied and returned to cargo tanks avoiding any wastage of the LNG being transported. The choice of this propulsion system became particularly attractive on ships with an increased capacity of about 200,000-260,000 m^3 and specifically in Q-flex and Q-max designs. The first vessels with two-stroke slow speed diesel engine with reliquefaction plant were delivered in 2007. The entirety of the Q-Class fleet is equipped with this propulsion type. The long routes and the increased volume of boil off gas in combination with the development of the LNG trade made the installation of the reliquefaction plant a feasible option. Thus, the two-stroke slow speed diesel engines with reliquefaction plant became a practical and appealing option for the ship owners. A typical main machinery configuration of a two-stroke diesel engine powered LNG carrier with reliquefaction plant is illustrated in the next figure.

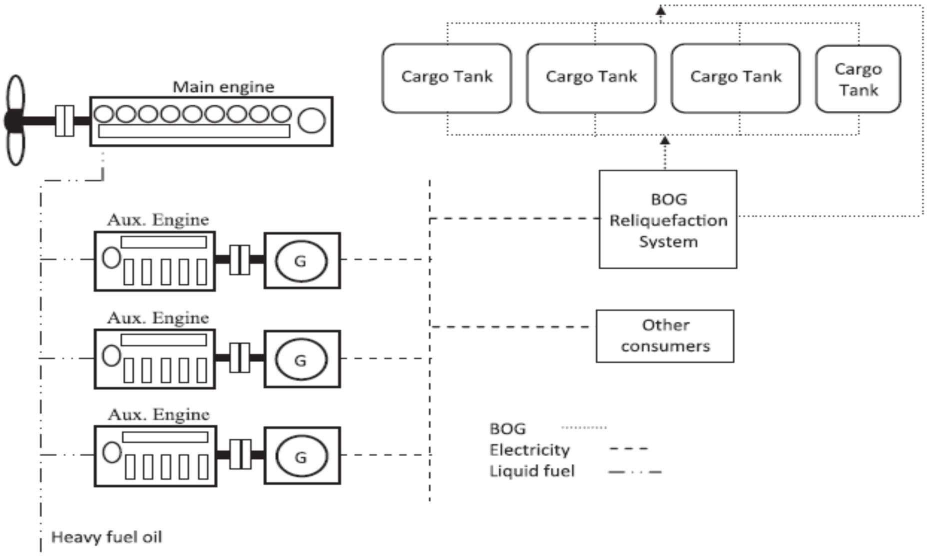


Figure 22: Propulsion system with 2S diesel engine and reliquefaction plant [48].

The above configuration consists of a main engine that drives a fixed pitch propeller while three, four-stroke diesel generators produce the necessary electrical power. The most common version of such a propulsion system, which predominates in Q-Flex and Q-max size, consists of two main engines, each coupled to a single axis line, due to the increasing demands of classification societies for high reliability, redundancy, and maintenance of equipment [48].

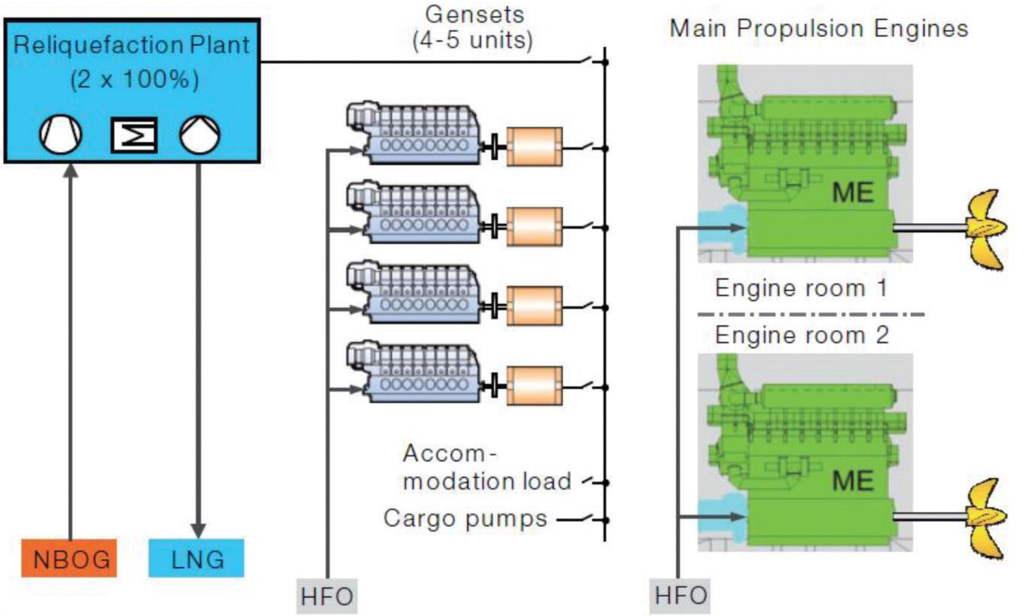


Figure 23: Propulsion system with two 2S main engines and reliquefaction plant [51].

The plant for re-liquefaction is used to re-liquefy the BOG produced in cargo tanks, maintaining proper cargo tank pressure and preventing any loss of the LNG being transported. A gas combustion unit (GCU) is also equipped to burn any generated BOG, which, in the event of a reliquefaction plant failure, would be impossible to treat and could result in significant damage for the ship and the environment.

The BOG reliquefaction principal is based on the closed Brayton cycle using nitrogen as a refrigerant, absorbing the heat from BOG. This cycle involves removing cargo boil off from the LNG tanks, compressing it to 5 bar with a low duty compressor, and then cryogenically cooling it to -160 °C in a heat exchanger. As a result, all of the BOG's hydrocarbons will condense and be able to be converted back into LNG, leaving the nitrogen and other non-condensables in a gaseous state. In a gas-liquid separator, where the LNG is separated and returned to the cargo tanks with the nitrogen-rich non-condensable gases, where the nitrogen-rich non-condensable gases are either discharged to the atmosphere or burned in the GCU [51].

A high electric power supply from auxiliary generators is necessary for a reliquefaction plant's operation, so it seems that in some cases the high efficiency of two stroke slow diesel direct propulsion is counterbalanced by significantly higher electric power consumption when compared to other propulsion options [59].

Below are some of the main advantages and drawbacks of the two-stroke slow speed diesel propulsion with reliquefaction plant [51], [57], [58].

Advantages

i. Low energy consumption and consequently lower operating costs when compared to steam plants due to high overall fuel efficiency of up to 50% (about 60% higher than for the steam plants).
ii. Compared to steam propulsion, less engine room is needed, resulting in more cargo space for a given vessel.
iii. As the BOG is reliquefied, a greater amount of LNG is delivered.
iv. There is full propulsion redundancy and increased safety margins against floods and fires in the engine room in the case of a design using twin diesel engines and separate engine rooms.
v. The reliquefaction plant makes sure that all cargo handling happens on the deck, preventing gas from entering the engine room. Operations in the engine room and for cargo become easier and safer as a result.
vi. The reliquefaction plant and the separation of the engine room from the cargo reduce the limitations on the design and type of fuel for the propulsion system.
vii. Smaller CO_2 emissions compared to a steam ship.

Disadvantages

i. The clean, readily available BOG is not utilized for the vessel's propulsion.
ii. Higher emissions of NOx and SOx compared to alternatives when using LNG instead of HFO.
iii. Less redundancy than the steam systems (in the single engine layout).
iv. Compared to steam turbines, diesel engines require more routine maintenance.
v. The operating costs are increased by lubricant oil consumption, compared to steam turbines.
vi. High consumption of the reliquefaction plant.
vii. The compliance with the new regulations requires fuels with low sulphur content or a technology to clean the exhaust gases (scrubbers).

4.4.5 Two stroke slow speed dual fuel engines

From around 2003 to 2012, the four-stroke dual fuel diesel electric engine option was the dominant propulsion system for the majority of LNGC new buildings while the evolution of two stroke dual fuel engines was slower and appeared in the LNG carriers market in the last decade. Two-stroke slow-speed dual fuel engines have a significant advantage over both steam turbines and DFDEs in terms of propulsive efficiency. MAN Diesel & Turbo and Wartsila are the two major manufacturers of two stroke dual fuel engines adopting separate technical routes. MAN implements the high-pressure concept, whereas Wartsila focuses on the low-pressure concept. The MDT high-pressure plant, known as its Mechanically Operated, Electronically Controlled, Gas Injection (ME-GI) diesel engine, piqued the interest of early LNG ship owners in two-stroke, dual-fuel propulsion while the WinGD low pressure X-DF two-stroke engines have also seen significant development and application in recent years [51].

4.4.5.1 High pressure

Following the trend of using high pressures in the gas injection of its industrial engines, MAN was the first to develop two stroke dual fuel engines for installation on LNG vessels. One of the ME-GI engine's benefits is its fuel flexibility, which is especially useful for owners of LNG carriers. The ideal way to burn the boil-off gas for the diesel working principle is to vary the heat value. The natural boil-off gas has a low heat value and a lot of nitrogen at the beginning of a laden voyage. When forced, boil-off gas can contain both ethane and propane and have a high heating value. Those various fuels can be burned in a two-stroke, high-pressure gas injection engine without the engine's thermal efficiency decreasing [50]. By operating directly off BOG, or fuel oil, if necessary, rather than re-liquefying the gas, ME-GI engines maximize the performance of slow speed engines operating on the diesel cycle.

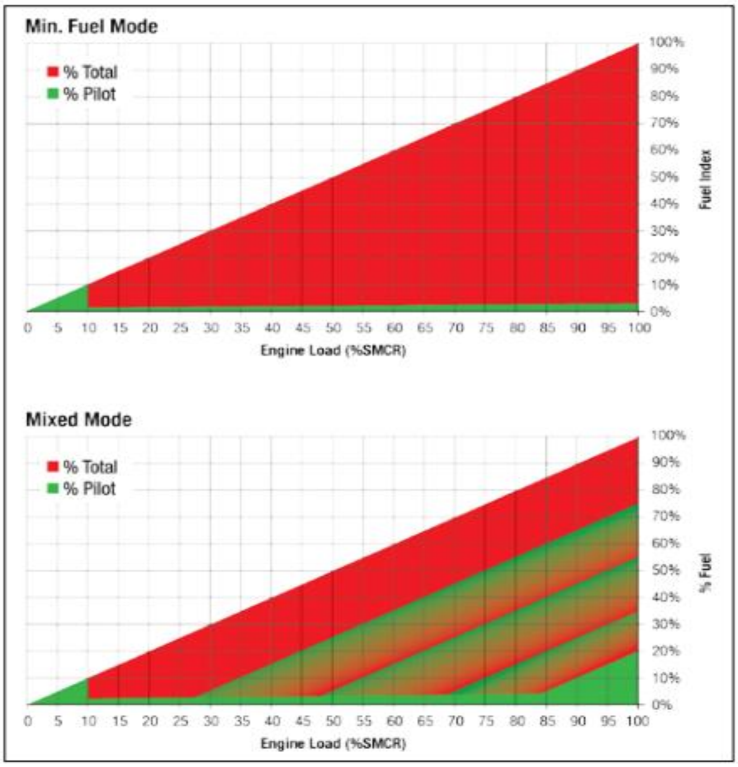


Figure 24: Fuel type modes for the ME-GI engines for LNG Carriers [50].

The main difference between four stroke dual fuel engines is that gas injection is performed directly in the combustion chamber at high pressures (250-300 bar). After the diesel pilot fuel has ignited close to the top dead center, the BOG is pressurized via the fuel gas supply system (FGSS) and then direct injected at high pressure into the cylinder. Due to the fact that the fuel gas is not involved in the compression stroke, this concept is claimed to have significant advantages over the premixed Otto cycle gas process, including the elimination of knocking risk and the ability to burn gas from any source regardless of the methane number. There are two basic system configurations for the ME-GI engines' high pressure FGSS. One system where a piston compressor supplies high-pressure fuel gas to the ME-GI, and one system where an LNG pump and a vaporizer supply high-pressure gas to the ME-GI [51]. An onboard reliquefaction plant can be installed for the treatment of the excess boil off gas. Figure 25 shows the schematic man machinery of ME-GI propulsion plant.

Despite the benefits offered by this system, in terms of emissions, applying EGR (Exhaust Gas Recirculation) or SCR (Selective Catalytic Reduction) is necessary to reduce NOx emissions and meet Tier III of IMO requirements.

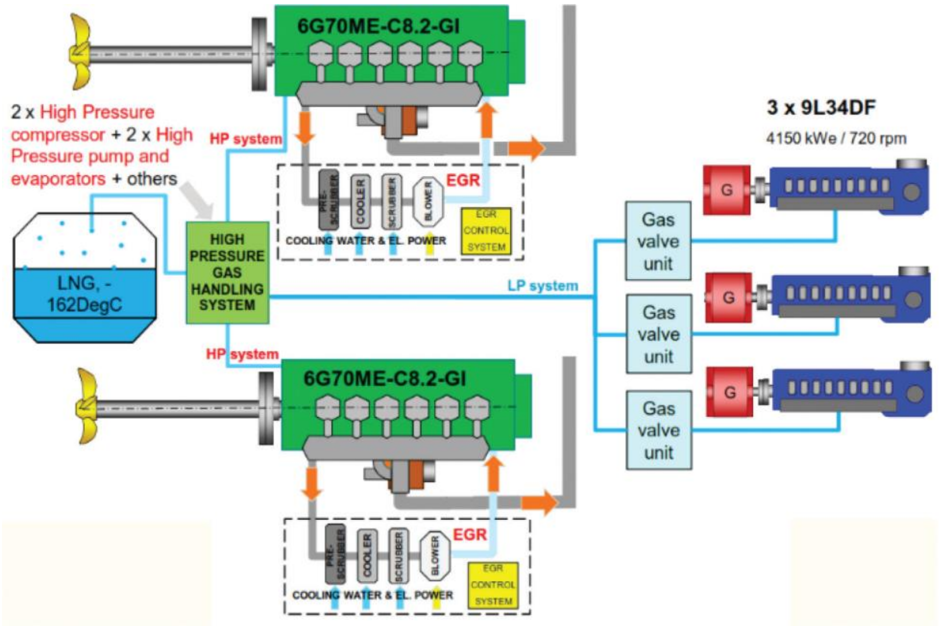


Figure 25: Schematic main machinery of the ME-GI propulsion plant.

4.4.5.2 Low pressure

Wärtsilä introduced its low-speed, two-stroke, dual-fuel engine in 2014. The lean-burn Otto-cycle combustion principle, which premixes fuel and air and burns them at a relatively high air-to-fuel ratio, is the foundation of low-pressure X-DF technology. This idea is already applied widely on medium-speed engines. When the cylinder is mid-stroke, gas injection is done at a pressure lower than 16 bar, mixing with the dry air blast. Combustion is started by injecting pilot fuel, which is 1% of the fuel injected at full load, after the mixture has been compressed. The pilot fuel is injected into pre-combustion chambers to ensure stable ignition under all circumstances [48]. The fuel gas supply system is considered simple since the required gas injection pressure is below 16 bar.

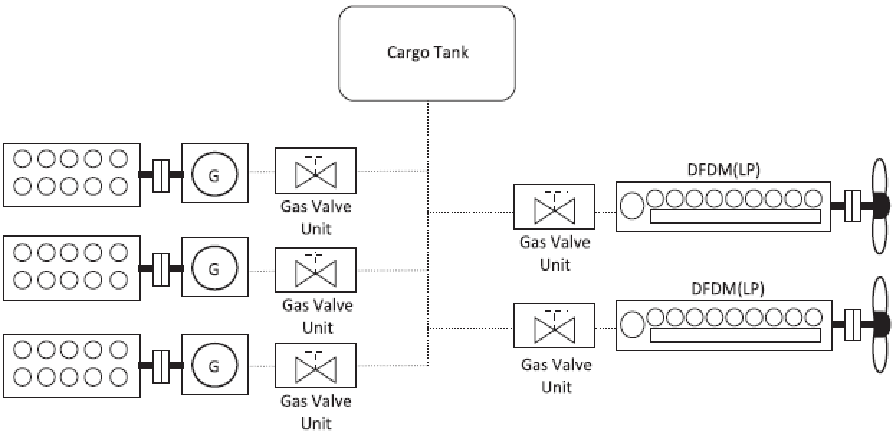


Figure 26: Propulsion system configuration of 2S low pressure DF engines [48].

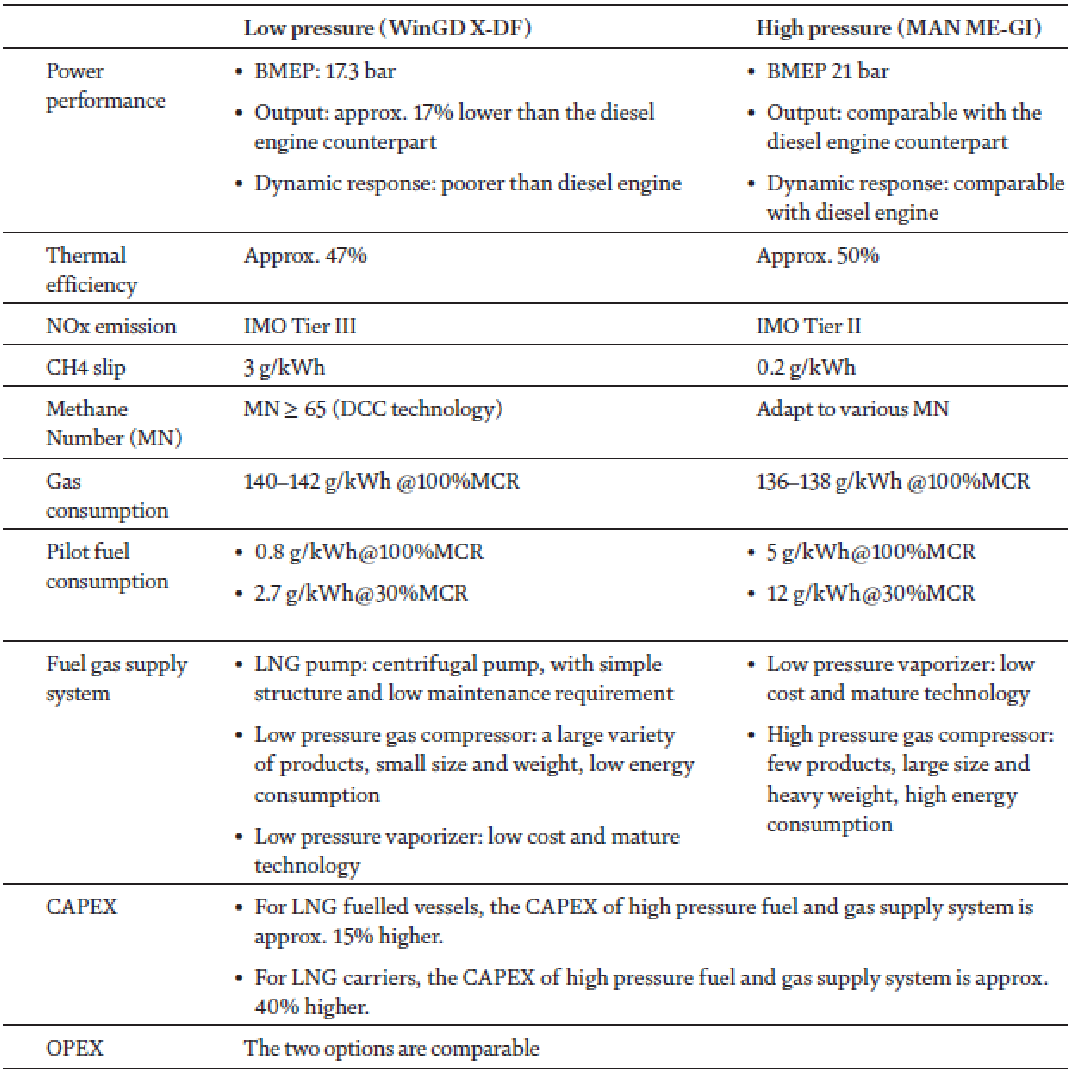
Figure 26 shows the configuration of a propulsion system for LNG vessels that uses low pressure two stroke dual fuel engines coupled directly to two independent axes. In this layout, each engine has its own gas treatment system to ensure greater safety in gas supply.

The low levels of NOx production and the compliance with the IMO Tier III limits are considered as the biggest advantages of this technology as there is no additional requirement for the emissions treatment.

4.4.5.3 Comparison of the two options

It is a fact that these two technologies from MAN and WIN GD are the most attractive options today and dominate the market as they combine the high efficiency of two-stroke engines with the multiple benefits of using liquid natural gas as a fuel. Each option, although, has its own advantages and disadvantages in terms of performance, compliance with the regulatory framework for emissions and economy. These are summarized in Table 13 [51], [61].

Table 13: Comparison of the high-pressure system (ME-GI) and the low-pressure system (X-DF) [61].



	Low pressure (WinGD X-DF)	High pressure (MAN ME-GI)
Power performance	• BMEP: 17.3 bar • Output: approx. 17% lower than the diesel engine counterpart • Dynamic response: poorer than diesel engine	• BMEP 21 bar • Output: comparable with the diesel engine counterpart • Dynamic response: comparable with diesel engine
Thermal efficiency	Approx. 47%	Approx. 50%
NOx emission	IMO Tier III	IMO Tier II
CH4 slip	3 g/kWh	0.2 g/kWh
Methane Number (MN)	MN ≥ 65 (DCC technology)	Adapt to various MN
Gas consumption	140–142 g/kWh @100%MCR	136–138 g/kWh @100%MCR
Pilot fuel consumption	• 0.8 g/kWh@100%MCR • 2.7 g/kWh@30%MCR	• 5 g/kWh@100%MCR • 12 g/kWh@30%MCR
Fuel gas supply system	• LNG pump: centrifugal pump, with simple structure and low maintenance requirement • Low pressure gas compressor: a large variety of products, small size and weight, low energy consumption • Low pressure vaporizer: low cost and mature technology	• Low pressure vaporizer: low cost and mature technology • High pressure gas compressor: few products, large size and heavy weight, high energy consumption
CAPEX	• For LNG fuelled vessels, the CAPEX of high pressure fuel and gas supply system is approx. 15% higher. • For LNG carriers, the CAPEX of high pressure fuel and gas supply system is approx. 40% higher.	
OPEX	The two options are comparable	

4.4.6 Steam Turbine and Gas Engine (STaGE)

STaGE systems are a Japanese innovation that have been produced exclusively by Mitsubishi Heavy Industries, with eight newbuilds delivered in 2018 and 2019. The term "STaGE" stands for "Steam Turbine and Gas Engine" and refers to a hybrid propulsion system with a dual-fuel diesel engine (DFE) and propulsion electric motor (PEM) plant on the starboard side and an ultra-steam turbine (UST) plant on the port side. The dual-fuel engine can operate on both gas and oil [62]. Efficiency is increased by recovering the exhaust gases from the dual fuel engine and using them to warm the steam turbine system's feed water. In comparison to steam turbine plants, a turbine generator is not required because the dual fuel engine provides both the propulsion motor with power and the auxiliary power requires for the vessel [63]. This hybrid system provides easy maintenance, excellent environmental performance, high reliability, and high redundancy by using different propulsion systems.

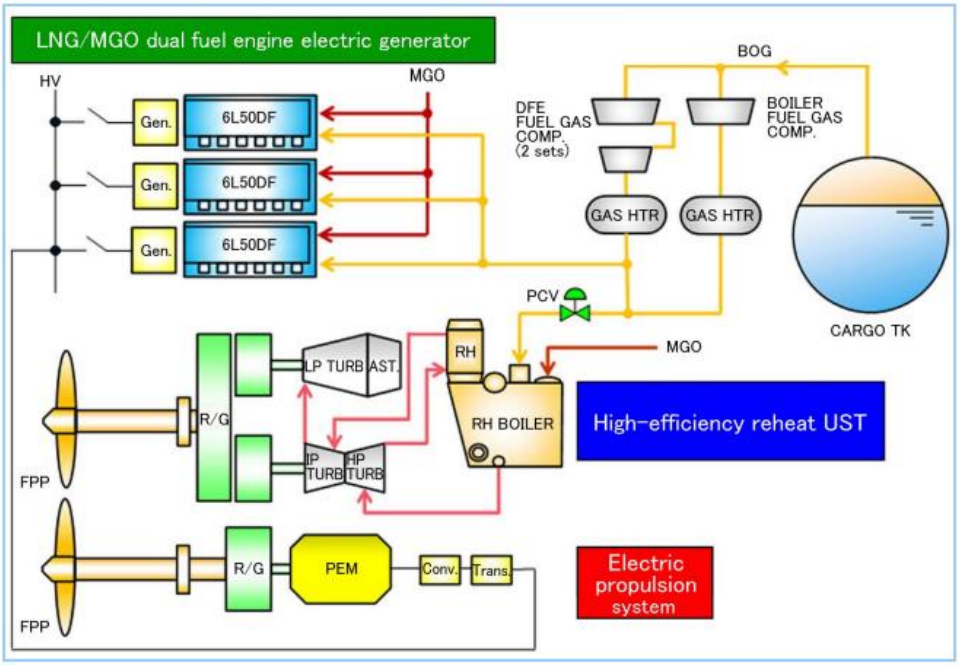


Figure 27: STaGE propulsion plant [62].

4.4.7 Gas Turbine

Because of their unrestricted ability to use diesel and BOG, their high reliability derived from the aeronautical industry, and their extremely high power/weight ratio, which results in a smaller system, the gas turbine (GT) was a technological innovation introduced on LNG vessels [48]. Although, the relatively low thermal efficiency and the need for MGO as a backup fuel, both of which come at a relatively high cost, prevent gas turbines from being a desirable option for use on LNG carriers. The high temperature of the exhaust gases produced by the gas turbine prompted the development of combined systems.

The Combined Gas turbine Electric & Steam system (COGES), which combines gas turbines with a steam turbine cycle for waste heat recovery, allows for an overall efficiency increase of 40%. An electric motor with frequency control turns the propeller. A heat recovery steam generator raises steam using the gas turbine's exhaust gases (HRSG). In turn, this steam powers the steam turbine generator, which also supplies the main switchboard [51].

4.4.8 Methane Slip

As a marine fuel, liquefied natural gas (LNG), which primarily contains methane, has significant environmental advantages in terms of air emissions like CO_2, NOx, SOx, and other emissions like particulate matter and black carbon. Since LNG has a carbon factor of 2.75, which is significantly lower than that of other conventional fuels like Heavy Fuel Oil (HFO), Marine Diesel Oil (MDO), Marine Gas Oil (MGO) and Low Sulphur Fuel Oil (LSFO), the substantial advantages of using LNG as a fuel are also reflected in compliance with the all-in-one and stricter regulatory framework. Due to this, the development of dual-fuel engines and LNG as a marine fuel has been rapid in recent years.

Methane is a greenhouse gas that contributes to global warming. The global warming potential of methane, using the standard time frame of 100 years (GWP100), is 28 according to the IPCC Fifth Assessment Report (AR5) [9].

Both two-stroke and four-stroke gas-burning engines have multiple ways in which methane can escape unburned into the atmosphere. The term "methane slip" refers to the methane that escapes combustion and escapes through the engine exhaust and crankcase ventilation [50]. As a result, methane slip could cancel out some of the potential CO_2 emission reductions.

There are numerous factors that influence methane emissions, including:

- Engine type.
- Engine size
- The engine load (higher slip at low engine loads).
- The thermodynamic cycle.

In the following figure, MAN [50] compares the main types of propulsion as a function of engine load in gas mode.

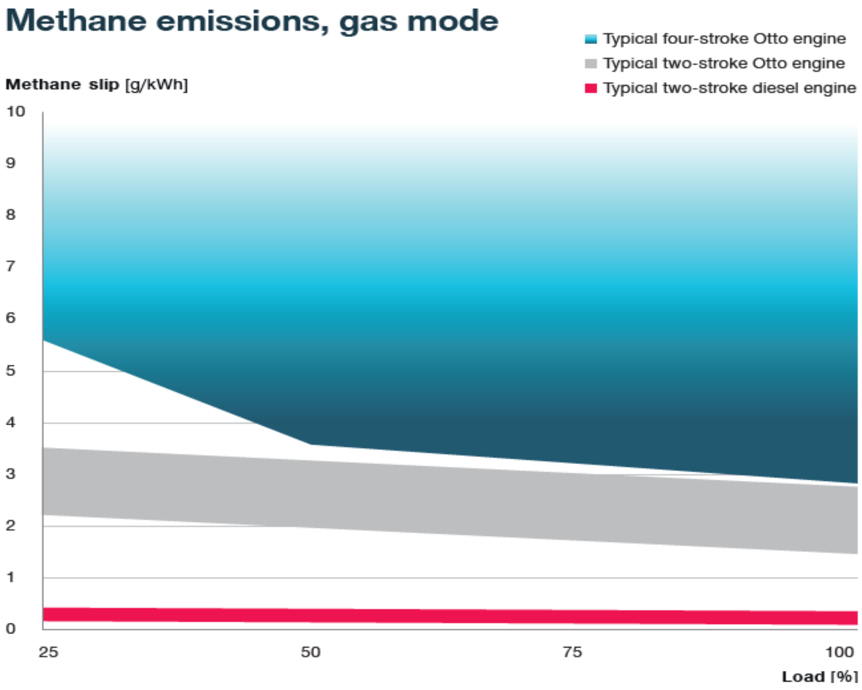


Figure 28: Methane emissions in gas mode-comparison of different engine types [50].

The highest methane emissions are produced by four stroke medium speed engines that run on the Otto cycle. The reason the methane slip problem is unique to four-stroke DFDEs is that in these engines, unburned methane is trapped in combustion chamber clearances like piston rings, anti-polishing rings, valve seats, etc. where the air/fuel ratio is such that the gas would not completely burn during combustion but would instead be released with the exhaust gases during the exhaust stroke. The gas injection engines, on the other hand, run with a direct gas injection, just like in traditional diesel engines, making sure that no gas is present during the compression stroke or scavenging period, which lowers methane emissions to levels that are almost comparable to those of traditional liquid fuel [7]. Additionally, low-pressure injection of lean mixtures results in more methane slip than high-pressure injection [64].

Several research have been carried to estimate methane slip between various engine technologies. The following are the main categories of engine technologies that apply to LNG carriers:

- Steam Turbines.
- Four stroke low-pressure injection dual fuel engines (LPDF).
- Two stroke LPDF engines.
- Two stroke high pressure injection dual fuel engines (HPDF)

For the above types, Pavlenko et al. [64] conducted extensive research and determined the methane slip emissions factors for each technology expressed in gCH_4/kWh, which were used in the fourth IMO GHG study [1]. The emission factors for methane slip are weighted to represent the IMO's E2 or E3 test cycles.

Table 14: Methane slip emission factors.

Engine type	Example of engine	Methane slip (gCH4/kWh)	Reference
Steam Turbines	UA-400	0.04	[64]
LPDF-4S	Wärtsilä 12V50DF	5.5	[64]
LPDF-2S	Wärtsilä/ WinGD 5X72DF	2.5	[64]
HPDF	MAN 5G70 ME-C9-GI	0.2	[64]

Compared to other technologies, steam turbines exhibit the smallest values with a noticeable difference. Leaks or insufficient combustion in the boiler are the main causes of methane slip in steam turbines.

Another recently proposed approach, related to the upcoming regulatory framework, is Fuel EU's [45] approach to calculate the greenhouse gas intensity limit of the energy used on board a ship. The engine's fuel slippage (non-combusted fuel) is expressed as a percentage of the fuel mass used.

The table below displays the suggested percentages for each type of engine that uses LNG as fuel.

Table 15: LNG slip proposed at FUEL EU regulation.

Engine type	C_{slip} as % of the mass of the fuel used by the engine
LPDF-4S	3.1
LPDF-2S	1.7
HPDF	0.2

According to all approaches four stroke DFDE’S propulsion types seem to have the bigger methane slip. The major engines manufacturers claim that there have been significant reductions in methane slip compared to the past, and research is focusing on further reductions using options such as exhaust gas after treatments and combustion process improvement. In regard to the four-stroke engines, the MAN’s technical department states that recently created aftertreatment solutions, specifically oxidation catalysts, have the potential to reduce methane slip by 70% and that they are working on ways to use the direct gas injection technology used in MAN's two-stroke DF engine. This will increase the possibility of reducing methane slip by a percentage greater than 90% [50].

5. Methodology and Data collection

5.1 Introduction

The present study has two main goals. The first goal is to estimate the carbon intensity indicator for the current fleet of LNG carriers and correlate it with important technical and non-technical characteristics of a ship, such as age, size, and type of propulsion, in order to draw some useful conclusions. The assessment of the LNG carrier fleet's compliance with the new IMO carbon intensity indicator regulation by the decade's end in 2030 is the second objective of the current study, and it is based on the estimation of the carbon intensity indicator. In other words, the goal is to assess the impact of the regulation on each ship and whether or not it will face challenges in complying with the regulation until 2030. In this context, and since the specific regulation is quite recent, with its form not yet fully finalized, and because the regulation is to be re-evaluated until 2026, certain trajectory scenarios are developed for the period after 2026, on which the study's results are based.

Therefore, the following two fundamentals are necessary to accomplish the aforementioned goals:

- The fleet of liquefied natural gas carriers, as well as their characteristics.
- The fleet's operational profile and emissions on an annual basis.

The collection of appropriate data and the methodology used to estimate the carbon intensity indicator are described in the following section of this chapter.

5.2 Data collection

As previously stated, the necessary data had to be gathered to begin achieving the study's objectives. The achieved carbon intensity indicator refers to a specific ship's CO_2 emissions over a calendar year. As a result, the calculation of the achieved carbon intensity indicator, which is the primary goal of the study and is an integral part of the second goal, requires knowledge of the ship and its annual CO_2 emissions. In general, data on basic characteristics and CO_2 emissions for each ship had to be collected for the entire fleet of LNG carriers.

5.2.1 Data for the LNG Carriers fleet

Data on the fleet of LNG carriers that are currently in operation needed to be collected first. The reliability and validity of the specific data are critical in the research process, as one of the primary goals of the current study is to evaluate and draw useful generalizable conclusions at the fleet level. As a result, finding a globally recognized database was important. IHS Markit was the database used. IHS Markit is a reliable source of information on ships, shipowners, shipbuilders, movements, fixtures, casualties, ports, and companies, according to [65]. It is the largest shipping database, with over 600 data fields on over 200,000 ships of 100 gross tons and above.

The data file obtained from this database corresponds to the month of March 2022. As the fleet changes over time, the data is updated. Any changes in the fleet composition are due to the withdrawal of ships that are later determined to be dead and do not participate in the existing fleet, as well as ships that enter the market as newly built (before they were on the orderbook), increasing the number of ships in the existing fleet.

The fact that the processed data corresponds to March 2022 rather than the present is regarded as acceptable because, as will be discussed in more detail in the chapter's next section, the study's primary target group is older ships that have been on the market for at least a few years.

The information obtained from the database applied to all ships with the designation "Gas ship" in the "Ship Type Profile Main" field. The data concerned the existing fleet and the orderbook ("ship status profile" field). This category, however, also included ship types such as "Liquefied Petroleum Gas Carriers," "CO_2 Carriers," and "Compressed Natural Gas Carriers." As a result, to keep only LNG Carriers, an initial filtering in the "Ship type Profile" category was deemed necessary. There were 805 ships that met this criterion (existing fleet and orderbook). The next step was to define a lower limit for the cargo capacity of the ships under consideration for the study. The capacity is expressed in deadweight tons in the calculation of CII and other energy efficiency indicators, but in LNG carriers, despite the existence of DWT, the capacity in cubic meters is more important. The lower bound of the capacity in cubic meters was set at 40,000 m^3. This value was chosen because, as mentioned in Chapter 4, smaller ships are not involved in large trades and are primarily used for coastal trades and bunkering purposes. After the second filtering, which excluded ships with capacities less than 40,000 m^3, the total number of ships in the existing fleet and orderbook is 765. The orderbook includes 166 ships, while the existing fleet includes 599 ships. The following figure illustrates a schematic representation of the process as well as the final number of ships.

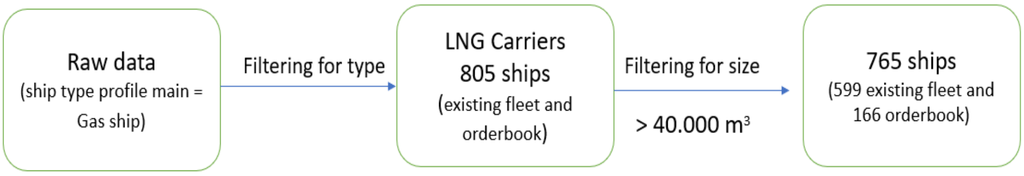


Figure 29: LNG carrier fleet as of March 2022.

The next step was to select the fields we were interested in, as the original data file had over 100 fields for each ship with both technical and commercial information. "Country of build profile", "Yard number", "Operator", "Operator domicile", "Country of economic benefit", "Class notation", "Contract year", "Ship manager domicile", "CFO Owner country", "Length", "Breadth", other ship particulars, etc. are some examples of fields. As a result, a selection of areas of interest had to be made based on the characteristics that would be useful in the subsequent study of the fleet. Some characteristics may not be directly used in the study or subsequent results, but they were deemed important at the time and were included in the final data file. The following table lists the information fields that were retained in the final file format by title.

Table 16: Fields in the final database.

IMO Number	Technical Manager
Vessel name	Service Speed
Gross Tonnage	Power
Deadweight	Propulsion type
LNG Carrier Size Profile	Number of screws
Year of Built	Total Oil engines
Current Age category	Total Steam Turbines
Age	Engine Designer
Country of build	Engine model
Shipbuilder	Cargo Containment System
Flag	Auxiliary Engines Narrative
Class	Newbuilding price
Owner	Standard ship design
Operator	Engine builder
Ship Manager	Lead vessel IMO Number

In addition to the filtering that was done to keep the information needed, some additional characteristics were added based on the table's basic categorizations.

- A necessary categorization is the type of propulsion. According to the data, the types of propulsion are "Steam turbine, geared drive", "Oil engine, electric drive", "Oil engine, Direct drive", "Steam turbine, geared drive & Oil engine, Electric drive", "Oil engine, geared drive & Oil engine, Electric drive", and "Oil engine, geared drive". All ships with two-stroke slow speed engines are classified as "Oil engine, Direct drive." However, those with Dual Fuel engines and those with exclusive Diesel engines (Qatar fleet) had to be separated. The engine model was used to make this distinction. For example, if the engine model was 6S70ME-C, it was classified as a diesel engine, whereas 7G70ME-C9-GI was classified as a dual fuel engine.

- A second categorization regarding propulsion type and ship engine technology was necessary. This classification was more focused on two-stroke slow speed dual fuel engines, which were divided into High Pressure Dual Fuel engines (HPDF) and Low-Pressure Dual Fuel engines (LPDF). The Wartsila/WinGD two-stroke dual fuel engines were categorized as LPDF. X62DF is an example of an LPDF engine. MAN's two-stroke dual fuel engines were categorized as HPDF. G70ME-C9-GI is an example of an HPDF engine. The four-stroke medium speed (diesel electric propulsion) engines were categorized as LPDF engines. This classification was necessary primarily to distinguish the engines in terms of methane slip, which is discussed analytically in Chapter 4 of this study.

For some ships, information is not available for all fields in the table above, and some fields do not apply to the entire fleet. The field "Standard ship design," for example, only applies to specific ship designs such as Q-Flex and Q-Max. The main engine model, for example, is missing from a small number of ships in the orderbook. However, basic information such as the DWT, age, and propulsion type are available for all vessels. Furthermore, the study is concerned with the existing fleet rather than the orderbook, which is constantly renewed and exists for completeness. As a result, it is assumed that there are no significant omissions in the final data file.

5.2.2 Operational data

The Carbon Intensity Indicator is solely based on a ship's operational profile, specifically the ship's actual fuel consumption and transport work over a year. After finalizing the database and the categorizations that may be included in the analysis and having a complete picture of the fleet of LNG carriers and the technical and non-technical characteristics of each ship, the next step was to search for the operational data involved in the calculation of the CII, particularly data on the CO_2 emissions and transport work of each ship during a calendar year.

According to the CII definition, the transport work is based solely on the distance traveled in nautical miles since the transported cargo is equal to the ship's DWT. Furthermore, the annual CII is calculated using reported IMO DCS data. However, according to [40], the data in the IMO Ship Fuel Oil Consumption Database are confidential and not publicly available. As a result, IMO DCS data were inaccessible and could not be used in the study. To make an estimate of the CII as close to reality as possible, reliable operational data corresponding to actual conditions had to be found. This data was gathered from the European Union's Monitoring, Reporting, and Verification system. As discussed in Chapter 3, the MRV regulation applies to ships calling at European Union ports and requires the reporting of CO_2 emissions as well as other information such as distance traveled, and cargo carried. The entire reporting and data verification procedure is managed by THETIS-MRV, and in accordance with Article 21 of Regulation (EU) 2015/757 [35] on the monitoring, reporting, and verification of CO_2 emissions from maritime transport, all information on CO_2 emissions reporting must be made publicly available by 30 June each year. All of these data were gathered from the THETIS MRV website [66], where the information can be accessed via the search tool, as shown in Figure 30, or exported in a spreadsheet for further analysis.

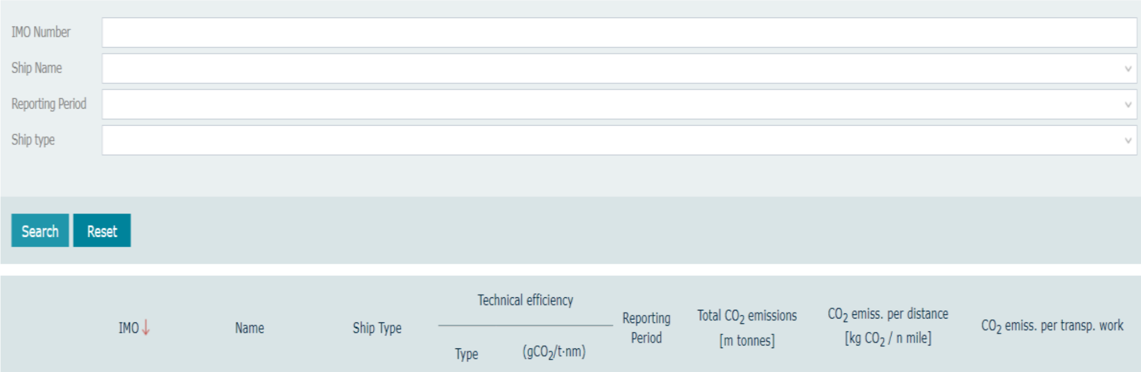


Figure 30: THETIS MRV CO2 EMISSION REPORT.

Each downloadable spreadsheet file is for one reporting period (each calendar year beginning in 2018) and has a specific Version and Generation Date because this file is updated regularly. As a result, CO_2 emissions data and other useful information were extracted from such a spreadsheet file.

The calendar year 2020 was chosen as the reporting period for the study, and the specific file on which the analysis is based is version 159 of reporting period 2020 generated on June 27, 2022. Any data provided or updated after this date are not taken into account in the analysis of this study.

The following is the key information contained in the MRV data file for each vessel in the year 2020:

- IMO Number
- Name
- Ship type
- Technical efficiency (EEDI or EIV, where applicable).
- Port of registry.
- Monitoring methods of fuel consumption.
- The annual total fuel consumption for voyages.
- The annual total CO_2 emissions.
- The annual time spent at sea.
- The annual average fuel consumption per distance [kg/ n mile].
- The annual average fuel consumption per transport work (mass) [g/m tonnes*n miles]
- The annual average CO_2 emissions per distance [kg CO_2/ n mile].
- The annual average CO_2 emissions per transport work (mass) [g/ m tonnes*n miles].

Many of the above information concern the ship's average energy efficiency, either in the form of consumption and emissions per distance or in the form of the EEOI. Distance traveled in nautical miles and cargo carried can be calculated indirectly by dividing total annual fuel consumption by annual average fuel consumption per distance and annual average fuel consumption per distance by annual fuel consumption per transport work. In addition to the information provided above, other voluntary or non-voluntary information is provided, as outlined in article 21 of the regulation [35].

The data presented above are available for each type of ship subject to the MRV regulation. As a result, the next step was to edit the file so that only the liquefied natural gas carriers relevant to the study remained. Only the types "LNG Carriers" and "Gas Carriers" were selected in the MRV data field where the ship type is mentioned, and the rest of the ship types were deleted. The study focuses solely on LNG Carriers, but it was noticed that some vessels classified as "LNG Carriers" in the IHS database are classified as "Gas Carriers" in the MRV data. To avoid exceptions in the study and to include all available liquefied natural gas carriers, regardless of the definition of ship type as demonstrated on their International Energy Efficiency Certificates as "LNG Carrier" or "Gas Carrier," the two ship types were kept in the MRV data file.

The IMO Number is the most important identification element of the ship and the only one used to merge data from the two files, the database from the IHS and the spreadsheet from the MRV data. Thus, the ships for which operational data is available for the year 2020 were searched using the Excel VLOOKUP command and the identification element IMO Number. For the reporting year 2020, there were 267 LNG Carriers for which operational data from the MRV was found. In the ship type field, 250 were classified as "LNG Carriers" and 17 as "Gas Carriers."

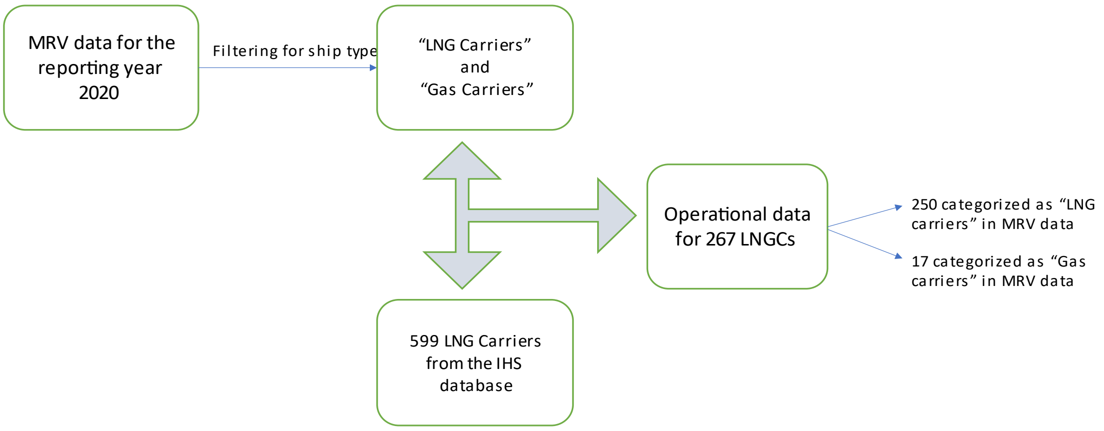


Figure 31: MRV data for LNG Carriers.

As previously stated, the existing fleet consists of 599 ships; therefore, it was not possible to find data for all ships for the following two reasons.

1. The existing fleet's number 599 refers to the month of March 2022, whereas the data from the MRV corresponds to the calendar year 2020. Logically, there is no data for new-build ships that entered the market in 2021 and until March 2022.
2. The MRV regulation applies to ships that call at any EU port during their voyage. Consequently, no data is available for LNG Carriers that trade outside of the European Union.

As a result, all of the analysis presented in the following chapter of the paper is based solely on the data for these 267 LNG Carriers, instead of the entire fleet, because no other data could be found.

The main assumption of the current methodology is that the MRV Data were used to calculate the Carbon Intensity Indicator rather than the IMO DCS data on which the indicator is based. In order to determine whether the MRV data could be used without any significant error that would cause an under- or overestimation of the indicator and ultimately inaccurate conclusions, an analytical comparison of the data from the two systems was considered necessary.

The main features of the two systems were compared in Chapter 3, but the following comparison focuses on the factors involved in CII calculation, namely CO_2 emissions and distance traveled. First, the reporting to the DCS system requires only the fuel consumption and the carbon factor of each fuel while the MRV requires both fuel consumption and calculation for CO_2 emissions by the following formula:

$$CO_2\ emissions\ =\ Fuel\ consumption\ \times\ emission\ factor$$

Both the IMO DCS (resolution MEPC 303 (78)) and the EU MRV regulation use the same default values for emission factors for the fuels used. Furthermore, the methods for gathering data for fuel oil consumption, specifically Bunker Delivery Notes, flow meters, bunker fuel oil tank monitoring on board, and direct CO_2 emissions measurements, are the same. Regarding the fuel oil consumption that must be reported under the MRV regulation, it is explained that the fuel consumption must include fuel consumed by:

- Main engines.
- Auxiliary engines.
- Gas turbines.
- Boilers.
- Inert gas generators.

According to [67], for the fuel oil consumption at the DCS, "Fuel oil consumption should include all the fuel oil consumed on board, including but not limited to the fuel oil consumed by the main engines, auxiliary engines, gas turbines, boilers, and inert gas generator, for each type of fuel oil consumed, regardless of whether a ship is underway or not.". Therefore, even though some additional consumptions may be reported in the DCS data, the two systems' primary fuel oil consumers are the same. An important clarification for LNG Carriers is whether Gas Combustion Unit (GCU) emissions are included in the reporting. The consumption of the GCU must be reported for the DCS system, as stated in [38]. Fuel oil, including gas, distillate, and residual fuels, is defined by MARPOL as "any fuel delivered to and intended for combustion purposes for propulsion or operation on board a ship." Because GCUs are involved in the operation, any gas burned there—even if only for flaring—is used for operational purposes and is therefore regarded as fuel oil, the consumption of which is required to be reported [38]. However, the inclusion of GCU consumption in reporting is unclear in the MRV system.

The distance traveled is another parameter that is used in the calculation of the CII and applies to both systems. The MRV Regulation, on a per voyage basis, provides two options: the actual distance travelled, expressed in nautical miles, or the distance covered by the most direct route between the ports of departure and arrival. The regulation specifies that if the most direct route is chosen, a conservative correction factor should be used to avoid significantly underestimating the distance travelled. In the IMO DCS system, the distance is distance travelled over ground while the ship is underway under its own propulsion. For example, the distance travelled can be measured using satellite data.

In conclusion, according to the regulations, the two parameters of consumption and distance travelled appear to be well correlated, but they do have a few minor discrepancies that could slightly impact the result of the carbon intensity indicator estimation.

Another critical assumption regarding MRV data is the geographic limitation. As previously stated, there is no data available for ships that operate solely outside of the European Union. However, for vessels where data is available, it is assumed that the operational data available for voyages with at least one European port call represents the vessel's operational profile for the entire year. For example, a ship may make voyages within the European Union during the year, but also exclusively outside, which are not accounted for in the MRV data, and thus the available data do not capture the entire time span of a year. This is an important assumption because the CII is calculated exclusively from operational data. The operational profile of the vessel may vary depending on the voyage and region and is affected by parameters such as speed and weather conditions, which can have a significant impact on fuel consumption and thus CO_2 emissions and the Carbon Intensity Indicator.

In the IMO 4th GHG study, for the year 2018, the representativeness of global shipping activity by the MRV dataset was carefully considered and tested considering the geographical restrictions on the MRV dataset. Investigations revealed that the fleet coverage and operation were both very representative of their global equivalents [1]. The MRV dataset used in the current study was based on the year 2020. Although the IMO study's above conclusion refers to another year, it is quite useful for assessing the overall quality and validity of the MRV data.

5.3 CII Calculation and basic assumptions

After collecting the necessary data for the LNG Carriers fleet as well as the operational profile in terms of CO_2 emissions and transport capacity in a calendar year, the next step was to estimate the attained Carbon Intensity Indicator for each ship. The IMO Number was the only characteristic that linked the data between the database with the fleet of LNG Carriers and their characteristics and the operational data from the MRV spreadsheet for the year 2020. Thus, with the basic characteristics of each ship and, in particular, the DWT that participates in the calculation of the CII, the operational data from the MRV were matched using the IMO Number. The parameter "The annual average CO_2 emissions per distance [kg CO2/n mile]" was used specifically. Dividing the specific parameter by the DWT of each ship yields the Annual Efficiency Ratio (AER) of each ship in its initial form, excluding the correction factors.

$$Attained\ CII = AER = \frac{CO_2}{DWT \times Distance\ travelled}\ (\frac{g\ CO_2}{t \times nm})$$

However, according to the most recent guidelines for calculating the Attained CII as formulated at MEPC 78 [31], some correction factors and voyage adjustments are used in the calculation of the Attained Annual Operational CII. Chapter 3 contains a detailed description of the formula.

The correction factor $FC_{electrical}$ related to cargo cooling/reliquefaction systems on Gas Carriers and LNG Carriers is the most important factor that can significantly affect the CII calculation exclusively on LNG Carriers. However, actual operational data for the fuel consumption of such a system could not be found. As a result, the estimate of the attained CII used in this study (as AER) is solely based on its initial form, as formulated in the above formula, and does not include the correction factors and voyage adjustments found in the most recent CII formula. This assumption is critical because it can lead to an overestimation of the achieved annual CII.

Another main assumption in the CII estimation is the fact that the attained CII is based solely on operational data for the year 2020 and is assumed the same for the following years. So, potential improvements in vessel efficiency for the following years until the end of the decade are not taken into account. For example, dry docking a vessel or installing an EST such as an Air Hull Lubrication System may have a significant impact on the ship's resistance and, as a result, fuel consumption.

After estimating the attained Carbon Intensity Indicator, a comparison with the required CII of each individual ship is made. The reduction factors formulated by the regulation are used in the calculation of the required CII for each calendar year until 2026. Some trajectory scenarios for the reduction factors had to be developed for the years following 2026 until 2030, as the regulation is about to be revised. The current annual reduction in the required CII until the year 2026 compared to 2019 is 2%. In light of the IMO's ambitious goals and the mention in the Resolution MEPC 378 (56) reduction factor guidelines that "annual reduction rates for the period 2027-2030 will be further strengthened," some trajectory scenarios with annual reduction rates of 2% or higher were developed. For the years 2027 to 2030, annual reduction rates of 2%, 3.5% and 5% were assumed. The next table shows the reduction factor for the CII relative to the 2019 reference line for each of the three trajectory scenarios.

Table 17: Reduction factors until 2030.

	Reduction factor relative to 2019		
Year	1st Trajectory scenario	2nd Trajectory scenario	3rd Trajectory scenario
2023	5%	5%	5%
2024	7%	7%	7%
2025	9%	9%	9%
2026	11%	11%	11%
2027	13%	14.5%	16%
2028	15%	18%	21%
2029	17%	21.5%	26%
2030	19%	25%	31%

Finally, the rating of each ship is determined by comparing the required CII for each year based on the corresponding trajectory scenario and the rating boundaries specified in the regulation. Ships with an A, B, or C rating are assumed to be compliant, whereas ships with an E or D rating for three years in a row are assumed to be non-compliant.

The methodology used and described above is illustrated schematically in Figure 32.

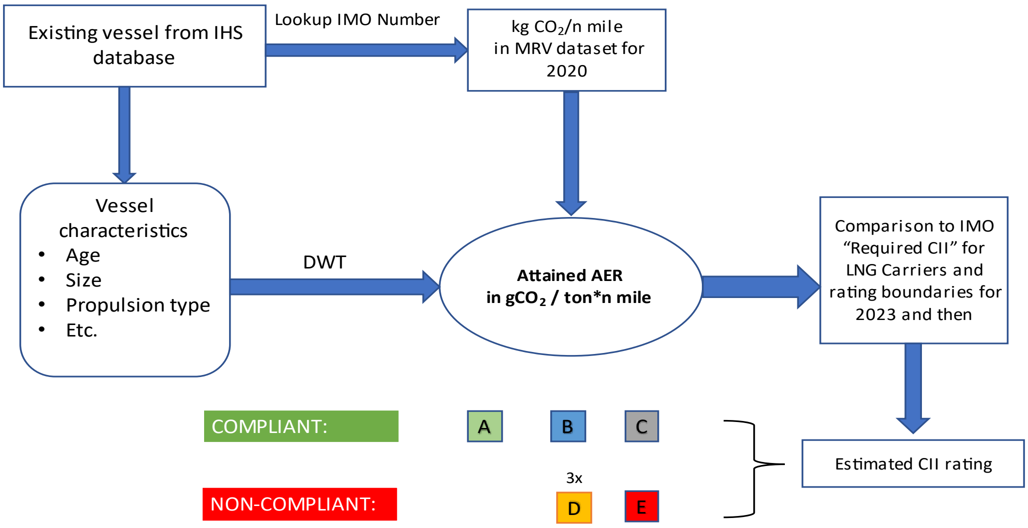


Figure 32: CII calculation methodology.

In addition to the above trajectory scenarios for the annual reduction factors, one additional assumption was made regarding regulatory compliance by including the effect of methane slip. In Chapter 4 of this study, the methane slip in LNG-fueled engines was analytically discussed. The Global Warming Potential (GWP) value used is 28, with a time horizon of 100 years (GWP 100). As a result, 1 gram of CH_4 equals 28 grams of CO_2-equivalent.

The percentage of fuel that escapes from each type of engine during combustion is the most important assumption that must be made to include methane slip in emissions. The values for methane slip per engine type were taken from the European Union's FUEL EU regulation. However, no value for steam turbines was included in these estimates. In the IMO 4th study, the methane slip factor in steam turbines was 0.04 gCH_4/kWh. Assuming a Specific Fuel Oil Consumption of SFCME = 285 g/kWh, methane slip as a percentage of fuel mass is equal to 0.014 percent. The table that follows lists the slip as a percentage of the fuel used by the engine for each engine technology.

Table 18: Slip by engine type.

Engine type	**C_{slip} As % of the mass of the fuel used by the engine**
LPDF-4S	3.1
LPDF-2S	1.7
HPDF	0.2
Steam Turbine	0.014

Assuming that one tonne of CH_4 is burned in the engine, one tonne of CH_4 burned equals 2.75 tonnes of CO_2 emitted.

Using the C_{slip} of the engine ,

$$1\ tonne\ CH_4\ gas\ fuel = 2.75 \times (1 - \frac{C_{engine\ slip}}{100})\ tCO_2 + \frac{C_{engine\ slip}}{100}\ tCH_4$$

$$C_F\ (t - CO2eq/t - CH4\ gas\ fuel) = 2.75 \times (1 - \frac{C_{engine\ slip}}{100}) \times GWP_{CO2} + \frac{C_{engine\ slip}}{100} \times GWP_{CH4}$$

$$Total\ CO_{2,equivalent} = M_{CH4} \times \left(2.75 \times (1 - \frac{C_{engine\ slip}}{100}) \times GWP_{CO2} + \frac{C_{engine\ slip}}{100} \times GWP_{CH4}\right)$$

$$Total\ CO_{2,equivalent} = M_{CH4} \times \left(2.75 \times (1 - \frac{C_{engine\ slip}}{100}) \times 1 + \frac{C_{engine\ slip}}{100} \times 28\right)$$

Where, M_{CH4} is the mass of gas fuel burnt.

Using the above equations, the CH_4 emission factors for each engine technology are listed in the table below.

Table 19: Emission factors including methane slip.

Engine type	**C_F (t-CO_{2eq}/t-gas Fuel)**
LPDF-4S	3.5328
LPDF-2S	3.1793
HPDF	2.8005
Steam Turbine	2.7535

Using the LNG emission factors listed above, CO_2 equivalent emissions for the LNG fleet, including methane slip, can be calculated. This would necessitate knowing the amount of LNG consumed by each ship over the duration of a year. The MRV data available, however, includes the total fuel mass in tonnes used but not the exact amounts for each fuel type. As previously stated, most LNG Carriers use two or three fuels, such as LNG, HFO, and MDO/MGO. As a result, without knowing the exact amount of each fuel, it was assumed that each ship burns only LNG, and the fuel tonnes reported in the MRV data are LNG tonnes. LNG Carriers with two-stroke diesel engines for propulsion, understandably, are excluded from this analysis. This assumption is important because it can lead to a slight overestimation or underestimation of emissions. For example, the emission factors for low pressure dual-fuel engines, including methane slip, are close to the emission factors for conventional fuel, and ships with steam turbines may use a significant amount of fuel oil. Nevertheless, this assumption was considered necessary for the progress of the calculations.

Following the methodology shown in Figure 32, a new estimate of the attained CII and ratings was made by recalculating the equivalent CO_2 emissions.

6. Results and analysis

6.1 Introduction

This chapter presents the results of the analysis conducted using the methodology described in the previous chapter. At the beginning of the chapter, there is a brief description of the existing fleet and the orderbook based on the study's data, as well as a summary presentation of the sample of the fleet studied in comparison to the total current fleet in terms of the main characteristics of the LNG Carriers. Then, to assess the impact of the CII, the results of CII compliance until 2030 are presented at the fleet level, as well as depending on the main characteristics of the LNG Carriers, developing some trajectory scenarios for the regulation's improvement until the end of the decade. Furthermore, if the methane slip is included in the emissions calculation, an analysis for compliance with the regulation is conducted. Finally, the attained CII between some similar vessels is examined in order to estimate the operational factor behind CII, and the operational efficiency with the form of CII is compared to the technical efficiency of the vessels.

6.2 Overview of the existing fleet and orderbook

A description of the existing fleet and orderbook of LNG Carriers in terms of basic characteristics such as age, size, propulsion type, and containment type is provided in the specific section of the chapter. All results are from the IHS datafile, as described in Chapter 5, and correspond to March 2022.

Existing fleet.

The current LNG Carriers fleet consists of 599 ships. Almost 90% of the fleet is made up of ships that are less than 20 years old. According to age range, nearly a third of the fleet is between 0 and 5 years old, and 50% is between 5 and 10 years old, reducing the average age of the fleet, indicating the growth of the LNG market in recent years and the significant increase in the global fleet. Ships aged 11 to 15 account for 24.5% of the fleet, with the remaining 25% belonging to older age groups.

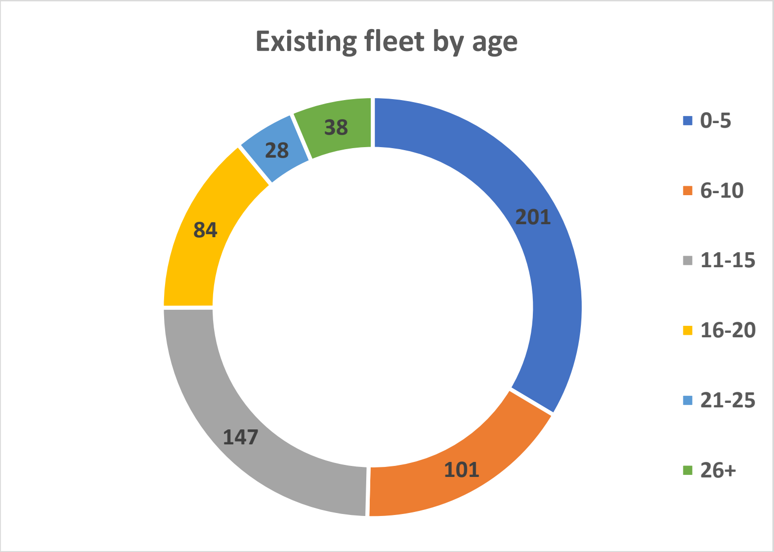


Figure 33: Existing fleet by age category.

The following table shows the detailed percentages along with the total capacity by age range in millions of cubic meters.

Table 20: Existing fleet by age category.

Age category	No. of vessels	% fleet	Capacity in million cb.m
0-5	201	33.6%	34.05
6-10	101	16.9%	16.21
11-15	147	24.5%	25.50
16-20	84	14.0%	11.63
21-25	28	4.7%	3.63
26+	38	6.3%	4.78
Total	599	100.0%	95.80

In terms of vessel capacity, the most common size in the existing fleet is between 150,000 and 180,000 m^3, accounting for 57% of the fleet. Furthermore, ships with a capacity of 125,000-150,000 m^3 account for 31.6% of the fleet, while the smallest and largest ships (Qatar fleet, > 200,000 m^3) account for a smaller percentage of the fleet.

Table 21: Existing fleet by size category.

Size category	No. of vessels	% fleet
40k - 125 k Cu.M	21	3.5%
125k - 150k Cu.M	189	31.6%
150k - 180k Cu.M	343	57.3%
180k - 200k Cu.M	1	0.2%
200k - 250k Cu.M	31	5.2%
250k+ Cu.M	14	2.3%
Total	599	100.0%

The relationship between age and size is significant because there are clear trends, as illustrated in Figure 34. The oldest ships are less than 150,000 m^3 in size. After around 2007, the average size of LNG Carriers being built began to rise. The development of the Qatar fleet with the Q-Flex and Q-Max vessels, which have capacities of over 200,000 m^3, played an important role. In the last decade, the majority of newbuild LNG Carriers have been between 150,000 and 180,000 m^3 in size, with the average capacity of recent vessels being close to 170,000 m^3.

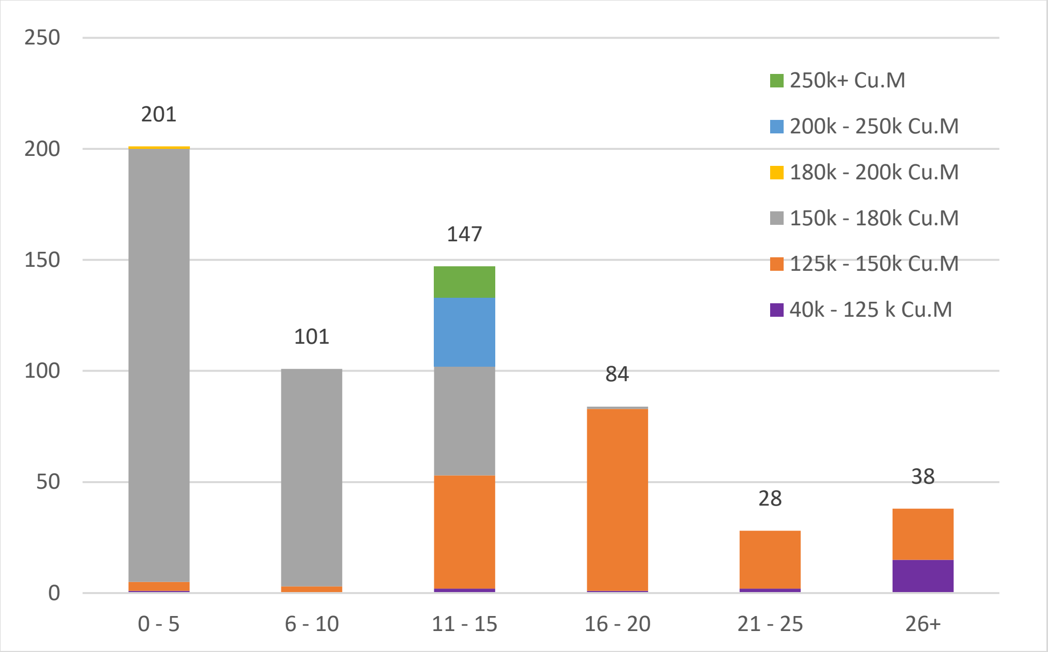


Figure 34: Existing fleet size by vessel age.

Another important categorization of the existing fleet is based on propulsion type. Since the beginning of the construction of LNG Carriers, as mentioned in Chapter 4, steam turbines have been the most common type of propulsion. Currently, there are 229 active vessels with steam turbine propulsion type, accounting for 38.2% of the total existing fleet. Diesel electric propulsion (DFEDE and TFDE) accounts for a sizable portion of the current fleet. DFDE or TFDE systems are currently installed on 161 vessels, accounting for 26.9% of the existing fleet. Slow speed diesel propulsion accounts for 8% of the fleet with 48 vessels, 44 of which are Q-Class vessels. Vessels with dual-fuel propulsion, including WIN GD and MAN low and high-pressure dual fuel engines, represent a significant part of the current fleet, accounting for 25.5% of the total. The Sayaringo STaGE propulsion system, which is equipped with a steam turbine and a dual-fuel engine manufactured exclusively by Mitsubishi, accounts for 1.3% of the current fleet.

Table 22: Existing fleet by propulsion type.

Propulsion type	**No. of vessels**	**% fleet**
Steam turbine	229	38.2%
Diesel Electric (DFDE/TFDE)	161	26.9%
Slow speed Diesel	48	8.0%
Slow speed Dual Fuel	153	25.5%
STaGE	8	1.3%
Total	599	100.0%

There is a correlation between age and type of propulsion, just as there is with size categorization. The older ships used only steam turbines for propulsion. The number of steam turbines available has decreased substantially, and only a few ships have been built in recent years with an improved version of the steam turbine known as steam reheat (or ultra-steam turbine). Diesel electric propulsion was introduced in 2006 and quickly replaced steam turbines in orders. Slow speed dual fuel engines appear to have dominated the market over the last five years.

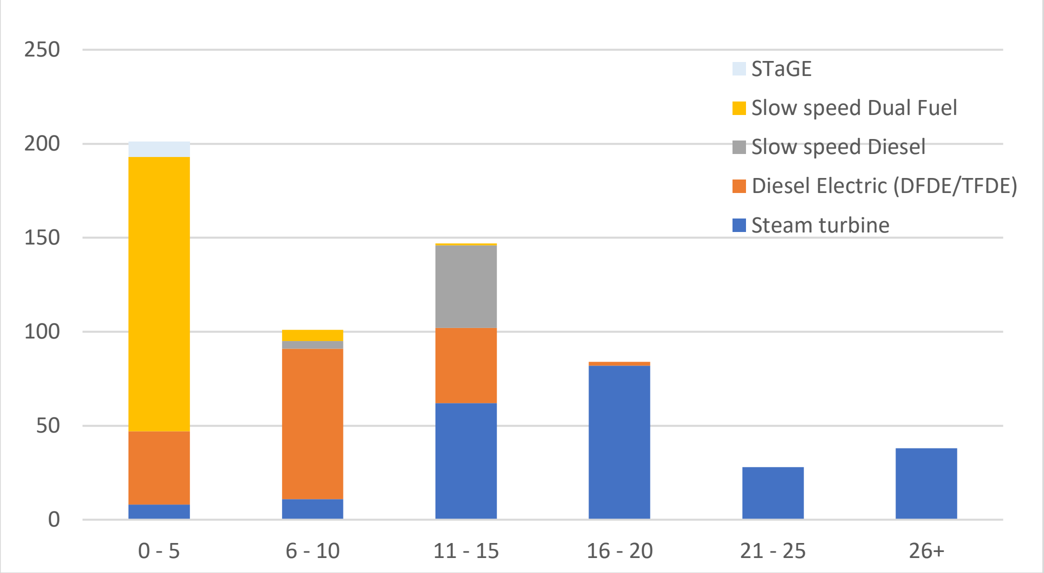


Figure 35: Existing fleet propulsion type by vessel age.

Regarding the cargo containment system of the existing LNG Carriers, 79% consists of membrane tanks, the majority of them developed by GTT, while 21% consists of independent tanks most of them with Moss Design and some with IHI design and Sayaringo - Sayaendo designs.

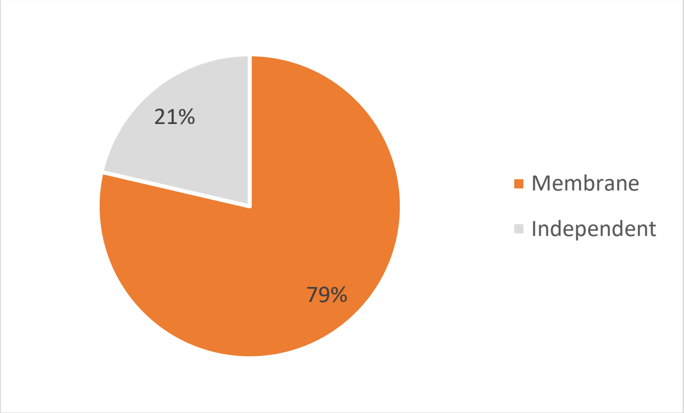


Figure 36: Existing fleet by containment type.

Orderbook.

According to the March 2022 data, the orderbook includes 167 LNG carriers. The orderbook is particularly large in comparison to recent years, approaching nearly 28% of the current fleet. This fact reflects the rise in LNG demand and trade. In regard to the size, 152 of the 166 LNG Carriers in the orderbook have a capacity of 150,000-180,000 m^3, 9 vessels have a capacity of 180,000-200,000 m^3, and 9 vessels have a capacity of less than 125,000 m^3. The order book has an average capacity of 168,382 m^3.

Dual fuel engines dominate in propulsion types, with slow-speed dual fuel engines having the largest market share. 107 vessels will be equipped with two stroke dual fuel engines from the major manufacturers, WIN GD and MAN. 27 vessels are designed with diesel electric propulsion, 3 vessels with liquid gas capacity 192,000 m^3 will have two stroke diesel engines, specifically the engine model 6G70ME-C10 from MAN, and the remaining 36 vessels in the order book have no information on the propulsion type. Regarding the cargo containment system, almost exclusively the membrane type cargo tanks, designed by Gaztransport and Technigaz, dominate the orderbook vessels with multiple possible design variations.

6.3 Overview of the fleet under study in comparison to the total existing fleet

As discussed in Chapter 5, the analysis included 267 LNG Carriers from the existing fleet because operational data for more vessels could not be found. So, the sample studied represents 44.5% of the existing fleet (267 out of 599 vessels). As a result, an overview of the ships studied based on their basic characteristics is required, as well as a projection to the current fleet, to determine whether the sample is representative of the entire global fleet and what specificities it presents. The analyzed sample is separated and compared to the global fleet based on the basic characteristics of age, size, and type of propulsion, as was done with the presentation of the existing fleet at the beginning of the chapter.

6.3.1 Overview of the fleet under study

The study fleet consists of ships ranging in age from 0 to 20, with the majority of ships falling into the 11-15 age range, with the remainder falling into the 0-5, 6-10, and 16-20 age ranges almost evenly distributed.

Table 23: Analyzed fleet per age category.

Age category	No. of vessels	% fleet
0-5	72	27.0%
6-10	65	24.3%
11-15	88	33.0%
16-20	42	15.7%
21-25	0	0.0%
26+	0	0.0%
Total	267	100.0%

In the categorization based on the type of propulsion, the largest percentage (40.4%) are ships with diesel electric propulsion, a quarter of the fleet have steam turbines and the remaining 33.7% consists of ships with slow-speed two-stroke diesel and dual fuel engines.

Table 24: Analyzed fleet per propulsion type.

Propulsion type	No. of vessels	% fleet
Steam turbine	64	24.0%
Diesel Electric (DFDE/TFDE)	108	40.4%
Slow speed Diesel	43	16.1%
Slow speed Dual Fuel	47	17.6%
STaGE	5	1.9%
Total	267	100.0%

Based on capacity, 62.2% of the fleet studied has a size between 150,000 and 180,000 m^3, 20.2% has a size between 125,000 and 150,000 m^3, the rest has bigger sizes, and only 1.1% have a size below 125,000 m^3.

Table 25: Analyzed fleet per size category.

Size	No. of vessels	% fleet
40k - 125k Cu.M	3	1.1%
125k - 150k Cu.M	54	20.2%
150k - 180k Cu.M	166	62.2%
180k - 200k Cu.M	0	0.0%
200k - 250k Cu.M	31	11.6%
250k+ Cu.M	13	4.9%
Total	267	100.0%

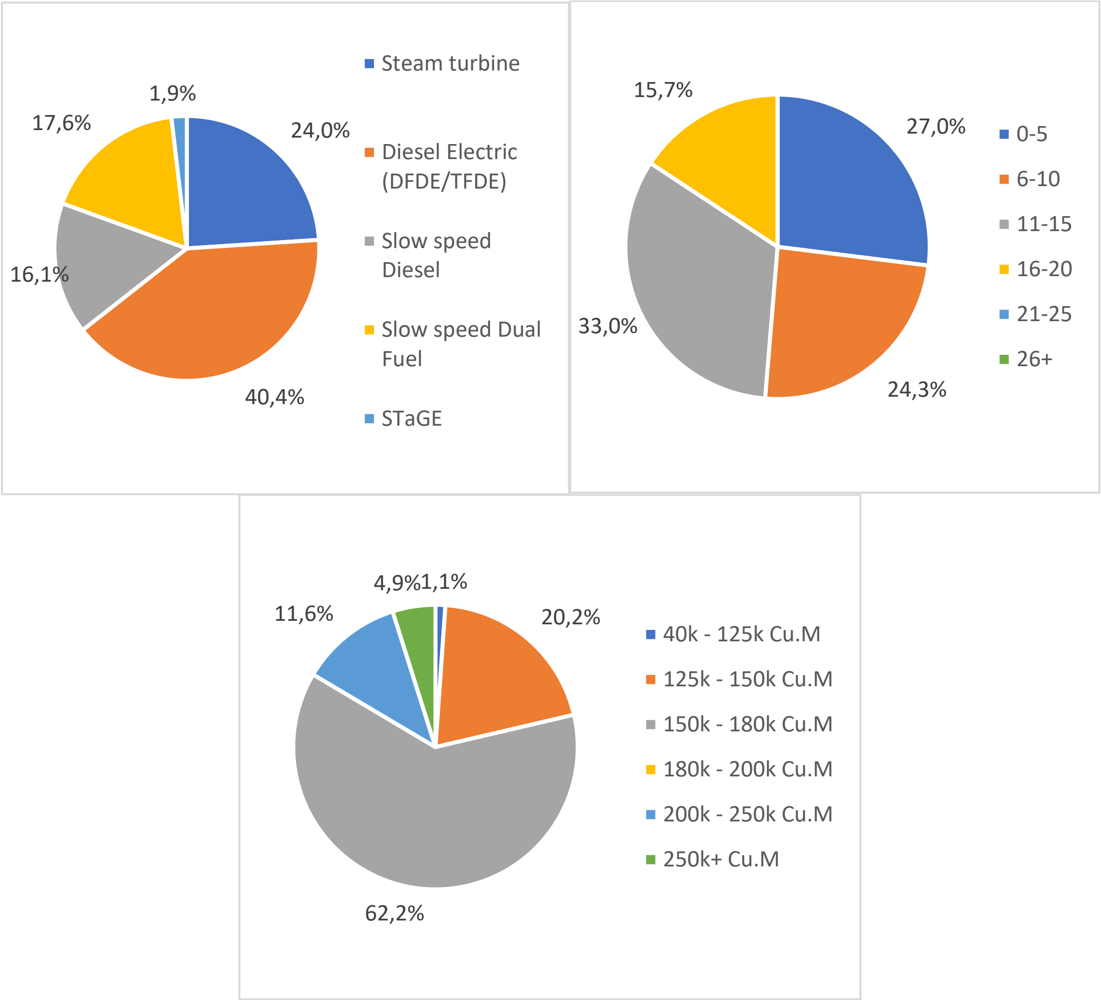


Figure 37: Overview of the fleet per propulsion type, age, size.

6.3.2 Comparison to the total existing fleet

The following tables compare the studied fleet to the total current fleet in the categories of age, size, and propulsion type in order to assess the sample's completeness and draw generalized conclusions for the entire LNG Carriers fleet.

Table 26: Comparison of the fleet under study to the total existing fleet based on age, propulsion type, and size.

	Total existing fleet	**Fleet analyzed**	**% of the total existing fleet**
Age category			
0-5	201	72	35.8%
6-10	101	65	64.4%
11-15	147	88	59.9%
16-20	84	42	50.0%
21-25	28	0	0.0%
26+	38	0	0.0%
Total	599	267	44.6%
Propulsion type			
Steam turbine	229	64	27.9%
Diesel Electric (DFDE/TFDE)	161	108	67.1%
Slow speed Diesel	48	43	89.6%
Slow speed Dual Fuel	153	47	30.7%
STaGE	8	5	62.5%
Total	599	267	44.6%
Size			
40k - 125k Cu.M	21	3	14.3%
125k - 150k Cu.M	189	54	28.6%
150k - 180k Cu.M	343	166	48.4%
180k - 200k Cu.M	1	0	0.0%
200k - 250k Cu.M	31	31	100.0%
250k+ Cu.M	14	13	92.9%
Total	599	267	44.6%

The analyzed sample does not include any ships older than 20 years, which account for 11% of the total existing fleet, while the percentage in the age category 0-5 is relatively small. Because the study's operational data refers to the year 2020, ships that entered the market in 2021 and 2022 (belonging to the age group 0-5) cannot be included in the sample. In the remaining age groups, the percentage is greater than 50%.

Regarding the type of propulsion, the percentage of ships with steam turbines is small, which coincides with the lack of data for the age categories over 20. Vessels with steam turbines are considered less efficient and are expected to have the most compliance issues with the regulation. Furthermore, the sample of two stroke dual fuel engines (30.7%) is small as they are the newest and most efficient propulsion type system. On the contrary, the percentage of ships powered by diesel electric propulsion is satisfactory, with data for 67.1% of all vessels.

Finally, the analysis includes nearly 90% of ships powered by two-stroke diesel engines (Q-Flex and Q-Max, Qatar fleet), providing us with a comprehensive picture of the CII and regulatory compliance of the specific ships.

6.4 Fleet compliance with the CII regulation

6.4.1 2023 - 2026 period

The first analysis was done concerns compliance with the regulation through the calculation of each ship's rating in the specific year. The Attained CII (or AER) has been calculated using the methodology described in Chapter 5. This section of the chapter presents the analysis for the entire fleet of the study, without taking into account the specific characteristics of each ship, intending to reach some generalized conclusions about the impact of CII regulation on a fleet level. It should be noted at this point that the results include all 16 LNG Carriers considered "Gas Carriers," as well as the corresponding reference lines of the Gas Carriers. The initial findings cover the period 2023-2026, and the reduction factors are calculated in accordance with the regulations.

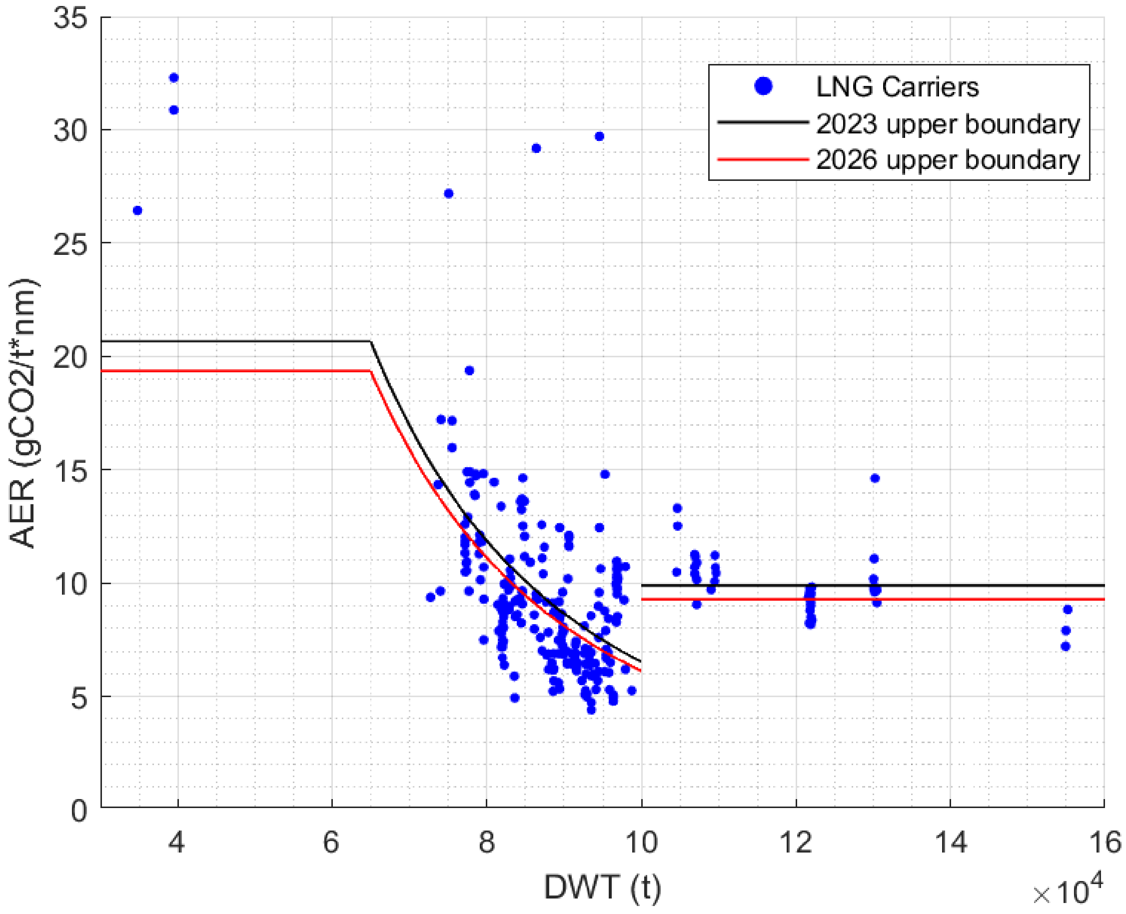


Figure 38: Attained AER in LNG Carriers fleet.

The blue dots in the figure above represent the achieved Carbon Intensity Indicator of each ship in the analyzed fleet as a function of DWT. In addition, the upper boundary of the required CII for 2023 and 2026 is featured in black and red, respectively.

The 16 vessels classified as "Gas Carriers" are not depicted in the scatter diagram above because they have different reference lines. For display purposes, only the curves corresponding to the upper boundaries of the required CII for each year were plotted. The dots above the upper boundary curve represent ships that received D or E ratings, while the dots below the upper boundary curve represent ships that received A, B, or C ratings.

The following table includes the precise number of ships for each rating as well as the percentage of the entire study fleet corresponding to the years 2023, 2024, 2025, and 2026.

The reduction factors relative to 2019 reference lines are 5%, 7%, 9% and 11% for the years 2023, 2024, 2025, 2026 respectively.

Table 27: CII rating statistics for the years 2023-2026.

CII RATING	No. of vessels	% of fleet analyzed	Capacity in m.cbm	% capacity of fleet analyzed
Results for 2023				
A	37	13.9%	6.38	14.2%
B	67	25.1%	11.28	25.1%
C	73	27.3%	12.38	27.5%
D	39	14.6%	6.35	14.1%
E	51	19.1%	8.57	19.1%
Total	267	100.0%	44.95	100.00%
Results for 2024				
A	31	11.6%	5.27	11.7%
B	60	22.5%	10.11	22.5%
C	72	27.0%	11.81	26.3%
D	46	17.2%	7.98	17.7%
E	58	21.7%	9.79	21.8%
Total	267	100.0%	44.95	100.00%
Results for 2025				
A	26	9.7%	4.42	9.8%
B	51	19.1%	8.58	19.1%
C	75	28.1%	12.31	27.4%
D	52	19.5%	8.90	19.8%
E	63	23.6%	10.75	23.9%
Total	267	100.0%	44.95	100.00%
Results for 2026				
A	22	8.2%	3.69	8.2%
B	44	16.5%	7.56	16.8%
C	77	28.8%	12.56	27.9%
D	52	19.5%	8.98	20.0%
E	72	27.0%	12.16	27.0%
Total	267	100.0%	44.95	100.00%

The table above contains some important information:

- In 2023, 39% of ships appear to be enough efficient and achieve A and B ratings, 27.3% are in the "grey zone" of C but remain compliant with the regulation, and the remaining 33.7% achieve D or E ratings and will need to take measures to increase their efficiency.
- In 2024, 34.1% receive A or B ratings, 27% receive C ratings, and 17.2% and 21.7% receive D and E ratings, respectively.
- In 2025, 43.1% attain D or E ratings and must take measures to comply with the regulation. As expected, as reference lines follow a steady annual decline, fewer and fewer ships achieve A and B ratings. Additionally, 12 ships (almost 4.5% of the fleet) that achieved a D rating on 2023, have attained an E rating until 2025, and are therefore forced to revise their SEEMP earlier than expected.
- In 2026, the last year with known reduction factors of the required CII, 143 ships (53.5% of the total fleet of the study) achieve A, B, or C ratings and are CII compliant. The remaining 46.5%, or 124 LNG Carriers, should have already taken measures to improve their energy efficiency or will need to do so in the near future. The 124 LNG Carriers with D or E ratings, with a total capacity of 21.14 million cubic meters, will face regulatory compliance challenges until 2026.

6.4.2 2027 - 2030 period

For the period after 2026, because the regulation is to be re-evaluated until 2026, certain trajectory scenarios were developed, as discussed in Chapter 5, on which the present results and conclusions are based. For the years 2027 to 2030, annual reduction rates of 2%, 3.5%, and 5% were assumed. The reduction factors for the CII relative to the 2019 reference line for each of the three trajectory scenarios can be found in Chapter 5 of the current thesis.

- 1st trajectory scenario.

The following table shows the CII rating statistics for the years 2027,2028,2029, and 2030 for the first trajectory scenario.

Table 28:CII rating statistics for the years 2027-2030, 1st trajectory scenario.

CII RATING	**No. of vessels.**	**% of fleet analyzed**	**Capacity in m.cbm**	**% capacity of fleet analyzed**
Results for 2027				
A	18	6.7%	3.04	6.8%
B	38	14.2%	6.50	14.4%
C	78	29.2%	12.69	28.2%
D	50	18.7%	8.19	18.2%
E	83	31.1%	14.53	32.3%
Total	267	100.0%	44.95	100.0%
Results for 2028				
A	14	5.2%	2.38	5.3%
B	31	11.6%	5.25	11.7%
C	76	28.5%	12.45	27.7%
D	59	22.1%	9.52	21.2%
E	87	32.6%	15.35	34.1%
Total	267	100.0%	44.95	100.00%

Results for 2029				
A	10	3.7%	1.71	3.8%
B	28	10.5%	4.70	10.5%
C	70	26.2%	11.47	25.5%
D	60	22.5%	9.74	21.7%
E	99	37.1%	17.33	38.6%
Total	267	100.0%	44.95	100.0%
Results for 2030				
A	7	2.6%	1.15	2.6%
B	25	9.4%	4.17	9.3%
C	71	26.6%	11.68	26.0%
D	60	22.5%	9.56	21.3%
E	104	39.0%	18.39	40.9%
Total	267	100.0%	44.95	100.0%

According to the first trajectory scenario, which is the most moderate because the annual reduction of the required CII is assumed to be the same as in the period 2023-2026, 103 ships remain compliant with the regulation until 2030, representing 38.6% of the fleet analyzed. The percentage of ships with D and E ratings is 61.4%, and they are expected to face challenges if their energy efficiency is not improved.

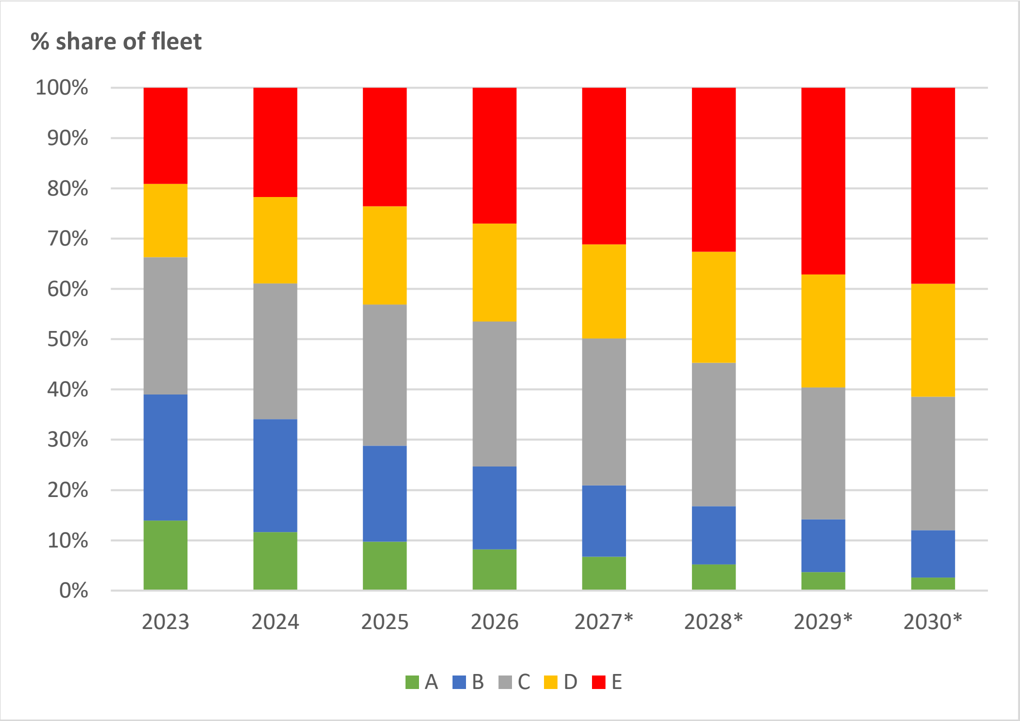


Figure 39: CII ratings for LNG Carrier fleet, 1st trajectory scenario.

The diagram below shows the number of vessels required to upgrade their SEEMP each year in order to comply with the regulation by 2030. The year this will be completed is determined by the definition of the CII regulation. For example, if a ship receives an E rating in 2023, it should upgrade the SEEMP in 2024, whereas if it receives a D rating in three consecutive years, 2023, 2024, and 2025, it should upgrade the SEEMP in 2026. To achieve a rating of C or better, 133 vessels (49.8%) will need to develop and implement an approved corrective action plan as part of SEEMP, according to the first trajectory scenario.

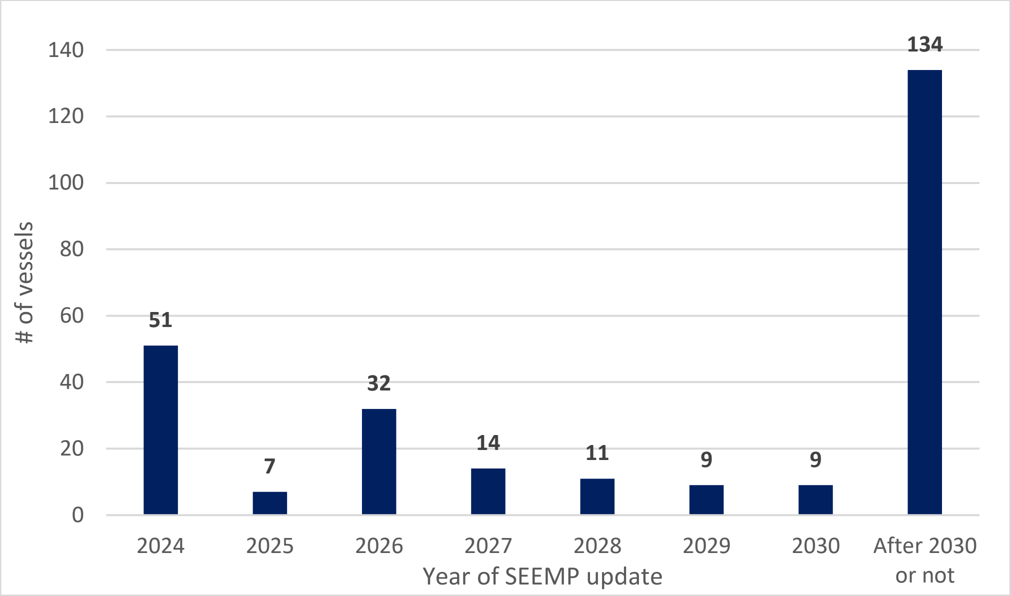


Figure 40: Year to update the SEEMP, 1st trajectory scenario.

- 2nd trajectory scenario.

The following table shows the CII rating statistics for the years 2027,2028,2029, and 2030 for the second trajectory scenario.

Table 29: CII rating statistics for the years 2027-2030, 2nd trajectory scenario.

CII RATING	No. of vessels	% of fleet analyzed	Capacity in m.cbm	% capacity of fleet analyzed
Results for 2027				
A	15	5.6%	2.56	5.7%
B	36	13.5%	6.13	13.6%
C	76	28.5%	12.34	27.5%
D	53	19.9%	8.57	19.1%
E	87	32.6%	15.35	34.1%
Total	267	100.0%	44.95	100.0%
Results for 2028				
A	8	3.0%	1.32	2.9%
B	28	10.5%	4.77	10.6%
C	71	26.6%	11.66	25.9%
D	59	22.1%	9.41	20.9%
E	101	37.8%	17.80	39.6%
Total	267	100.0%	44.95	100.0%

Results for 2029				
A	4	1.5%	0.65	1.4%
B	24	9.0%	4.02	9.0%
C	61	22.8%	10.00	22.2%
D	71	26.6%	11.27	25.1%
E	107	40.1%	19.01	42.3%
Total	267	100.0%	44.95	100.0%
Results for 2030				
A	3	1.1%	0.48	1.1%
B	17	6.4%	2.88	6.4%
C	42	15.7%	6.87	15.3%
D	86	32.2%	13.70	30.5%
E	119	44.6%	21.03	46.8%
Total	267	100.0%	44.95	100.0%

According to the above results for the second trajectory scenario, which assumes an increase in the annual reduction factor, 205 vessels (76.8% of the fleet) will achieve D or E ratings by 2030. The remaining 62 vessels (23.2%) appear to comply with the CII regulation until the end of the decade.

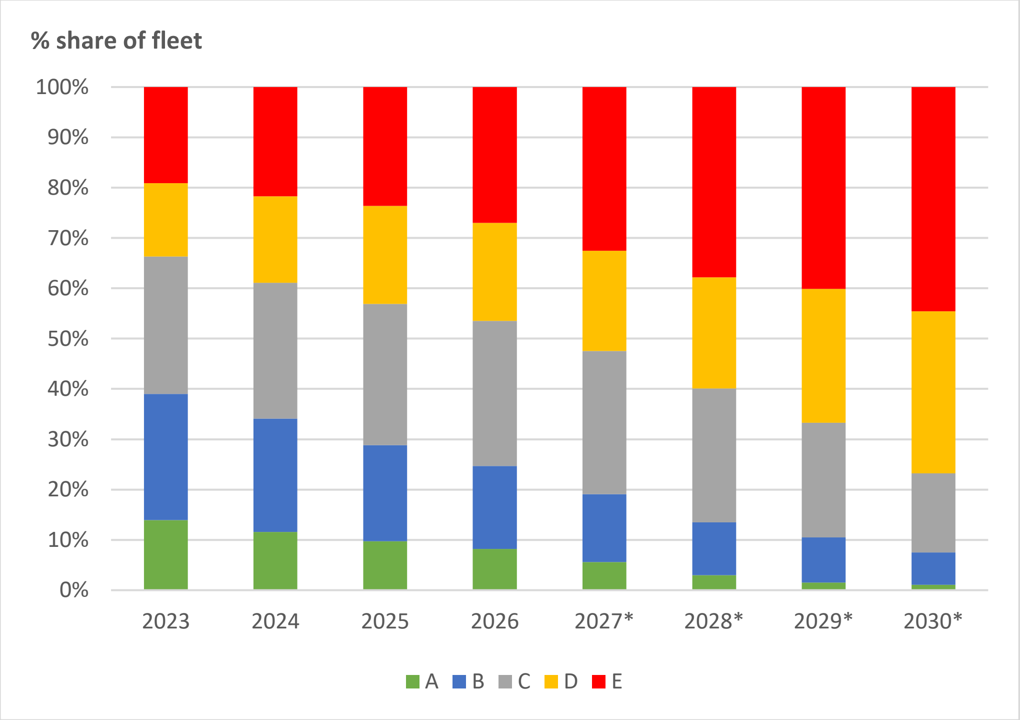


Figure 41: CII ratings for LNG Carrier fleet, 2nd trajectory scenario.

As shown in the next diagram, with the assumption of the same operational profile each year, 142 vessels (53.2%) will need to develop corrective actions to improve their ratings until the end of the decade while 125 vessels will have to improve their efficiency after 2030 or not at all.

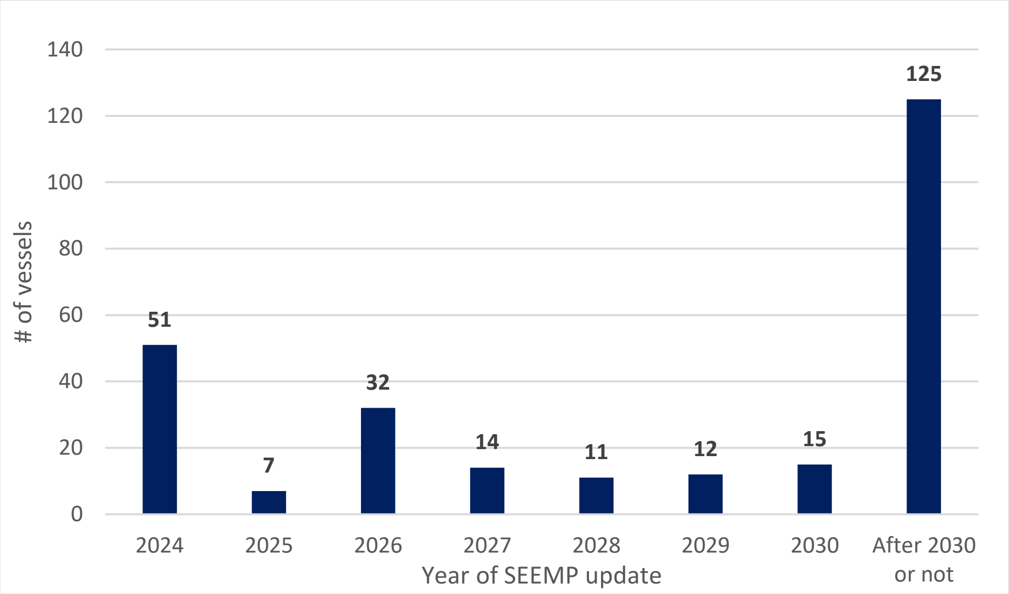


Figure 42: Year to update the SEEMP, 2nd trajectory scenario.

- 3rd trajectory scenario.

The following table shows the CII rating statistics for the third trajectory scenario for the years 2027,2028,2029, and 2030.

Table 30: CII rating statistics for the years 2027-2030, 3rd trajectory scenario.

CII RATING	No. of vessels	% of fleet analyzed	Capacity in m.cbm	% capacity of fleet analyzed
Results for 2027				
A	11	4.1%	1.87	4.2%
B	28	10.5%	4.71	10.5%
C	73	27.3%	11.92	26.5%
D	61	22.8%	9.99	22.2%
E	94	35.2%	16.46	36.6%
Total	267	100.0%	44.95	100.0%
Results for 2028				
A	5	1.9%	0.82	1.8%
B	24	9.0%	4.02	8.9%
C	64	24.0%	10.53	23.4%
D	67	25.1%	10.57	23.5%
E	107	40.1%	19.01	42.3%
Total	267	100.0%	44.95	100.0%

Results for 2029				
A	1	0.4%	0.15	0.3%
B	16	6.0%	2.63	5.9%
C	41	15.4%	6.82	15.2%
D	88	33.0%	14.05	31.3%
E	121	45.3%	21.30	47.4%
Total	267	100.0%	44.95	100.0%
Results for 2030				
A	1	0.4%	0.15	0.3%
B	5	1.9%	0.83	1.8%
C	29	10.9%	4.76	10.6%
D	86	32.2%	13.82	30.8%
E	146	54.7%	25.39	56.5%
Total	267	100.0%	44.95	100.0%

According to the third and stricter trajectory scenario, 232 vessels (86.9%) will fall into D or E ratings until 2030, while only 35 vessels will achieve A, B, or C ratings and remain compliant with the CII regulation.

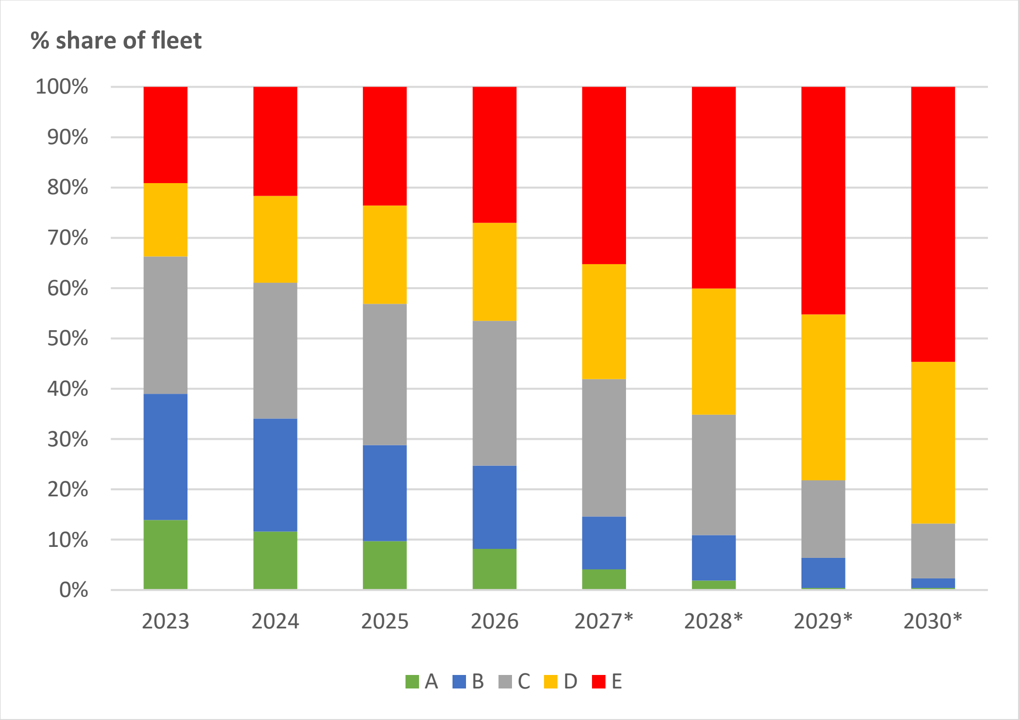


Figure 43: CII ratings for LNG Carrier fleet, 3rd trajectory scenario.

As shown in the next diagram, with the assumption of the same operational profile each year, 158 vessels (59.2 %) will need to develop corrective actions to improve their ratings until 2030 while 109 vessels will have to improve their efficiency after 2030 or not at all.

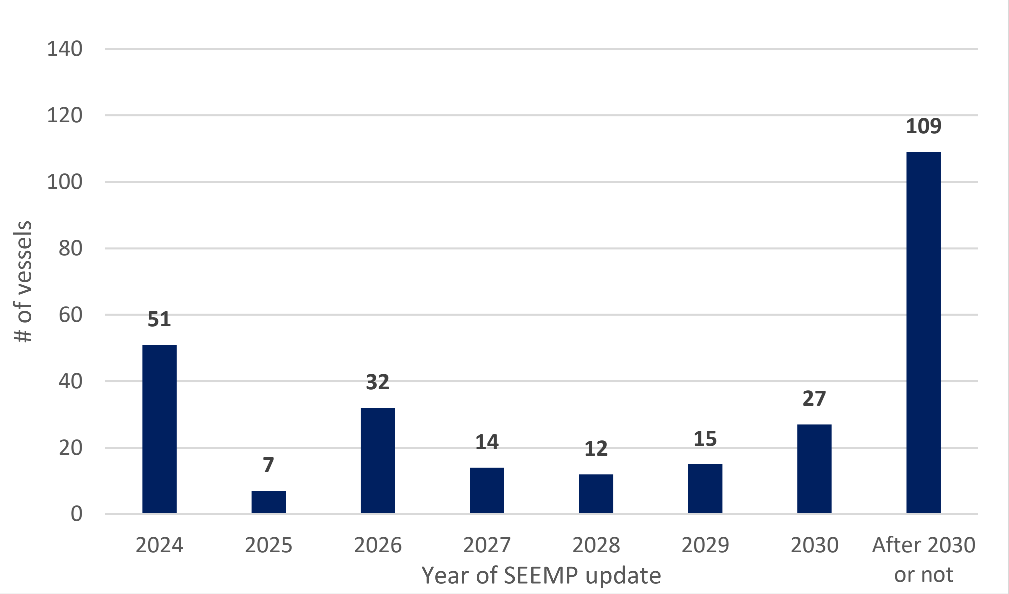


Figure 44: Year to update the SEEMP, 3rd trajectory scenario.

6.4.3 Fleet compliance per age category

The previous section of the chapter provides a summary of LNG Carriers fleet compliance with the regulation. The following section of the analysis presents the results of the regulatory compliance and ratings of the fleet's vessels by categorizing the vessels based on some of their basic characteristics and sub-categories to investigate if there is a correlation between each characteristic and the Annual Efficiency Ratio. The first classification is based on the age of each ship. The age category subcategories are the same as those used to describe the existing fleet at the beginning of the chapter.

- 0 - 5
- 6 - 10
- 11 - 15
- 16 - 20

At this point, it should be noted that all percentages in the following tables refer to the sample of LNG Carriers studied.

The following scatter diagram depicts the achieved Annual Efficiency Ratio per age category, as indicated by the colors in the legend, as well as the CII upper boundary curves for 2023 and 2026.

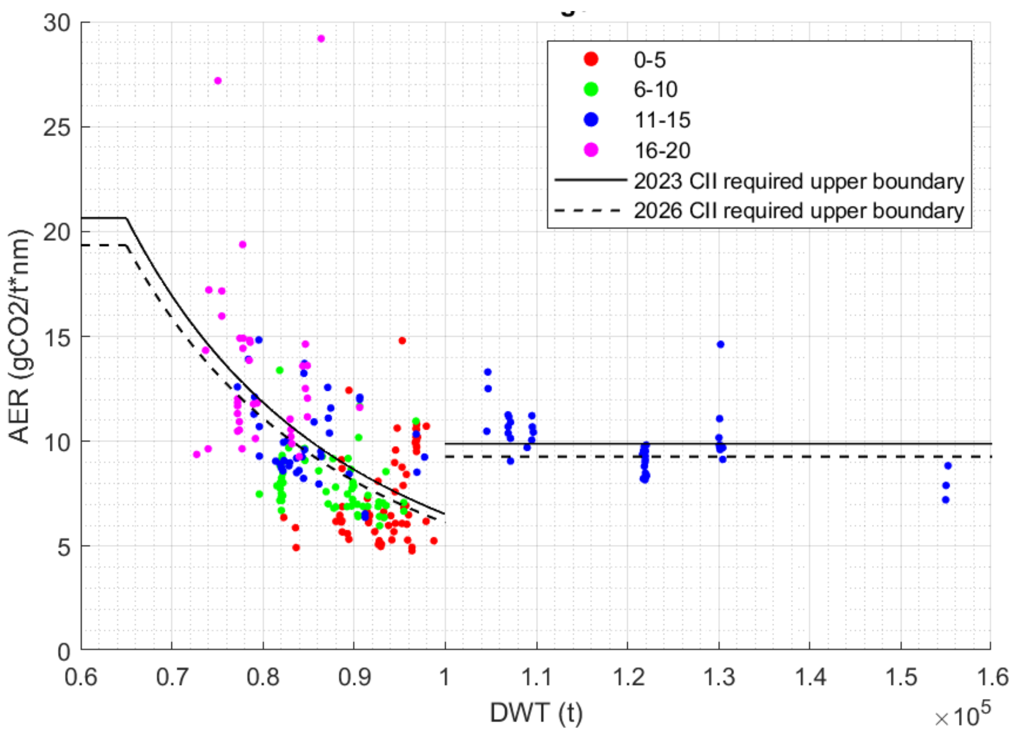


Figure 45: AER in LNG Carriers fleet per age category.

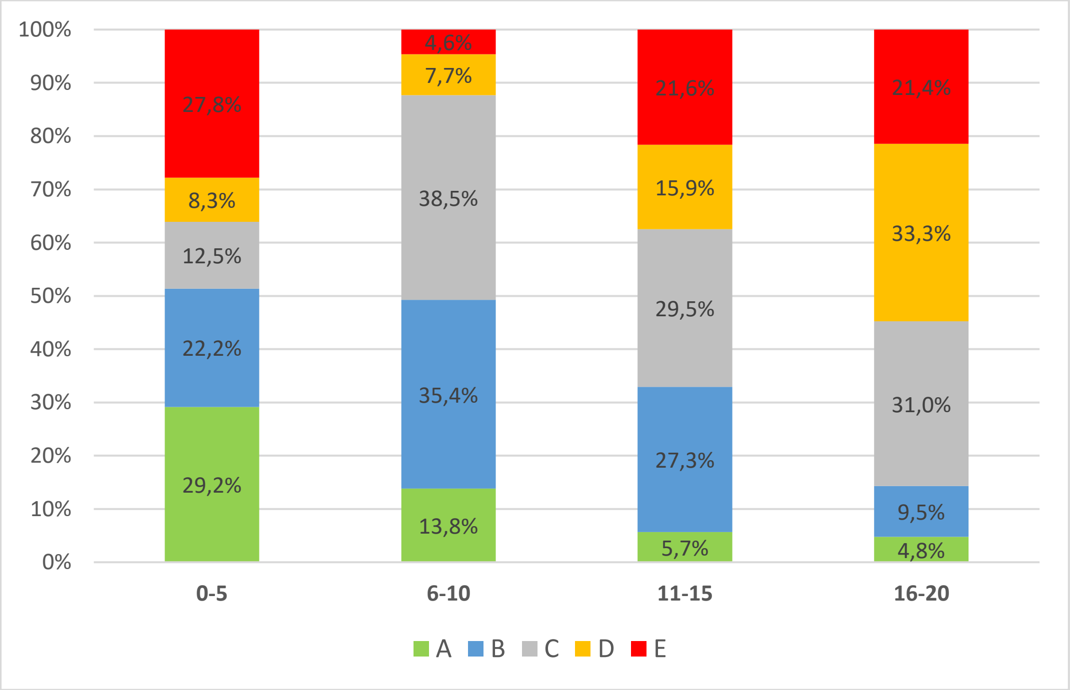


Figure 46: 2023 CII ratings per age category.

As can be observed from the diagrams above, the older LNG Carriers are less efficient than the younger vessels. In particular, 54.7% of ships in the age category 16-20 receive D or E ratings for 2023. In the 11-15 age group, 37.5% receive D or E ratings, while the remaining 62.5% appear to comply with the regulation. The age group 6-10 has the highest rate of compliance with the CII regulation, with 87.7% receiving an A, B, or C rating. Unexpected is the percentage of ships receiving an E rating in the age category 0-5, as newer ships should be more energy efficient. For 2023, 20 vessels, or 27.8% of those aged 0 to 5, receive an E rating. A closer examination of these vessels revealed that 14 of the 20 are sister vessels, and they must reduce their CII by 30.2% on average in order to comply with the regulation in 2023. The specific type of vessel will be discussed in the following section of the chapter.

The following table shows the CII ratings as well as the percentages in each age category for the years 2023 and 2026.

Table 31: CII ratings per age category for 2023,2026.

Age category	**No. of vessels**	Ratings				
		A	B	C	D	E
			2023			
0-5	72	29.2%	22.2%	12.5%	8.3%	27.8%
6-10	65	13.8%	35.4%	38.5%	7.7%	4.6%
11-15	88	5.7%	27.3%	29.5%	15.9%	21.6%
16-20	42	4.8%	9.5%	31.0%	33.3%	21.4%
			2026			
0-5	72	19.4%	23.6%	16.7%	9.7%	30.6%
6-10	65	7.7%	23.1%	47.7%	13.8%	7.7%
11-15	88	1.1%	12.5%	27.3%	26.1%	33.0%
16-20	42	4.8%	2.4%	23.8%	31.0%	38.1%

6.4.4 Fleet compliance per size category

Even though the size of the ship is involved in CII calculation with the form of DWT, it was chosen to analyze the fleet compliance based on the size in the form of capacity in cubic meters. Therefore, the second categorization concerns the size of the ship and the subcategories are the same as those used in the description of the existing fleet.

- 40,000 – 125,000 Cubic meters
- 125,000 – 150,000 Cubic meters
- 150,000 – 180,000 Cubic meters
- 200,000 – 250,000 Cubic meters
- 250,000+ Cubic meters

The following scatter diagram illustrates the achieved Annual Efficiency Ratio per size category based on the colors in the legend, as well as the CII upper boundary curves for 2023 and 2026.

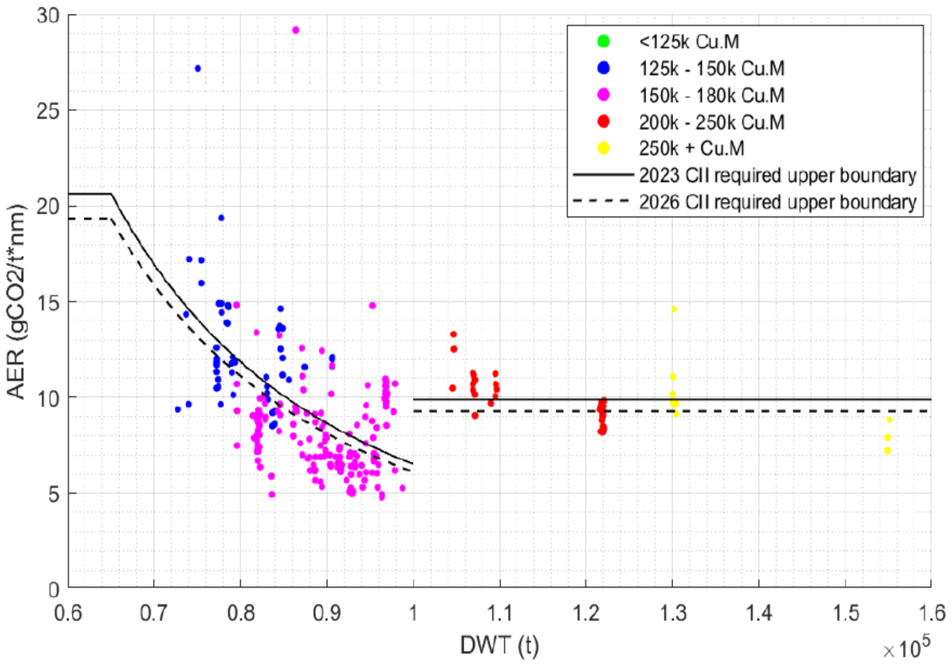


Figure 47: AER in LNG Carriers fleet per size category.

Table 32: CII ratings per age category for 2023,2026.

Size category	No. of vessels	Ratings				
		A	B	C	D	E
2023						
40k - 125k Cu.M	3	0.0%	0.0%	0.0%	0.0%	100.0%
125k - 150k Cu.M	54	3.7%	14.8%	31.5%	31.5%	18.5%
150k - 180k Cu.M	166	18.1%	30.1%	25.3%	9.6%	16.9%
200k - 250k Cu.M	31	9.7%	22.6%	25.8%	16.1%	25.8%
250k+ Cu.M	13	15.4%	15.4%	46.2%	7.7%	15.4%
2026						
40k - 125k Cu.M	3	0.0%	0.0%	0.0%	0.0%	100.0%
125k - 150k Cu.M	54	3.7%	1.9%	29.6%	31.5%	33.3%
150k - 180k Cu.M	166	11.4%	21.7%	32.5%	13.3%	21.1%
200k - 250k Cu.M	31	0.0%	19.4%	16.1%	22.6%	41.9%
250k+ Cu.M	13	7.7%	7.7%	15.4%	46.2%	23.1%

Based on the above results, ships of smaller size, specifically those in the 125,000-150,000 cubic meters subcategory, have lower ratings than those in the 150,000-180,000 cubic meters subcategory. The effect of DWT on ratings appears to be significant depending on the size sub-category, as there is a region between the values of 80,000 and 90,000 tons DWT where the increase in DWT is not consistent with the increase in capacity in cubic meters. For example, two ships with similar cubic capacity may have different DWT and CII for the same CO_2 emissions.

6.4.5 Fleet compliance per propulsion type

The third and most important categorization of the LNG Carriers fleet is based solely on technical characteristics and is the type of propulsion. The efficiency of each vessel is highly dependent on the main engine type, as this consumes the most fuel and thus is the most polluter in terms of CO_2 emissions.

In this section of the chapter, first, a general analysis by propulsion technology is completed, and then results are presented by propulsion type, including more detailed features such as the inclusion of methane slip, in order to draw both general and specialized conclusions about CII compliance and the dependence of the AER on the propulsion technology.

The following propulsion sub-categories are included in the propulsion type categorization.

- Steam turbine.
- Diesel electric propulsion (Dual Fuel Diesel Electric and Tri-Fuel Diesel Electric).
- Slow speed diesel.
- Slow speed Dual Fuel.
- STaGE

The following scatter diagram illustrates the achieved Annual Efficiency Ratio per propulsion type based on the colors in the legend, as well as the CII upper boundary curves for 2023 and 2026.

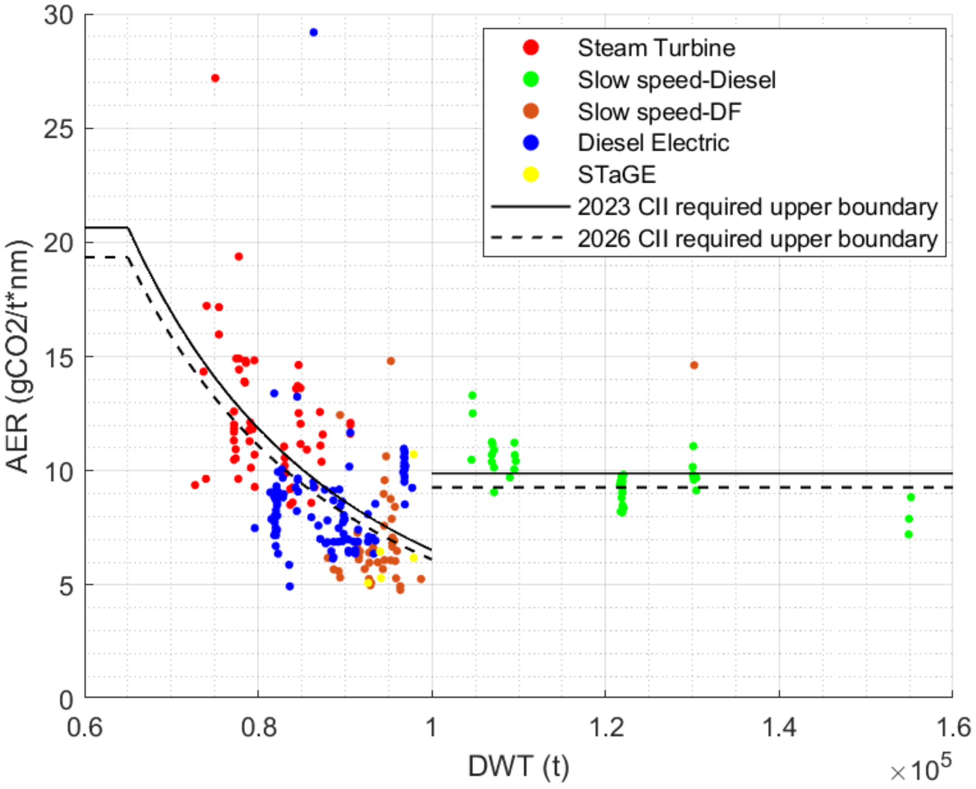


Figure 48: AER in LNG Carriers fleet per propulsion type.

The LNG carriers with steam turbine propulsion appear to face the greatest compliance challenges at first glance in the scatter diagram above, whereas the vessels with diesel electric propulsion and slow speed dual fuel appear to be more efficient.

The chart diagrams below show, in accordance with the reference lines of the regulation, the CII ratings for each propulsion type category for the years 2023 and 2026.

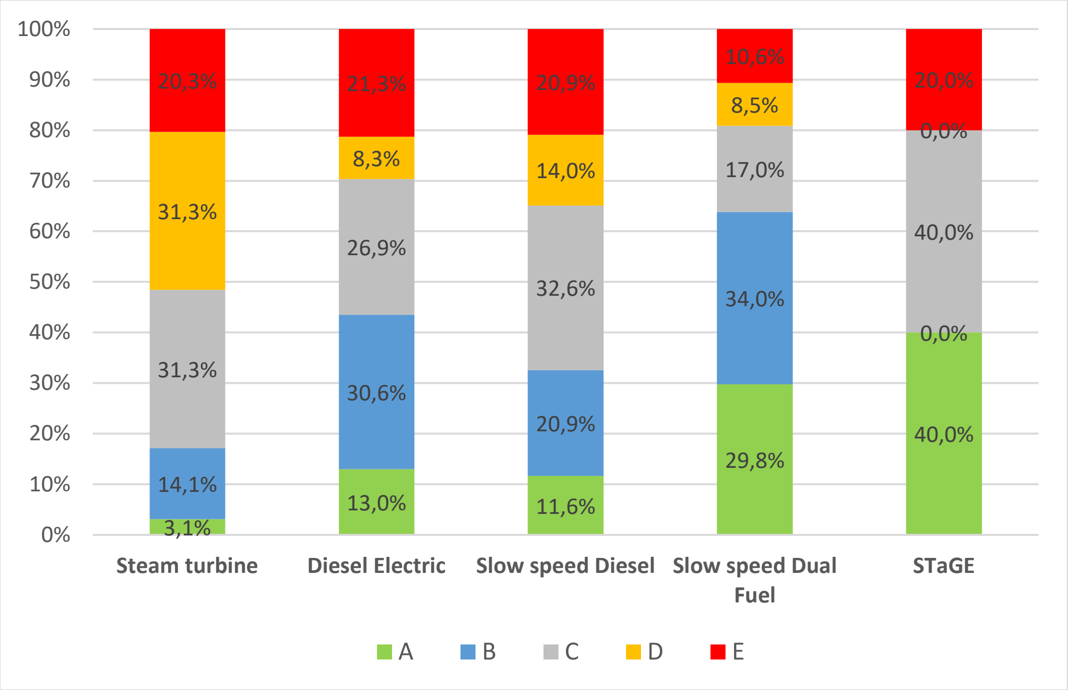


Figure 49: 2023 CII ratings per propulsion type category.

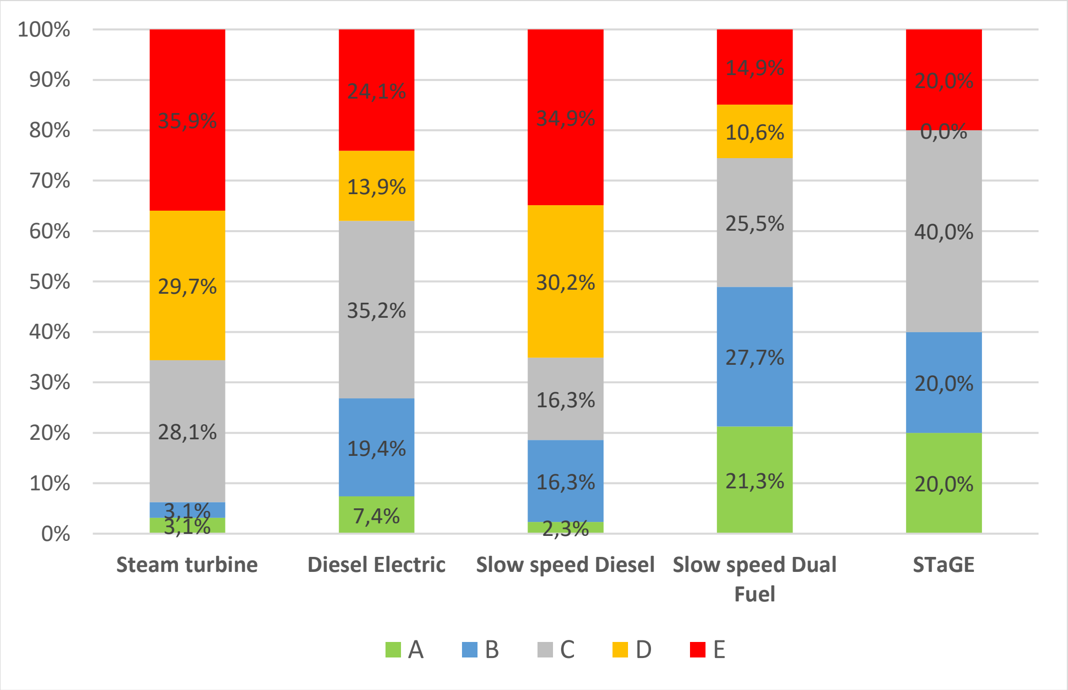


Figure 50: 2026 CII ratings per propulsion type category.

- LNG Carriers with steam turbine for propulsion are by far the least efficient based on AER. In 2023, only 17.2% of ships receive A and B ratings, while 62.6% receive C or E ratings equally. In 2023, 20.3% of ships with steam turbines achieve an E rating, increasing to 35.9% in 2026. Compliance with the CII regulation requirements for these ships is expected to be difficult as early as 2023, let alone until the end of the decade in the 2030s.

- The LNG Carriers with two-stroke slow speed diesel engines for propulsion are the second most affected category by the regulation. In 2023, 34.9% (15 vessels) achieve D or E ratings, while the remaining 65.1% (28 vessels) appear to comply with the CII regulation. The sample's satisfactory completeness in terms of the total global fleet in this propulsion type subcategory, combined with the fact that the fuel is exclusively Diesel (rather than a mixture of Diesel and LNG, which can result in significant differences depending on operational conditions), allows for more assured conclusions about the impact of the regulation on these ships.

- Vessels with diesel electric propulsion, either dual fuel or tri-fuel, comply with the regulation adequately. In 2023, 13% will have an A rating, 30.6% will have a B rating, and 26.9% will have a C rating and be in compliance with the requirements of the CII regulation. 32 vessels have received D or E ratings and must take action to comply with the CII regulation's requirements in the upcoming years.

- Slow speed dual fuel propulsion is the most energy efficient type of propulsion. This conclusion was predictable given that the majority of these ships are outfitted with engines from the most current development, which are more efficient. In 2026, the compliance percentage of these vessels with the regulation is slightly less than 80%, with a large percentage of these vessels labeled with A and B ratings. However, several ships with D or E ratings will require efficiency improvements. As a result, even in the theoretically most efficient vessels, compliance with the CII regulation until the end of the decade is expected to have an impact.

- Although the small number of ships (5 in this sample) limits the ability to draw safe conclusions, LNG Carriers with STaGE propulsion appear to be efficient enough in terms of AER.

In conclusion, as expected, the type of propulsion appears to have a direct correlation with the achieved CII and the rating of each ship with LNG Carriers equipped with dual fuel engines (either four stroke or two stroke) to achieve better compliance with the CII regulation. The correction factors in the CII calculation, particularly the one concerning the consumption of the reliquefication system, may provide advantageous circumstances for newer vessels and those outfitted with such systems.

6.4.5.1 Including the effect of methane slip

In this section of the chapter, unburnt methane emissions were included in total CO_2 emissions using the GWP100 of CH_4 to reassess fleet compliance in a regulation review scenario that would include the methane slip per type of propulsion, as described at the end of Chapter 5. This analysis excludes LNG carriers with two-stroke diesel propulsion and STaGE propulsion, while the slow speed dual fuel category includes two subcategories: high-pressure engines and low-pressure engines.

The table below lists the percentages based on the ratings using the reference lines for the years 2023 and 2026.

Table 33: CII ratings per propulsion type in 2023,2026 (including methane slip).

Propulsion type	**No. of vessels**	Ratings				
		A	B	C	D	E
2023						
Steam turbine	64	3.1%	15.6%	29.7%	31.3%	20.3%
Diesel Electric	108	0.9%	5.6%	19.4%	41.7%	32.4%
Slow speed Dual Fuel (LPDF)	19	21.1%	36.8%	36.8%	0.0%	5.3%
Slow speed Dual Fuel (HPDF)	28	14.3%	32.1%	25.0%	14.3%	14.3%
2026						
Steam turbine	64	3.1%	4.7%	29.7%	34.4%	28.1%
Diesel Electric	108	0.9%	2.8%	13.0%	43.5%	39.8%
Slow speed Dual Fuel (LPDF)	19	5.3%	42.1%	42.1%	5.3%	5.3%
Slow speed Dual Fuel (HPDF)	28	7.1%	25.0%	28.6%	17.9%	21.4%

Because of the small percentage of unburned methane escaping, the effect of methane slip on ships with steam turbines is negligible. The methane slip effect varies depending on engine technology in two stroke dual-fuel engines, which dominate the orderbook and are considered the most efficient propulsion technology today. The methane slip is lower in MAN's high-pressure dual fuel engines, increasing the Carbon Intensity Indicator by nearly 1.8% without having a significant effect. On the contrary, methane slip is significantly higher in low-pressure dual fuel engines manufactured by WIN GD, increasing the Carbon Intensity Indicator as the carbon factor increases by nearly 15.6%, a significant enough percentage to change a ship's rating. The carbon factor of four stroke dual fuel engines (or tri-fuel) increases by 28.5% as a result of methane slip. In the normal scenario, where methane slip is not considered, LNG Carriers with diesel electric propulsion appear to be efficient enough to achieve satisfactory compliance with the regulation, as 70.5% of the analyzed fleet achieves A,B, or C ratings by 2023. When methane slip is considered and analyzed, the efficiency and high rating of DFDE/TFDEs are compromised, as the percentage of vessels with A, B, or C ratings is only 25.9%.

As a result, the inclusion of methane slip in the CII regulation will have a significant impact on LNG Carriers with diesel electric propulsion, as well as vessels with two stroke low pressure dual fuel engines, while the impact on steam turbine propelled vessels and those with two stroke high pressure dual fuel engines is expected to be minimal. Overall, and because low pressure dual fuel engines are more efficient than steam turbines, the potential inclusion of methane slip will increase the percentage of non-compliant ships significantly until the end of the decade.

The scatter diagrams below show the achieved AER with and without methane slip for each propulsion type listed in the table above.

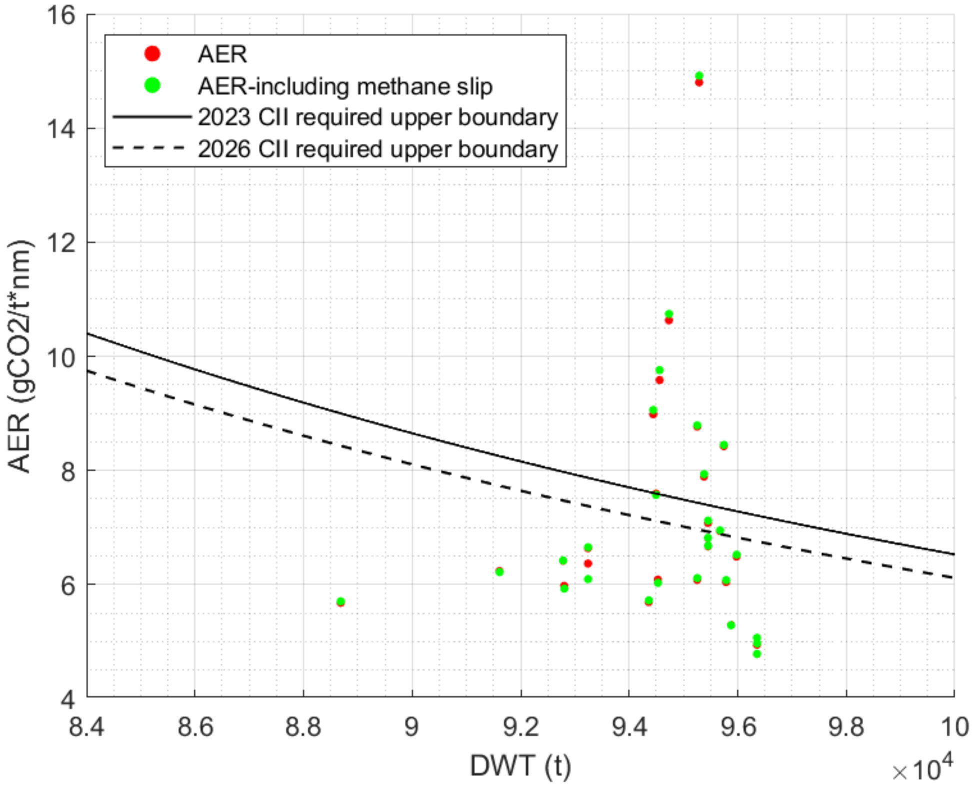


Figure 51: AER - 2S High Pressure Dual fuel engines.

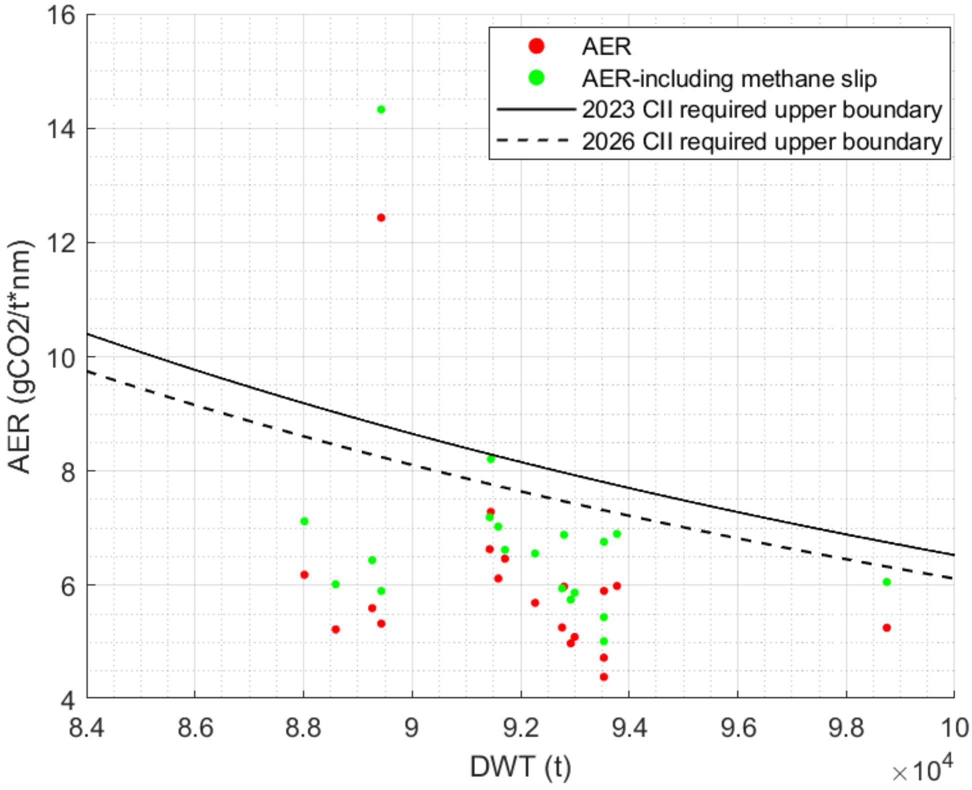


Figure 52: AER - 2S Low Pressure Dual Fuel engines.

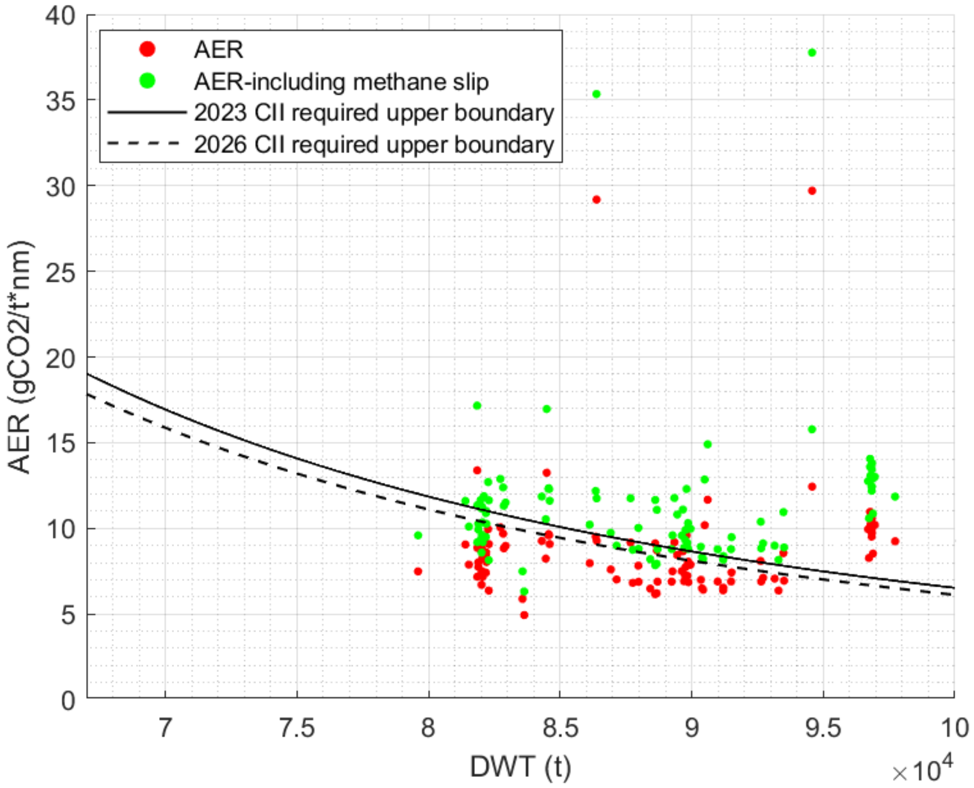


Figure 53: AER - 4S Low Pressure Dual Fuel engines.

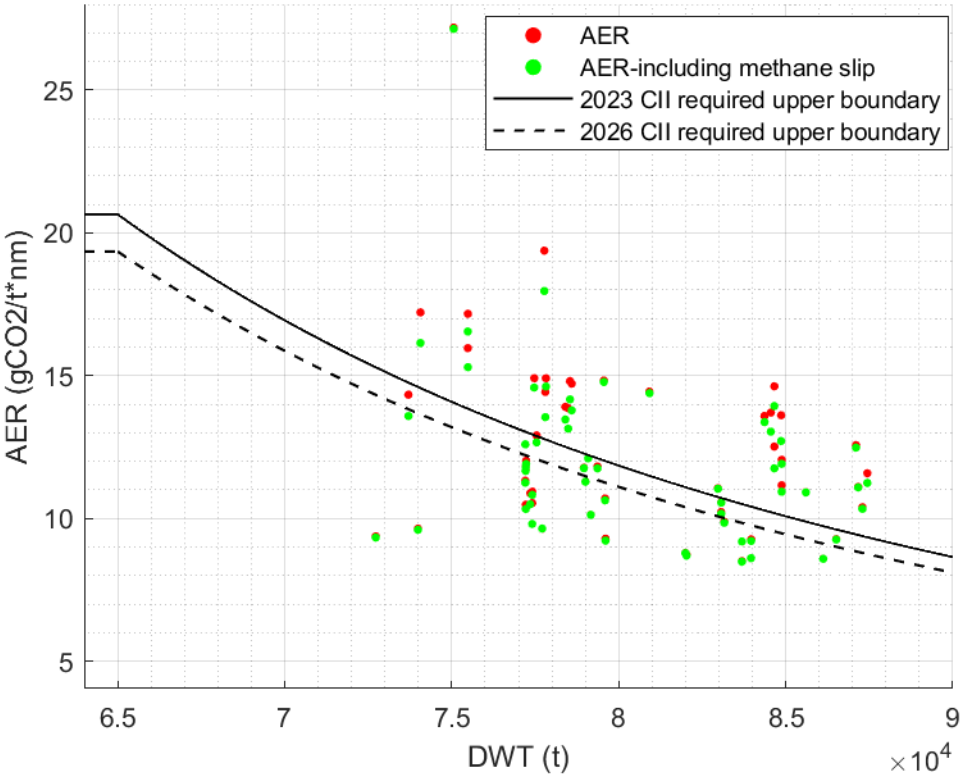


Figure 54: AER - Steam turbines.

6.5 CII in similar vessels

This section of the chapter compares the achieved CII (or AER) of similar ships. The analysis goal is to evaluate the operational factor underlying the CII and the potential for improvement in operation and subsequent compliance with the regulation. As a result, the CII is compared between sister vessels that have mostly the same technical characteristics but may differ in the attained CII and ratings. The "Lead vessel IMO number" field in the datafile is used to identify the sister vessels. Certain ship categories were chosen for this analysis in order to have as many sister vessels as possible covering a wide range of LNG Carriers. Ten different types of LNG Carriers were chosen to be examined.

The following two tables show the basic technical and non-technical characteristics, as well as basic estimates for the calculated CII, such as the average, minimum, and maximum CII for each of the ten vessel types.

Table 34: AER in sister vessels, Types 1-5.

	Vessel Type 1	**Vessel Type 2**	**Vessel Type 3**	**Vessel Type 4**	**Vessel Type 5**
Size category (cu.m)	150,000-180,000	150,000-180,000	200,000-250,000	200,000-250,000	250,000+
Age category	0-5, 6-10	0-5	11-15	11-15	11-15
Service speed (kn)	16	19.5	19.5	19.5	19
Propulsion type	Diesel Electric	STaGE	Slow speed Diesel	Slow speed Diesel	Slow speed Diesel
Engine model	12V50DF	MR21-II	6S70ME-C	6S70ME-C	7S70ME-C*
CCS Design	Gtt96 Gw	Sayaringo-Moss	Gtt Mkiii	Gtt Mkiii	Gtt Mkiii
Shipbuilder	DSME	Mitsubishi SB Nagasaki	HHI - Ulsan	SHI - Geoje	SHI - Geoje
Standard ship design	DSME Yamalmax	Sayaringo STaGE	Q-Flex	Q-Flex	Q-Max
Number of vessels	15	5	8	7	10
Average CII (gCO2/t*nm)	10.254	6.750	10.936	10.648	10.341
Standard Deviation	0.448	2.293	1.352	0.613	1.583
Min CII	9.513	5.088	9.057	9.706	9.140
Max CII	10.961	10.720	13.301	11.260	14.618
Higher rating	E	A	B	C	B
Lower rating	E	E	E	E	E
The CII ratings are based on the reduction factor of 2023.					
*** The 7S70ME-C8-GI engine model is installed in one vessel.**					

Table 35: AER in sister vessels, Types 6-10.

	Vessel Type 6	Vessel Type 7	Vessel Type 8	Vessel Type 9	Vessel Type 10
Size category (cu.m)	150,000-180,000	150,000-180,000	150,000-180,000	150,000-180,000	125,000-150,000
Age category	6-10	0-5	0-5	6-10	11-15,16-20
Service speed (kn)	19.5	15	19.5	19.5	16
Propulsion type	Diesel Electric	Slow speed Dual Fuel	Slow speed Dual Fuel	Diesel Electric	Steam Turbine
Engine model	12V50DF	5G70ME-C9-GI	5X72DF	9L50DF	UA-400
CCS Design	Gtt Mkiii	Gtt96 Gw	Gtt Mkiii	Gtt96 L03	Gtt96 Design
Shipbuilder	SHI - Geoje	DSME	HHI - Ulsan, HSHI	DSME	IZAR
Standard ship design	-	-	-	-	-
Number of vessels	8	5	4	9	6
Average CII (gCO2/t*nm)	7.836	7.588	5.004	7.817	11.659
Standard Deviation	0.711	1.715	0.645	1.050	0.713
Min CII	6.705	5.694	4.397	6.862	10.481
Max CII	8.793	9.583	5.901	9.594	12.595
Higher rating	A	B	A	B	B
Lower rating	B	E	B	D	C
The CII ratings are based on the reduction factor of 2023.					

- Despite being built in the last decade and using diesel electric propulsion, all vessels of type 1 receive E ratings. If no adjustments are done to the CII calculation via correction factors, these vessels are expected to face significant difficulties complying with the regulation, as they require an average reduction of 30%.

- The vessels of type 2 appear to comply with the regulations sufficiently. The fact that a ship receives an E rating with nearly double the CII could indicate a problem with reporting and data quality.

- Types 3 and 4, with Q-Flex designs, appear to have a close average CII, though ratings in both types may range from B to E and C to E, respectively. The operational factor in these vessels is quite important, with a difference of up to 16% in type 4.

- The difference between type 5 sister ships with Q-Max design is close to 20%. Despite the fact that one vessel's engine has been converted to dual fuel, it has the highest CII. This paradox may be due to poor data quality, but it also highlights the operational factor, as the specific vessel should have achieved a significantly lower CII.

- Type 6 vessels receive A and B ratings, with a CII difference of close to 30% between two similar vessels.
- There are significant differences in the ratings of type 7 vessels for 2023, with ratings ranging from B to E. The vessels of type 8 are enough energy efficient to achieve A and B ratings, while the biggest difference in the attained CII is 34%.
- The CII of the vessels of type 9 also varies greatly, ranging from 6,862 to 9,594 gCO_2/t*nm. Apart from the operational factor, this great difference may be due to poor reporting data quality.
- The AER of the six vessels of vessel type 10 with steam turbine appears to be close, with the biggest difference being 20%. As a result, improving the operational profile of such a ship can result in a rating change from C to B.

In conclusion, differences in CII between similar ships in some types of LNG Carriers exist due to the operational profile of the ships, which can be eliminated and be a solution to comply with the regulation. Significant CII differences between sister ships may indicate reporting errors and, as a result, poor data quality. Finally, it turns out that the Carbon Intensity Indicator and the differences in ratings are highly sensitive.

The following scatter diagrams depict the achieved Annual Efficiency Ratio per vessel type, as indicated by the colors in the legend, as well as the CII boundary curves for 2023.

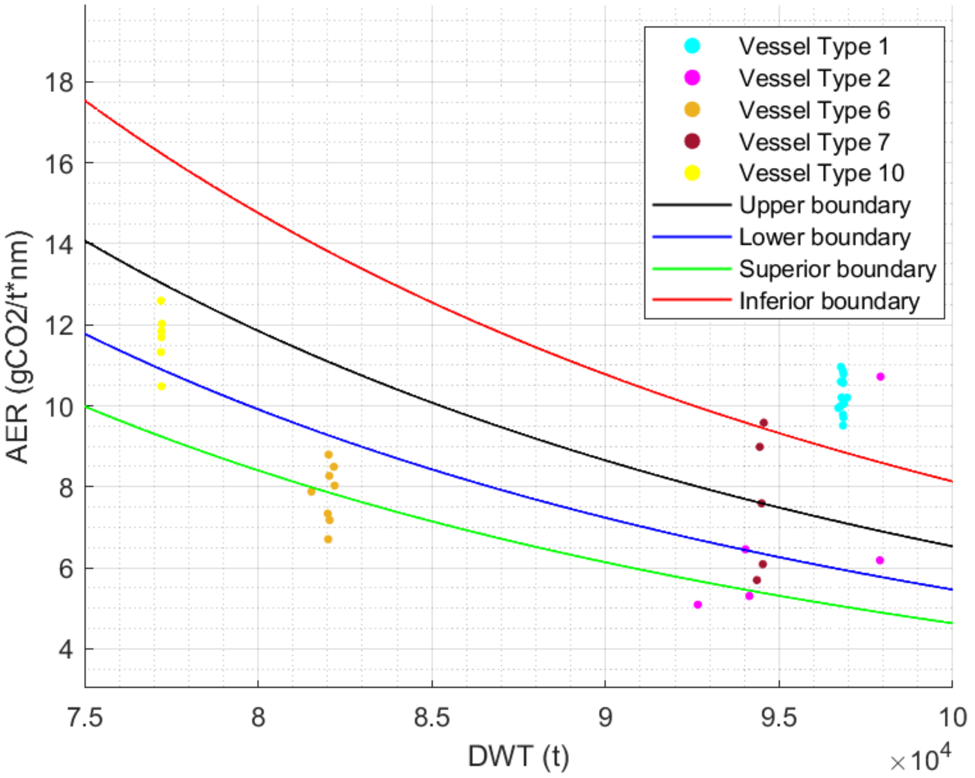


Figure 55: AER in similar vessels-Types 1,2,6,7,10.

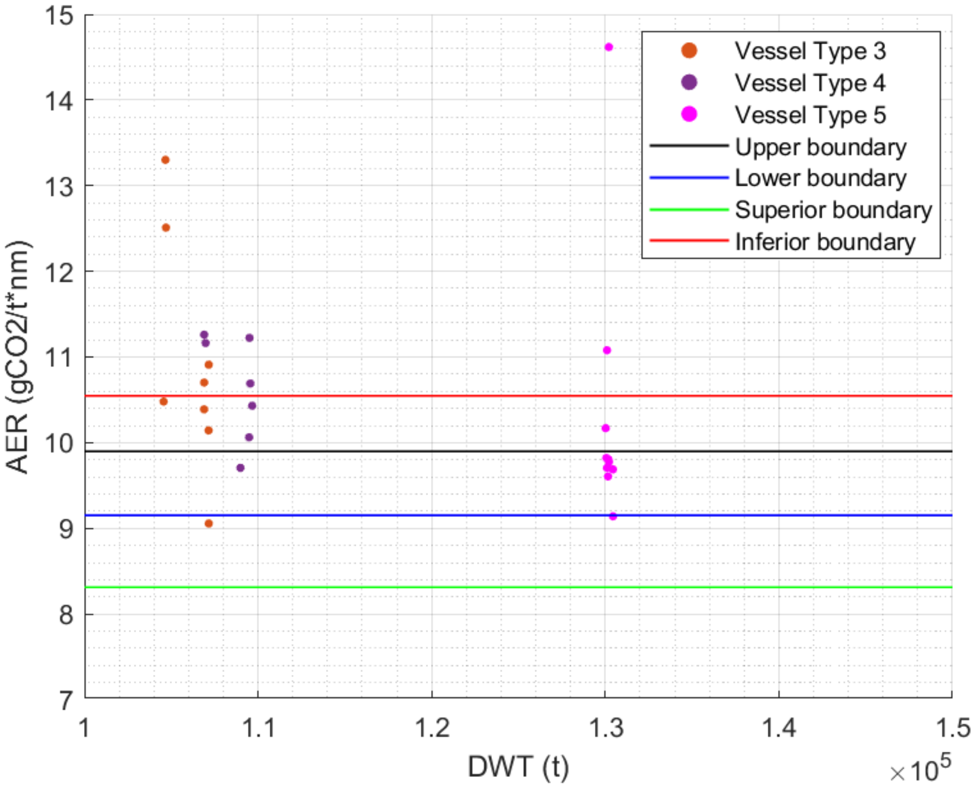
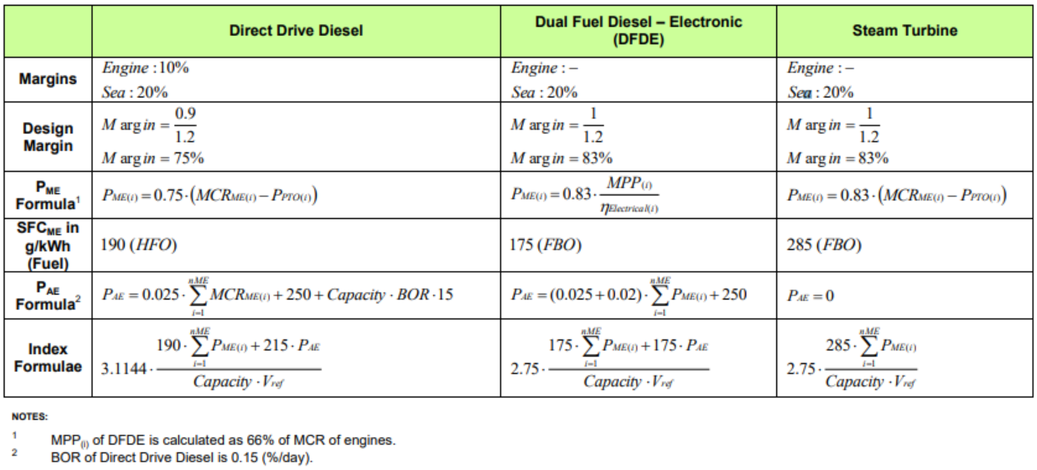


Figure 56: AER in similar vessels, Types 3,4,5.

6.6 Estimated Index Value (EIV) and Energy Efficiency Design Index (EEDI) vs Carbon Intensity Indicator (CII).

As there is data on technical efficiency from the MRV in the form of EIV or EEDI, it was chosen to compare the theoretically expected technical efficiency and the actual operational performance from the CII calculation in the form of AER. Most LNG Carriers have no EEDI data but only EIV data because they are either pre-EEDI ships or the companies have chosen to report only EIV. The form of EIV for LNG Carriers is provided in MEPC 231 (65) and is shown in the table below.

Table 36: Equation for calculating the index value of reference line for LNG Carriers [68].



	Direct Drive Diesel	**Dual Fuel Diesel – Electronic (DFDE)**	**Steam Turbine**
Margins	$Engine: 10\%$ $Sea: 20\%$	$Engine: -$ $Sea: 20\%$	$Engine: -$ $Sea: 20\%$
Design Margin	$M\arg in = \frac{0.9}{1.2}$ $M\arg in = 75\%$	$M\arg in = \frac{1}{1.2}$ $M\arg in = 83\%$	$M\arg in = \frac{1}{1.2}$ $M\arg in = 83\%$
P_{ME} Formula[1]	$P_{ME(i)} = 0.75 \cdot (MCR_{ME(i)} - P_{PTO(i)})$	$P_{ME(i)} = 0.83 \cdot \frac{MPP_{(i)}}{\eta_{Electrical(i)}}$	$P_{ME(i)} = 0.83 \cdot (MCR_{ME(i)} - P_{PTO(i)})$
SFC_{ME} in g/kWh (Fuel)	190 (*HFO*)	175 (*FBO*)	285 (*FBO*)
P_{AE} Formula[2]	$P_{AE} = 0.025 \cdot \sum_{i=1}^{nME} MCR_{ME(i)} + 250 + Capacity \cdot BOR \cdot 15$	$P_{AE} = (0.025 + 0.02) \cdot \sum_{i=1}^{nME} P_{ME(i)} + 250$	$P_{AE} = 0$
Index Formulae	$3.1144 \cdot \frac{190 \cdot \sum_{i=1}^{nME} P_{ME(i)} + 215 \cdot P_{AE}}{Capacity \cdot V_{ref}}$	$2.75 \cdot \frac{175 \cdot \sum_{i=1}^{nME} P_{ME(i)} + 175 \cdot P_{AE}}{Capacity \cdot V_{ref}}$	$2.75 \cdot \frac{285 \cdot \sum_{i=1}^{nME} P_{ME(i)}}{Capacity \cdot V_{ref}}$

NOTES:

[1] $MPP_{(i)}$ of DFDE is calculated as 66% of MCR of engines.

[2] BOR of Direct Drive Diesel is 0.15 (%/day).

The diagrams below show the number of ships per percentage difference between the CII and the EIV or EEDI depending on the type of propulsion. The CII is compared to the EIV index for ships with steam turbines, DFDE, and diesel propulsion, and the EEDI index for vessels with two stroke dual fuel engines for propulsion. It should also be noted that there was no technical efficiency data for all LNG Carriers in the MRV dataset.

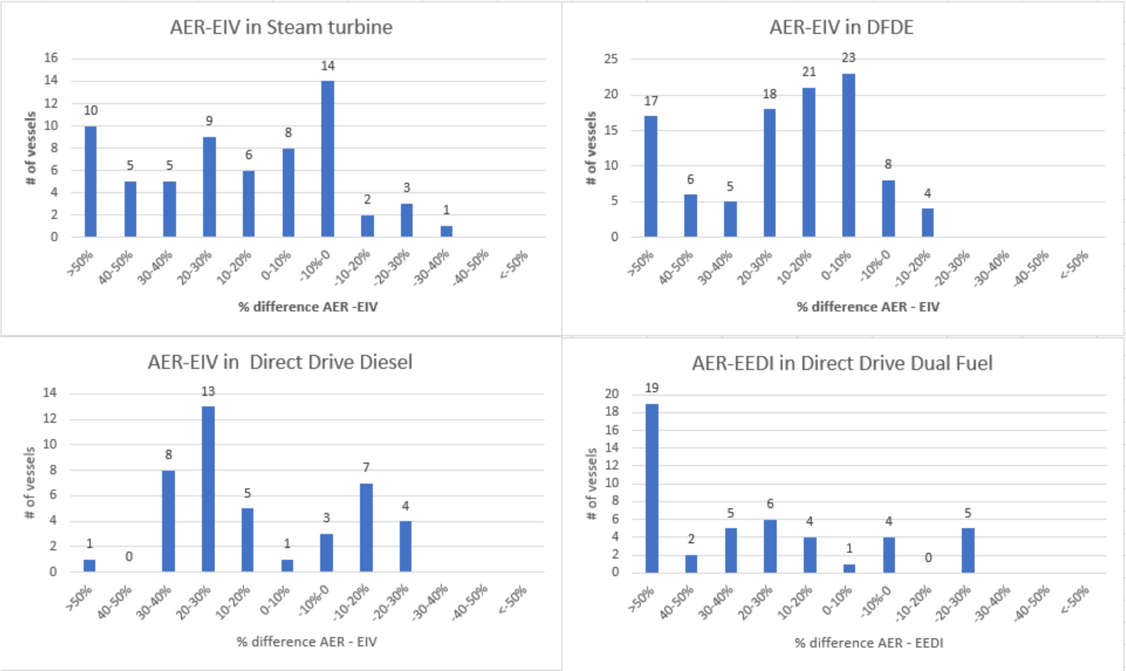


Figure 57: AER vs EIV/EEDI

As shown in the diagrams above, the general conclusion for all types of vessels is that their operational performance is worse than their technical efficiency. More specifically, in ships with DFDE propulsion, the EIV index appears to be closer to the AER, despite the fact that the number of ships with an AER vs EIV difference greater than 50% and above is remarkable in this category. LNG Carriers with steam turbines for propulsion are the only category where operational efficiency is slightly better than technical efficiency in a significant percentage of the sample, nearly one-third. Furthermore, in more newly built vessels with two stroke dual fuel engines, technical efficiency is significantly lower than operational efficiency, with nearly half of the ships having an AER vs EEDI difference greater than 40%.

7. LNG vs COAL footprint

7.1 Introduction

The last three years have seen remarkable changes in everyday life, affecting all aspects of human activity and having a significant impact on the global economy and trade. The COVID-19 pandemic and the impact of the Russia-Ukraine war on global trade are the two factors that have contributed to this unrest. The economic disruption caused by the COVID-19 pandemic and global lockdowns resulted in a drop in activity, primarily in the industrial and power sectors. As a result, according to [69], total carbon emissions in 184 countries decreased by 438 Mt in 2020 compared to 2019. The majority of emissions, as expected, come from the power sector, where fuel demand is much higher. The following graph depicts the global power mix in percentages for each energy source for the years 2019, 2020, and 2021.

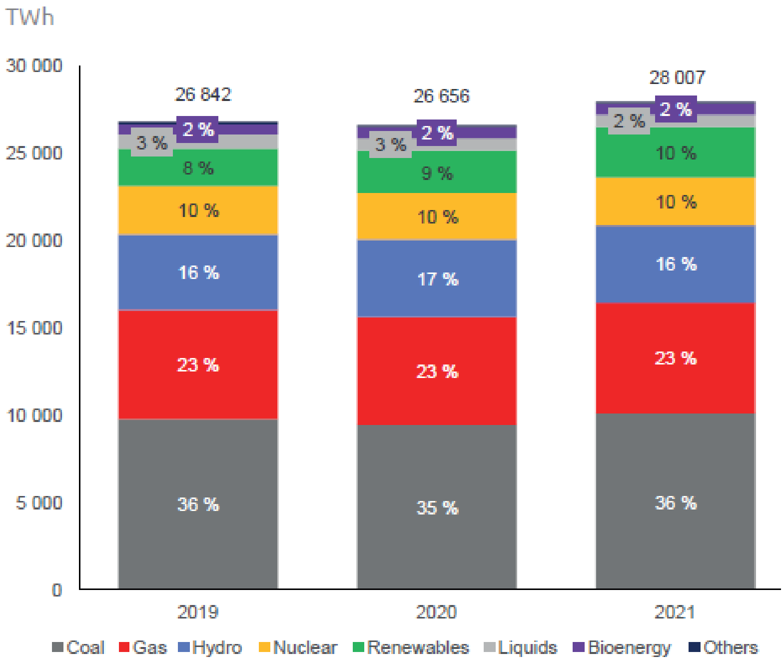


Figure 58: Global power mix for 2019,2020 and 2021 [70].

As can be seen, coal and gas are the two main drivers of the global power mix, accounting for nearly 60% of the total. As a result, these two fossil fuels are responsible for the vast majority of air emissions. Carbon dioxide emissions (in carbon dioxide equivalent) from energy use, industrial processes, flaring, and methane increased by 5.7% to 39.0 $GtCO_2e$ in 2021, with carbon dioxide emissions from energy increasing by 5.9% to 33.9 $GtCO_2$, which was close to 2019 levels [71]. Coal has the highest carbon content and is the largest single source of CO_2 emissions. This increase in CO_2 emissions contradicts the Paris Agreement's goal of avoiding dangerous climate change by limiting global warming to well below 2°C and pursuing efforts to limit it to 1.5°C. The goals of the Paris agreement to tackle climate change and reduce global warming require the involvement of alternative energy sources in the energy mix. In order to accelerate the global energy transition and support the global decarbonization, natural gas and decarbonized, low- or zero-carbon gases would need to play a significant role. However, switching to less polluting energy sources is not as simple because it is influenced by a variety of factors. Following is a brief overview of the trade in the two primary movers of the global energy mix, gas and coal.

7.1.1 Gas

In 2020, the demand for gas decreased by 2% globally, according to [70]. Imports decreased significantly from the second quarter of the year due to the emergence of COVID-19 and the imposition of stringent lockdowns globally. China's strong economic rebound in 2021, combined with unusually cold weather in Europe and Russia, caused global gas demand to rise 4.3% from 3,753 Bcm in 2020 to around 3,913 Bcm in 2021. As demand increased, China ramped up LNG imports to around 80 million tonnes, surpassing Japan as the world's largest importer. In Europe, gas consumption increased by 3% in 2021, almost reaching 2019 levels [70]. Nearly 40% of the total natural gas consumed by the EU in 2021 was imported from Russia via pipeline and LNG [71].

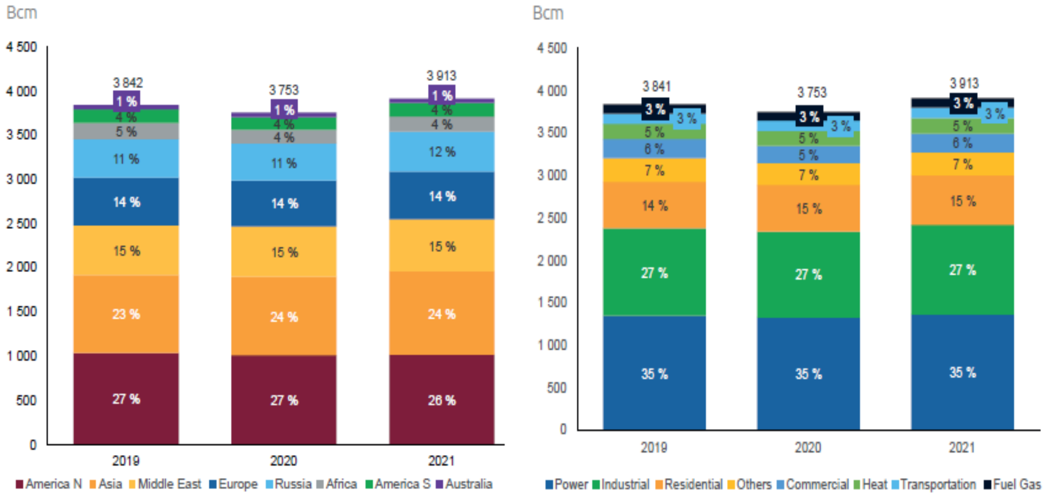


Figure 59: Global gas demand, split by continent and demand sector (2019-2021) [70].

In terms of supply, the effects of COVID-19 resulted in a 3.5% decrease in global LNG production in 2020, because of lower industry investments due to low oil and gas prices [70]. A rise in economic activity in 2021 increased industrial, residential, and power sector consumption, which resulted in a 4% increase in global gas production, reaching levels of 4028 Bcm. In order to meet the expanding demand in Europe and Asia, gas production was increased in the US, Russia, and the Middle East.

Due to a sharp increase in LNG imports brought on by the robust post-pandemic recovery, global LNG trade increased by 4.5% between 2020 and 2021, reaching an all-time high of 372.3 million tonnes [72]. Gas prices reached record highs because of intense competition for LNG cargoes between buyers in Europe and Northeast Asia. As demand increased, cargoes were also rerouted to Europe, where prices were more attractive to suppliers [70]. According to [70], the price of gas in Europe increased by 397% between 2020 and 2021.

7.1.2 Coal

Between 2019 and 2020, there was a significant decline in the demand for coal, with electricity generation using coal driving the decline, particularly in advanced economies. Then, in 2021, coal demand exhibited a significant recovery that even exceeded 2019 levels, but this recovery was primarily driven by an increase in Chinese demand [70]. Particularly, coal consumption increased by more than 6% in 2021, slightly higher than in 2019, and reached its highest level since 2014, with China and India accounting for more than 70% of the increase in coal demand in 2021 [71].

Because of the supply and demand imbalance caused by increased demand for LNG, the price of LNG has risen, allowing the return of cheaper energy solutions such as coal. All of this was compounded by the consequences of the Ukraine crisis, which included a limited supply of Russian gas in regions such as Europe. Due to the gap between gas and coal prices, which is caused by the tightening of the world's energy supply in 2021–2022, and the conflict between Russia and Ukraine in 2022, a gas-to-coal switch has occurred. As stated in [70], since 2020, emissions have been increasing, particularly in the power generation sector, which has been exacerbated by the post-pandemic surge in power demand and increased coal emissions due to this gas-to-coal switching.

7.2 Scope

Given the situation described above, as well as the risks of a backshift in climate change mitigation due to the gas-to-coal switch, in addition to the increased role of shipping in the LNG supply chain and the global energy transition, security, and efforts at decarbonization, it was chosen to compare the energy content of two ship cargoes and their contributions to the decarbonization process. The cargoes are LNG and coal, and they are transported by an LNG Carrier and a Bulk Carrier, respectively. This study is carried out through a case study, which includes various sub-cases of the ship type in order to form a complete picture. This section of the thesis has the following objectives:

- A detailed analysis of greenhouse gas emissions during LNG cargo ship transport by LNG Carriers using various propulsion types.
- The estimation of greenhouse gas emissions during the transport of a coal cargo by a Capesize and a Panamax bulk carrier.
- The calculation of greenhouse gas emissions from the fuel combustion during transportation of the above cargoes from a lifecycle perspective.
- The comparison of the energy content of two different cargoes as well as the GHG emissions in CO_2 equivalent over the cargo's entire lifecycle, from production to combustion for energy production.
- The calculation of the achieved Carbon Intensity Indicator (on a voyage basis).

7.3 Methodology, assumptions, and data

The main assumptions and data used in the calculations are derived from reliable sources such as published papers, studies, reports, and globally recognized databases. An analysis of a case study is used to compare the different vessels. First and foremost, a voyage profile had to be defined in order to make an equal comparison. The travel distance of 5500 nautical miles was chosen. This value is not fortuitous, as such a distance corresponds to several LNG routes from the United States to Europe, such as from the Corpus Christi terminal to the Toscana FSRU.

The next step was the selection of the ships to be used in the case study.

7.3.1 LNG Carriers

In order to study the complete spectrum of the existing fleet of LNG Carriers, four cases were selected and studied, depending on the type of propulsion.

1. Steam turbine propulsion system.
2. Dual Fuel Diesel Electric propulsion system.

3. ME-GI propulsion system (two stroke dual fuel engine).
4. X-DF propulsion system (two stroke dual fuel engine).

The above systems' technical characteristics and fuel consumption data were gathered from published papers and studies.

The consumptions of the ships examined with steam turbine and DFDE propulsion are derived from existing LNG Carriers [8], [73]. The fuel consumption values used in Attah and Bucknall's research for ships with steam turbine and DFDE propulsion correspond to actual operational data. In the present study, the approach of [74] is used, where consumption was calculated for the same vessels by taking the average of the results from [8], [73] and discarding the values that deviated significantly in order to obtain more accurate results. The next table shows the consumption of each fuel for the two types of propulsion, as well as the speeds of the vessels.

Table 37: Consumptions of steam turbine and DFDE [74].

	Steam Turbine	DFDE
Speed (kn)	19.75	20.4
HFO (tones/day)	54	1.86
LNG (tones/day)	107	161.4
MDO (tones/day)	2	1.8
MDO (tones/day), in terminal	0.2	1.8

The consumptions of the main engine and the auxiliary engines were taken from [75] for the other two cases of LNG Carriers with two stroke dual fuel engines for propulsion and are shown in the following table.

Table 38: Consumptions of the ME-GI and X-DF propulsion systems ([75]*,own calculations).*

Speed (kn)	Machinery	ME-GI	X-DF
Fuel consumption in laden voyage (Gas mode)			
19.5	Main engine	69.2 ton/day	72.6 ton/day
	Generator engine	14.4 ton/day	11.8 ton/day
Fuel consumption in ballast voyage (Gas mode)			
16	Main engine	38.6 ton/day	40.7 ton/day
	Generator engine	9.0 ton/day	8.3 ton/day
Consumptions for both systems during Maneuvering, loading, and unloading			
	Maneuvering	Loading	Unloading
	29 ton/day	20.6 ton/day	32.3 ton/day

Based on the above table and the data from [75], both propulsion systems are assumed to be operating on gas mode. In "gas mode," a mixture of fuel oil and gas is burned, with gas serving as the main fuel. For the ME-GI engines, the ratio is 95% gas fuel and 5% fuel oil, while it is 99% gas fuel and 1% fuel oil for the X-DF system. The same ratio of liquid fuel oil to gas fuel is assumed for all generator engines as for X-DF. It is assumed that the pilot fuel oil is MDO. During maneuvering, loading, and unloading, only generators are assumed to be in operation, with a fuel consumption of 170.6 g/kWh, and all calculations are based on data from [76].

The required values are estimated using the speed and distance traveled per trip. The cargo delivered at the end of the journey plays an important role in the analysis, which is why it is necessary to obtain values for the Boil-Off-Rate in each condition. The following equations are used to calculate time per roundtrip and BOG. Additionally, Table 39 provides information on BORs and other significant factors along with the pertinent citations from the literature.

Time for Laden, Ballast voyage: $t = \frac{s}{V} \quad (hours)$

s: Distance (nm)

V: Service speed (kn)

Time per roundtrip $T = t_1 + t_2 + t_3 + t_4 + t_5 + t_6$ (hours)

t_1: Laden voyage time (h)

t_2: Ballast voyage time (h)

t_3: Maneuvering time (h)

t_4: Other modes time (h)

t_5: Loading time (h)

t_6: Unloading time (h)

Basic data for BOG rates:

Volume of BOG (methane): $V = BOR \times C \times ML(m^3)$

BOR: Boil-off rate (%/day)

C: Cargo capacity (m^3)

ML: Maximum loading (%)

Delivered Cargo: DC = C – TBOG – HE (m^3)

C: Cargo capacity (m^3)

TBOG: Total used or lost LNG per trip (m^3)

HE: Minimum level of LNG for cargo tank cooling (heel) (m^3)

Table 39: Data and assumptions for the LNG Carriers.

	DFDE		STEAMER		ME-GI		X-DF	
	Value	Ref	Value	Ref	Value	Ref	Value	Ref
Capacity (m^3)	173,400	[73], [74]	141,052	[8], [74]	173,400	[75]	173,400	[75]
Maximum Loading (%)	98.5%	[58]	98.5%	[58]	99.17	[75]	99.17	[75]
Service speed, Laden(kn)	20.4	[73], [74]	19.75	[8], [74]	19.5	[75]	19.5	[75]
Service speed, Ballast (kn)	20.4	[73], [74]	19.75	[8], [74]	16	[75]	16	[75]
BOR, laden (%/day)	0.12	[58]	0.12	[58]	0.108	[75]	0.108	[75]
BOR, ballast (%/day)	0.06	[58], [75]	0.06	[58], [75]	0.06	[75]	0.06	[75]
BOR, maneuvering (%/day)	0.10	[58], [75]	0.10	[58], [75]	0.10	[75]	0.10	[75]
BOR, loading (%/day)	0.08	[58], [75]	0.08	[58], [75]	0.08	[75]	0.08	[75]
BOR, other modes (%/day)	0.10	[58], [75]	0.10	[58], [75]	0.10	[75]	0.10	[75]
BOR, unloading (%/day)	0	[58], [75]	0	[58], [75]	0	[75]	0	[75]
LHV of LNG (kJ/kg)	49100	-	49100	-	49100		49100	
Average density of liquid BOG (methane) (kg/m3)	465	-	465	-	465	-	465	-
t_3 (hours)	10	[75]	10	[75]	10	[75]	10	[75]
t_4 (hours)	5	[75]	5	[75]	5	[75]	5	[75]
t_5 (hours)	30	[75]	30	[75]	30	[75]	30	[75]
t_6 (hours)	30	[75]	30	[75]	30	[75]	30	[75]
Reliquefaction system	NO	-	NO	-	YES	-	YES	-
HE (%)	2	-	2	-	2	-	2	-

The main technical characteristics of the LNG Carriers are listed in the next three tables.

Table 40: Characteristics of the vessels with ME-GI and XDF propulsion [75].

Ship principal characteristics	**Two stroke DF propulsion (ME-GI)**	**Two stroke DF propulsion (X-DF)**
Capacity (m3)	173400	173400
Nominal speed (kn)	19.5	19.5
Number of propellers	2	2
Type of propulsion	ME-GI	X-DF
Model	5G70 ME-C 9.5GIx2	5X72DFx2
Power (kW)	12590x2	12500x2
Generator engines	8L34DFx2/6L34DFx2	8L34DFx2/6L34DFx2
Gen. engines power (kW)	4587.5x2 / 3437.5x2	4587.5x2 / 3437.5x2

Table 41: Characteristics of a typical LNGC DFDE vessel [73].

1. Ship Principal Characteristics		
Characteristics	**Value**	**Comments**
Ship Type	LNG Carrier	
Date of Delivery	2010	
Summer Draught	12.32 m	
Draught, Ballast	9.78 m (Normal & Heavy Weather)	
Cargo Tank Capacity	173,400 m3	At 100%
Deadweight, Summer Draught	79,541 t	
Displacement, Summer Draught	113,567 t	
Service Speed	20.4 knots	@ Design Draught 11.95 m
2. Propulsion System		
Descriptive Notes: Electric Propulsion Driver Via Gearbox		
Make and Model	Converteam N3HXC 1120LL	
Output	32,400 kW	Shaft: 16,000KW x 83.3rpm each Motor: 16,500KW x 610 rpm each
Specific Fuel Consumption at rated power	191 g/kWh (MGO) 7410 kJ/kWh (Gas)	
Propeller (2 sets)	5 Bladed 8.6m diameter	Fixed Pitch
3. Generators		
Diesel Generators:		
Engine Make and Model	Wartsila 12V50DF x 3 Wartsila 9L46 x 1	
Generator	11400 kW at 514rpm 10395 kW at 514rpm	
Fuel	Methane/HFOIMGO	
4. Auxiliary boiler		
Make and Model	Kangrim PA0403P38	
Rating	6500 kg/h at 7 Bar saturated steam	Max pressure 10 bar
Rated Fuel Consumption	491 kg/h	
Fuel	HFO/MGO	

Table 42: Characteristics of a typical LNGC Steam Turbine vessel [8].

1. Ship Principal Characteristics		
Characteristics	**Value**	**Comments**
Ship Type	LNG Carrier	
Date of Delivery	2006	
Summer Draught	12.32 m	
Draught, Ballast	9.78 m (Normal & Heavy Weather)	
Cargo Tank Capacity	141,052 m3	At 100%
Deadweight, Summer Draught	79,541 t	
Displacement, Summer Draught	113,567 t	
Service Speed	19.25 knots	@ Design Draught 11.25 m
2. Propulsion System		
Descriptive Notes: Steam Turbine Shaft Via Gearbox		
Make and Model	Mitsubishi MS 36-2 Steam Turbine	
Rating (Turbine)	23,500 kW	HP Turbine: 5,685 rpm LP Turbine: 3,351 rpm Propeller: 81 rpm
Specific Fuel Consumption at rated power		
Propeller (2 sets)	5 Bladed 8.6m diameter	Fixed Pitch
3. Generators and Boilers		
Turbo Generators: Two Steam Turbo Generators		
Make and Model (Turbine)	HHI RG92-2	8145 rpm
Generator	4062.5 kVA at 1800 rpm	
Specific Fuel Consumption at rated Power	13.65 t/h	Steam
Diesel Generators: Two 6-Cylinder Direct injection Diesel Engines		
Engine Make and Model	Hyundai MAN- B&W 8L28/32H	2 x 1,600 kW at 720 rpm
Generator	2,000 kVA at 720 rpm	
Fuel	LSDO	
Boilers: Two Top Fired Water Tube		
Make and Model	HHI 2 X MB-3E	
Rating	47 t/h 515°C at 60 Bar	Maximum 55 t/h
Rated Fuel Consumption	4001 kg/h	Maximum Burner Capacity
Fuel	HFO/Methane/MGO	

7.3.2 Bulk Carriers

For the Bulk Carriers, two ship types were studied: a Capesize Bulk Carrier and a Panamax Bulk Carrier. Because of their size, these two types were chosen as they are widely involved in the coal trade and carry out large trades, achieving economies of scale. Fuel consumption is calculated more simply than in the case of LNG Carriers since daily consumption values are based solely on the literature [77].

Table 43: Consumptions and basic characteristics of the bulk carriers.

	Capesize Bulk Carrier	**Panamax Bulk Carrier**
Typical Speed (kn)	13.6	13.8
Fuel consumption of ME (tons/day)	50	33.9
Fuel consumption of AE (tons/day)	5.6	3.8
Fuel consumption in port (tons/day)	3.2	3.2
DWT (tons)	182,466	77,000
Hold grain capacity (m^3)	195,291	89,500

It is assumed that both vessels are equipped with a scrubber, and during voyage their main engines and the auxiliary engines use HFO as fuel. To complete the scenario, the time in port for loading and unloading is assumed to be 50 hours. In both cases, the fuel consumption at the port is assumed to be 3 ton/day HFO and 0.2 ton/day MGO. Finally, the capacity in cubic meters and the DWT of the two vessels participating in the case study are listed in the Table 43.

7.3.3 Emissions calculation

7.3.3.1 GHG emissions during transportation

Three approaches were used to calculate the Greenhouse Gas emissions deriving from fuel combustion during cargo transportation (TTW).

1. In the first approach, GHG emissions are calculated in the business-as-usual scenario, where only CO_2 is considered, and the calculation is based on the emission factors in tons CO_2 per tons fuel, as shown in Table 3 in Chapter 3 of the present study.
2. In the second approach, fugitive emissions (e.g., methane slip), as well as CH_4 and N_2O emissions, as well as CH_4 and N_2O emissions are taken into account for TtW GHG emissions, with the final result expressed in CO_2 equivalent units based on the GWP100 of each GHG. For this purpose, new emission factors for each fuel and engine type are developed. The equations for calculating GHG emissions, emission factors, and more default values are based on the methodology specified in Annex I of the proposed FuelEU Maritime Regulation for establishing the greenhouse gas intensity limit on the energy used on-board by a ship, with the difference that only the results in tons of CO_2 equivalent are calculated in the present study. The formula for calculating total TtW GHG emissions in CO_2 equivalent is as follows.

$$Total\ TtW\ CO_{2,equivalent} = \sum_{i}^{n\ fuel} \sum_{j}^{m\ engine} M_{i,j} \times \left[\left(1 - \frac{1}{100} C_{engine\ slip\ j}\right) \times (CO_{2eq,TtW,j}) + (\frac{1}{100} C_{engine\ slip\ j} \times CO_{2eq\ TtW,slippage,j})\right]$$

Where,

- i : index corresponding to the fuel
- j : index corresponding to the fuel combustion units on board the ship.
- Mi,j : Mass of the specific fuel i oxidised in consumer j [g Fuel]
- C engine slip j : Engine fuel slippage as a percentage of the mass of the fuel i used by combustion unit j [%]
- $C_{fCO2,j}$, $C_{fCH4,j}$ $C_{fN2O,j}$:TtW GHG emission factors by combusted fuel in combustion unit j [gGHG/gFuel]

- $CO_{2eq,TtW,j}$: TtW CO_2 equivalent emissions of combusted fuel i in combustion unit j [gCO2eq/gFuel]

$$CO_{2,eq,j} = C_{f\ CO2,j} \times GWP_{CO2} + C_{f\ CH4,j} \times GWP_{CH4} + C_{f\ N2O} \times GWP_{N2O}$$

- $C_{sf\ CO2,j}$, $C_{sf\ CH4,j}$ $C_{sf\ N2O,j}$: TtW GHG emissions factors by slipped fuel towards combustion unit j [gGHG/gFuel]
- $CO_{2eq,TtW\ slippage,j}$: TtW CO2 equivalent emissions of slipped fuel i towards combustion unit j [gCO2eq/gFuel]

$$CO_{2,eq,j} = C_{sf\ CO2,j} \times GWP_{CO2} + C_{sf\ CH4,j} \times GWP_{CH4} + C_{sf\ N2O} \times GWP_{N2O}$$

- GWP_{CO2} , GWP_{CH4}, GWP_{N20} : CO_2, CH_4 , N_2O Global Warming Potential over 100 years with values 1 , 28, 265 respectively [9].

3. The third approach includes the WtT GHG emissions from the fuels used during cargo transportation. WtT GHG emissions are expressed in grams CO_2 equivalent per MJ Lower Heating Value of the fuel. The values for each fuel are taken from the Fuel Eu maritime regulation.

The values of the quantities used in the calculations of GHG emissions in the second and third approaches are shown in the table below.

Table 44: Data for calculating emissions for each fuel.

Fuel	LCV [MJ/g]	CO2eq WtT [gCO2eq/ MJ]	Engine type	C_{fCO2} [gCO2/gFuel]	C_{fCH4} [gCO2/gFuel]	C_{fN2O} [gCO2/gFuel]	Cslip As % of the mass of the fuel used by the engine
HFO	0.0405	13.5	ALL	3.144	0.00005	0.00018	-
VLSFO	0.041	13.2	ALL	3.206	0.00005	0.00018	-
LFO	0.041	13.2	ALL	3.151	0.00005	0.00018	-
MDO/MGO	0.0427	14.4	ALL	3.206	0.00005	0.00018	-
LNG	0.0491	18.5	LNG Otto (Dual fuel medium speed)	2.750**	0	0.00011	3.1
			LNG Otto (Dual fuel medium speed)				1.7
			LNG Diesel (Dual fuel slow speed)				0.2
			Steam Turbine*				0.014**
***This type is not available in FUEL EU regulation.**							
**** The carbon factor in FUEL EU is 2.755, although is considered 2.750 according to IMO.**							
***** The value for steam turbine is based on own calculation as referred in Chapter 5.**							

After establishing the main assumptions and methodology, the GHG emissions from fuel combustion can be calculated for each case of a ship using the three approaches described above.

7.3.3.2 GHG emissions of cargo carried

The cargo's value in terms of lifecycle emissions and energy carried is another aspect of the current study that is of interest. The results are expressed in grams of GHG emissions per energy carried or in grams of CO_2 equivalent per MJ. Because, as stated in the introduction, the majority of pollution from coal and LNG is due to energy production, it is assumed that the final cargo unloaded from the ship is used for power generation, and the emission factors used are referred to stationary combustion.

The default values for stationary combustion of coal and gas are derived from the IPCC's Emission Factor Database (EFDB) [78]. There are three types of coal used in power generation. The bulk density of coal is assumed to be 0.8 kg/m^3.

Table 45: Emission factors for stationary combustion.

Cargo	LHV (MJ/kg)	CO_2 (g/MJ)	CH_4 (g/MJ)	N_2O (g/MJ)
Bituminous coal	25.8	94.6	0.001	0.0015
Sub-bituminous coal	18.9	96.1	0.001	0.0015
Lignite	11.9	101	0.001	0.0015
Natural gas	48	56.1	0.001	0.0001

In addition to GHG emissions during the final phase of each cargo's life, which is the combustion for power generation, GHG emissions during the other phases of each cargo's lifecycle are also important.

For the LNG there are GHG emissions during the gas production, processing, and pipeline transport and during gas liquefaction before the transport by an LNG Carrier. The GHG emissions from the LNG supply chain vary by region. The data was derived from a study [79], where values for the global average of GHG emissions in grams of CO_2 equivalent per MJ (LHV) are presented. Because the aforementioned study is about LNG as a marine fuel, the data obtained pertains to the stages prior to ship transport.

Table 46: WtT emissions of LNG

Stage in fuel cycle	WtT-LNG GHG (gCO_2eq/MJ)
Gas production, processing and pipeline transport	6.1
Gas liquefaction (incl. purification)	9.2

The data on WtT GHG emissions from coal were obtained from a report [80] that conducts an extensive analysis of coal's lifecycle emissions and energy. The findings of this study are referred to coal from Australia that is used to generate electricity. GHG emissions data are collected for the stages of coal mining and extraction, as well as coal preparation prior to transport with a Bulk Carrier. For each GHG, the values are expressed in kilograms per tonne coal feed to the power station.

The data are converted to grams CO_2 equivalent per MJ using the GWP100 and LHV of each type of coal.

Table 47: WtT emissions of coal.

Stage in fuel cycle	GHG emissions (kg/tonne coal feed to power station)			GHG emissions (kg CO_2eq/tonne coal feed to power station)
	CO_2	CH_4	N_2O	
Coal mine	37.1	2.9703	0.0011	120.5599
Coal Preparation	2.3	-	-	2.3
Sum	39.4	2.9703	0.0011	122.8599

Using data from the literature on GHG emissions for all stages of the coal and gas lifecycles except cargo transportation by ship, where the calculation of GHG emissions is thoroughly analyzed in the current work, a comparison can be made between the pollutants and the energy content of the two fossil fuels.

7.4 Results

The results obtained using the described methodology, as well as the objectives of this part of the thesis, are presented in this section of the chapter. The ratio of emissions per energy of the cargo carried in grams of CO_2 (or CO_2 equivalent) per MJ is used to compare all types of ships. It should be noted that all analysis, results, and conclusions are based on the assumptions and data presented above.

The following diagram represents the emissions per energy content during transportation for all cases, based on the approach used to calculate the emissions.

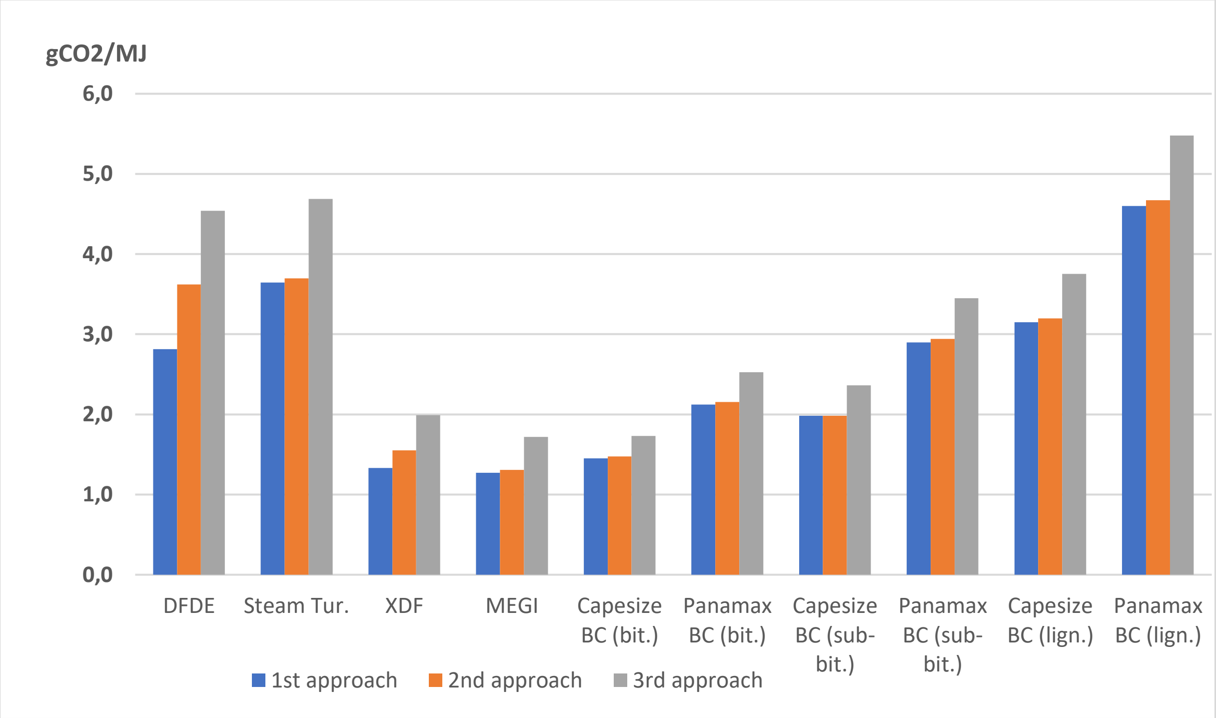


Figure 60: Emissions per energy content from transportation.

According to the above diagram, among the LNG Carriers, the vessel with steam turbine propulsion has the highest emissions per energy content (3.643 gCO_2/MJ) from the perspective of the first approach. As expected, the vessels with two stroke dual fuel engines are far more efficient, emitting nearly 100% fewer emissions per energy content than the vessels with diesel electric propulsion and steam turbine. The existence of the reliquefaction system and the maintenance of the LNG cargo make significant contributions to this. Following the second approach, the difference between vessels with DFDE and steam turbine propulsion is noticeably decreasing due to methane slip and remains significantly larger than vessels with ME-GI and X-DF propulsion. When the 3rd approach is followed, where all the lifecycle emissions of the fuels burned are taken into account, the results remain almost the same as the 2nd approach.

When the emissions per energy content carried in gCO_2/MJ ratios of LNG Carriers and Bulk Carriers are compared, the following results emerge:

- According to the first approach, the panamax bulk carrier transporting the lower grade of coal, lignite, has the highest emissions per energy content of 4.601 gCO_2/MJ. The LNG Carrier with a steam turbine comes next, followed by the Capesize Bulk Carrier transporting lignite. The more efficient LNG Carriers with X-DF and ME-GI propulsion have lower emissions per energy content ratios than the other vessels. The vessel with ME-GI propulsion, for example, has a lower ratio of 14.2% than the most efficient bulk carrier, a capesize transporting bituminous coal, the highest grade of coal.
- The trends of the results in the second approach remain the same, with the exception that the LNG Carrier with DFDE propulsion has a higher value in gCO_2eq / MJ than the Capesize Bulk carrier that transports lignite.
- According to the third approach to estimating emissions, the trends remain the same; however, the emissions of LNG Carriers have increased more than those of Bulk Carriers. This is because of LNG having higher WtT emissions values than HFO and MDO/MGO.

In conclusion, it is observed that LNG Carriers with two stroke dual fuel propulsion outperform all types of Bulk Carriers in terms of emission per energy carried, regardless of the grade of coal they carry. The less efficient LNG Carriers with diesel electric and steam propulsion have the highest ratios of emissions per energy carried from the other vessels except from bulk carriers that transport lignite.

Table 48 contains all the values for the following quantities based on the method used to calculate emissions.

- GHG emissions (in CO_2 equivalent) per energy carried [gCO_2/MJ].
- GHG emissions (in CO_2 equivalent) per tonne cargo landed [$kgCO_2$/tonne fuel].
- GHG emissions (in CO_2 equivalent) per roundtrip [tonnes].
- Attained CII on a per voyage basis [$gCO_2/t*nm$].

Table 48: Calculations for each vessel.

Vessel type	**1st approach**				**2nd approach**				**3rd approach**			
	GHG emissions per energy carried (gCO2/MJ)	GHG emissions per tonne cargo landed (kgCO2/ tonne fuel)	Emissions per roundtrip (tonnes CO2)	Attained CII (gCO2/t* nm)	GHG emissions per energy carried (gCO2eq/MJ)	GHG emissions per tonne cargo landed (kgCO2eq/ tonne fuel)	Emissions per roundtrip (tonnes CO2eq)	Attained CII (gCO2eq/t *nm)	GHG emissions per energy carried (gCO2eq/MJ)	GHG emissions per tonne cargo landed (kgCO2eq/tonne fuel)	Emissions per roundtrip (tonnes CO2eq)	Attained CII (gCO2eq /t*nm)
DFDE	2.812	138.1	10246.3	11.711	3.620	177.8	13191.4	15.077	4.538	222.8	16535.8	18.899
STEAM TUR.	3.643	178.9	10881.3	12.437	3.695	181.4	11036.4	12.614	4.689	230.2	14005.9	16.008
XDF	1.333	65.4	5010.3	5.694	1.552	76.2	5835.8	6.632	1.991	97.7	7482.7	8.503
MEGI	1.272	62.4	4790.2	5.443	1.308	64.2	4925.2	5.597	1.718	84.3	6470.6	7.353
CAPESIZE*	1.453	37.5	5855.7	2.917	1.476	38.1	5948.1	2.963	1.731	44.7	6976.2	3.476
PANAMAX*	2.122	54.7	3919.9	4.744	2.155	55.6	3981.7	4.818	2.528	65.2	4670.0	5.651
CAPESIZE**	1.983	37.5	5855.7	2.917	1.983	38.1	5948.1	2.963	2.363	44.7	6976.2	3.476
PANAMAX**	2.897	54.7	3919.9	4.744	2.942	55.6	3981.7	4.818	3.451	65.2	4670.0	5.651
CAPESIZE***	3.150	37.5	5855.7	2.917	3.199	38.1	5948.1	2.963	3.752	44.7	6976.2	3.476
PANAMAX***	4.601	54.7	3919.9	4.744	4.673	55.6	3981.7	4.818	5.481	65.2	4670.0	5.651

***The cargo of the bulk carrier is sub-bituminous coal.**

***The cargo of the bulk carrier is bituminous coal.**

***The cargo of the bulk carrier is lignite.**

An interesting comparison is that between emissions during ship transport and energy production from cargo combustion. The comparison is made using the ratio of grams CO_2 equivalent per energy in MJ, which is depicted schematically in the following diagram for each case studied. The third approach was used for emissions during ship transport.

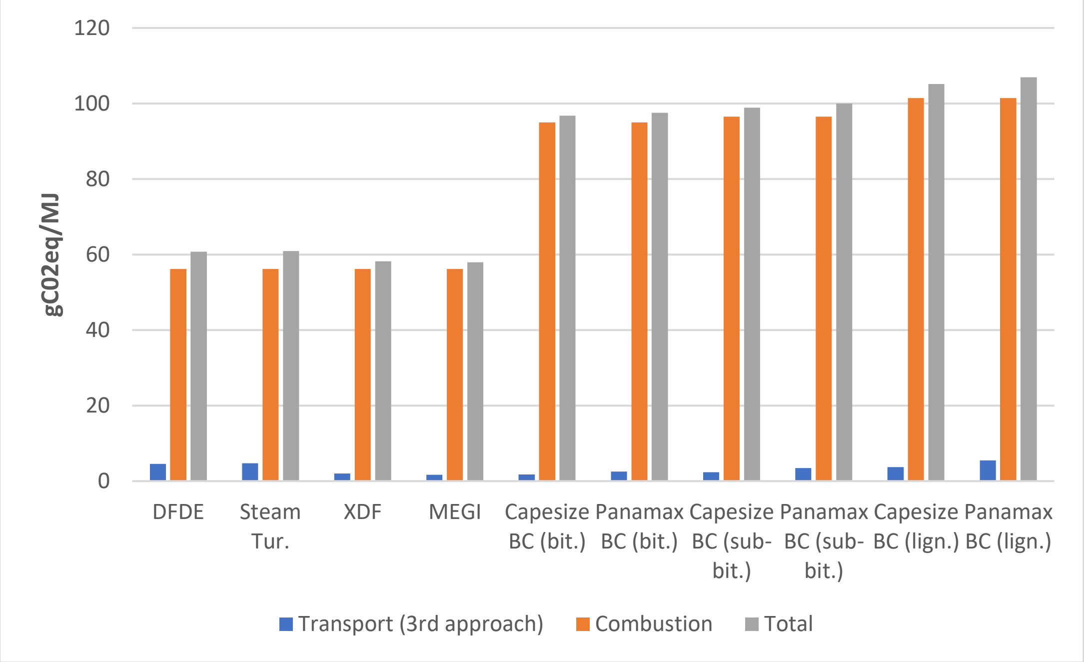


Figure 61: Emissions per energy content during transport and combustion.

As can be seen, the emissions from transportation are much lower than those from burning the cargo for energy. In the case of the LNG Carrier with a steam turbine, which has the highest consumption and thus is the least efficient, the ratio of grams CO_2 equivalent per energy in MJ during transport is only 8.3% of the ratio from combustion. This estimate is even lower in other ship categories. As a result, whether the cargo is LNG or any other type of thermal coal, emissions during transportation are much lower than those during combustion.

The next figure includes the emissions during the lifecycle of LNG and coal as ship cargoes for all the different cases studied. The values for WtT emissions were listed at the beginning of the chapter.

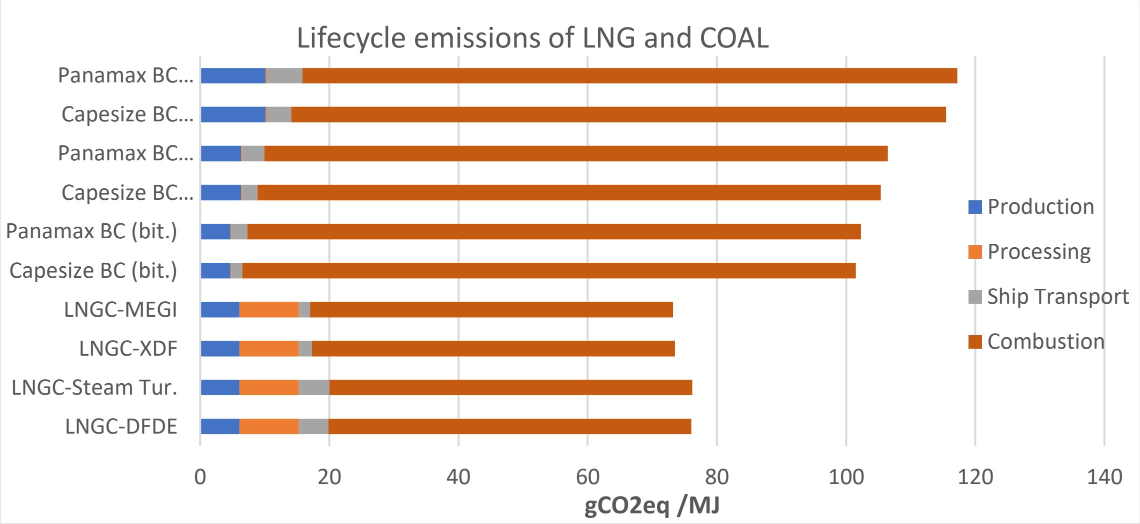


Figure 62: Lifecycle emissions per energy content in gCO_2eq/MJ.

Emissions from transporting LNG with older vessels propelled by steam turbines and diesel electric engines, which make up a large portion of the market today, can be higher than those of a bulk carrier, but there are also cases where the opposite occurs. However, when the entire lifecycle of the ship's two cargoes, LNG and coal, is considered, LNG has significantly lower GHG emissions than coal. This conclusion extends to all sub-cases involving different types of vessels.

For the same cargo, emissions per unit of energy are lower for coal when transported by a Capesize bulk carrier than by a Panamax, and for LNG, emissions per unit of energy are lower when transported by more modern vessels with dual fuel propulsion types.

As a result, it is understandable that LNG has a significant advantage and contribution to the global decarbonization process when compared to coal, the other major competitor in the power sector. The role of LNG Carriers in energy security and transition today is huge, and the effects of a regulation like CII on the available capacity of the fleet may cause market disruption, affecting the entire LNG market, and having the opposite effect on global decarbonization.

8. Conclusions

In summary, the present thesis aimed to determine the impact of the CII regulation on LNG Carriers. The CII was calculated using MRV data for a considerable part of the fleet that did trades in the European Union in 2020. The analyzed sample covered a wide spectrum of the global fleet. With the appropriate assumptions, it was estimated whether and when each ship will need to improve its energy efficiency in order to comply with the CII regulation. The following are the main conclusions derived from this section:

- By 2026, a significant portion of the fleet, more than 40%, will have received D or E ratings and should have already taken measures to improve their energy efficiency or will need to do so in the near future.
- Regarding the trajectory scenarios for the period after 2026, in the third and stricter scenario, almost 60% of the fleet will need to develop corrective actions to stay compliant until 2030.
- According to the age categorization, the older vessels are by far the least efficient in terms of CII, although there is a significant number of vessels of lower age that will face challenges in compliance with the regulation.
- According to the size categorization, ships of smaller size will face more difficulties in compliance.
- According to the third and most important categorization of the LNG Carriers based on the propulsion type, vessels with steam turbine will face the most difficulties, and compliance with the CII regulation requirements for these ships is expected to be challenging as early as 2023. LNG Carriers with two-stroke slow speed diesel engines for propulsion are the second most affected category by the regulation, while vessels with diesel electric propulsion and two stroke dual fuel propulsion seem to comply with the regulation adequately. However, in some cases compliance with the CII regulation up until the end of the decade will have an impact even on the theoretically most efficient vessels.
- The potential inclusion of methane slip in the CII regulation will change the situation, rendering a large share of the fleet non-compliant, particularly in vessels with low pressure four stroke dual fuel engines, which account for a considerable part of the existing fleet.
- Regarding CII between similar vessels, in some types of LNG Carriers the differences seem to exist due to the operational profile of the vessel which can be eliminated and be a solution to comply with the regulation. Although, in many cases there are huge differences that may indicate reporting errors and, as a result, poor data quality. It turns out that the CII and the differences in ratings are highly sensitive.

Considering the above, it is concluded that a large percentage of the fleet does not meet the requirements of the CII regulation and that this share may grow significantly in future regulatory revisions. As expected, these ships will be mandated to follow a compliance strategy, or they will be scrapped or converted to an FSRU/FSU. Slow steaming is the most common solution for increasing energy efficiency in other types of ships; however, the unique characteristics of LNG Carriers, such as the nature of the cargo, which requires high speeds, and the low efficiency of steam turbines at lower loads, are impediments to its adoption. This strategy may be followed by vessels equipped with reliquefaction systems, such as those powered by two-stroke diesel engines, but the significant consumption of the reliquefaction plant for cargo prevention must also be taken into account. Installing energy saving technologies, particularly in older vessels, may be a compliance strategy, but the investment's feasibility must also be considered. In addition, the uncertainty about the future of the regulation can lead to not feasible decisions.

For example, the installation of an energy-saving technology may provide the required reduction of the CII for compliance until 2026 but may not be sufficient until 2030 in a scenario with an increased reduction factor after 2026.

As indicated by the case study in the final section of the thesis comparing LNG and coal as ship cargoes in terms of lifecycle emissions per energy content, LNG has significant advantages and plays a crucial role in the road to decarbonization and climate change mitigation. Given that the power sector is responsible for the majority of emissions, as well as the risks of a backshift in climate change mitigation due to the gas-to-coal switch, it is concluded that the role of LNG Carriers in energy transition and security is more important than ever.

Many shipowners are expected to be conflicted about whether to invest in technologies or scrap the vessel as a result of the CII regulation. The potential removal of many LNG Carriers could reduce capacity and affect price at a time when LNG trade is increasing, causing market disruption.

Based on the present thesis and the above conclusions, some suggestions for further research are listed.

- Repeat the analysis with possible regulatory revisions and more recent operational data and compare the results to the present study.
- A comparison of the calculated Carbon Intensity Indicator over time.
- Evaluation of the impact of EEXI compliance in the CII.
- A techno-economic study of various technologies, such as a reliquefaction system on an LNG Carrier, and their impact on CII reduction.
- A techno-economic analysis of compliance strategies with the CII regulation, including the implementation of the ETS.

In conclusion, the role of LNG Carriers in energy security and transition is crucial, and the impact of the regulation of CII may affect the entire LNG market, having the opposite effect on global decarbonization. As a result of the facts and circumstances, LNG Carriers should be treated differently by the IMO's policy so that efforts to decarbonize shipping do not impede the global energy transition.

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