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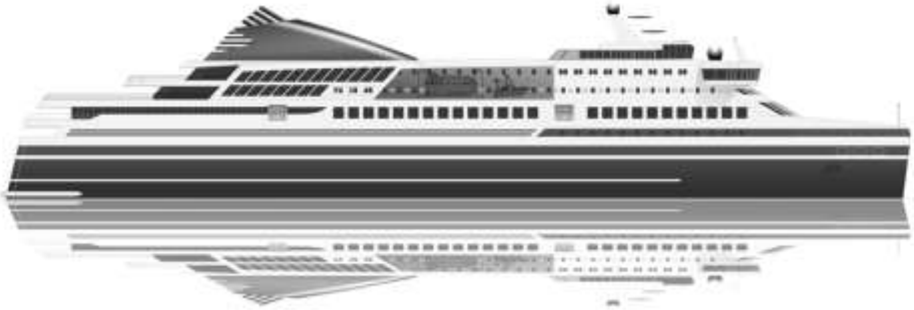
Diploma Thesis



The Impact of Alternative Fuels and Speed Reduction on the Carbon Footprint of RoPax Ships Operating in Greek Territory

Alexandros Panagou

Supervisor: Christos Papadopoulos

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List of abbreviations

AER Annual Efficiency Ratio

AFI Alternative Fuels Insight

ASTM American Society for Tests and Materials

BOG Boil-off Gas

BV Bureau Veritas

CCS Carbon Capture and Storage

CH_4 Methane

CO_2 Carbon Dioxide

CODOG Combined Diesel or Gas

COP 21 Conference of Parties

CPP Controllable pitch propellers

CII Carbon Intensity Index

DCS Data Collection System

D/G Diesel Generator

DME Dimethyl ether

DNV Det Norske Veritas

DWT Deadweight

ECA Emission Control Area

EEXI Energy Efficiency eXisting ship Index

EEDI Energy Efficiency Design Index

EU European Union

ELA Electric Load Assesment

EPA Environmental Protection Agency

EDGAR Emission Database for Global Atmospheric Research

EEA European Environmental Agency

ESDs Energy Saving Devices

ETS Emission Trading System

EMSA European Maritime Safety Agency

EL.E.MED. Electrification in the Eastern Mediterranean

FAME Fatty Acid Methyl Ester

FSRU Floating Storage and Regasification

GBS Gravity Based Structure

GHG Greenhouse Gases

GT Gross Tonnage

H_2 Hydrogen

HFO Heavy Fuel Oil

HVAC Heating, ventilation, and air conditioning

HVO Hydrotreated Vegetable Oil

IFO Intermediate Fuel Oil

INEA Innovative and Networks Executive Agency

IP Institute of Petroleum

IPCC International Panel on Climate Change

IMO International Maritime Organisation

ISPI Individual Ship Performance Indicator

LCV Lower Calorific Value

LFO Light Fuel Oil

LNG Liquefied Natural Gas

LPG Liquefied Petroleum Gas

LR Lloyd’s Register

MARPOL International Convention for the Prevention of Pollution from Ships

MDO Marine Diesel Oil

MeOH Methanol

MEPC Marine Environment Protection Committee

MGO Marine Gas Oil

MRV Monitoring, Reporting and Verification

NH_3 Ammonia

NO_X Nitrous oxides

MTPA Mega Tonnes Per Annum

OPEX Operational Expenses

ORV Open Pack Vaporizers

PM Particulate Matter

PTI Power Take In (shaft motor)

PTO Power Take Out (shaft generator)

Ropax Ro-ro passenger

Ro-ro roll-on roll-off

SAE Society of Automotive Engineers

SEEMP Ship Energy Efficiency Management Plan

SECA Sulphur Emission Control Area

SFOC Specific Fuel Oil Consumption

SNG Synthetic Natural Gas

SO_X Sulphur oxides

ISO International Organisation of Standardisation

Ttw Tank-to-wake

UNFCCC United Nations Framework Convention on Climate Change

Wtw Well-to-wake

WtT Well-to-tank

Abstract

Throughout history, several technological and industrial revolutions have taken place, which were responsible for the reshaping both the present and future of human life. These revolutions significantly enhanced efficiency and productivity, leading to unprecedented growth in global commerce. Advancements in technology and industry facilitated faster transportation, improved communication, and the creation of new markets, driving economic development worldwide. Unfortunately, nothing comes without a cost. Although rapid industrial development has benefited humanity in various ways, it has also become a significant contributor to global environmental pollution. The primary types of environmental pollution include soil, air, and water pollution, with many different industries playing a pivotal role in worsening the situation. Among these, the maritime industry is a considerable contributor to air pollution and the greenhouse gas effect through the emission of gaseous pollutants and particulate matter.

With this phenomenon intensifying significantly in recent years, the necessity for decarbonization and the transition to cleaner energy systems are at the doorstep of the shipping market. Although it is a challenging venture, it is vitally important for the shipping sector to adapt to new data and rely less on fossil fuels in an effort to mitigate pollutants and emissions that harm the environment. International and regional regulations, either coming from IMO or the EU, have increasingly focused on reducing the carbon footprint of shipping activities. Given that the Mediterranean Sea will be characterized as a SECA on January 1st, 2025, and considering the many RoRo passenger ships sailing its waters, this diploma thesis investigates the potential of alternative fuels and speed reduction strategies to lower the carbon footprint of RoPax ships operating in Greek territory. At the same time, apart from the environmental, the economic benefits of implementing these measures in the existing fleet are evaluated.

This study is divided into six chapters and sheds light on all aspects of the topic. Firstly, the theoretical part is presented, providing essential information for a better understanding of the study. More specifically, the first chapters delve into environmental pollution, as well as the rules and regulations enacted due to increasing pollution in recent years. In addition, various ways to mitigate pollutants emitted by the shipping sector, such as the use of alternative fuels, innovative technologies and speed reduction strategies are presented, along with general information on the types of ships studied in this thesis. After the theoretical part, more detailed information regarding the case study follows, including the assumptions made for the calculations, the methodology followed, and the simulations. Finally, the conclusions based on the calculations are discussed, the commentary on the final results is provided, and future work is suggested, especially with the upcoming establishment of stricter regulations.

Keywords: CO_2, conventional fuels, alternative fuels, LNG, Methanol, cold ironing, speed reduction, EU ETS, CII, RoPax, carbon footprint

Περίληψη

Κατά τη διάρκεια της ιστορίας, έχουν λάβει χώρα αρκετές τεχνολογικές και βιομηχανικές επαναστάσεις, οι οποίες ήταν υπεύθυνες για την αναμόρφωση τόσο του παρόντος όσο και του μέλλοντος της ανθρώπινης ζωής. Αυτές οι επαναστάσεις αύξησαν σημαντικά την αποτελεσματικότητα και την παραγωγικότητα, οδηγώντας σε πρωτοφανή ανάπτυξη στο παγκόσμιο εμπόριο. Οι εξελίξεις στην τεχνολογία και τη βιομηχανία διευκόλυναν ταχύτερες μεταφορές, βελτίωσαν την επικοινωνία και τη δημιουργία νέων αγορών, οδηγώντας την οικονομική ανάπτυξη παγκοσμίως. Δυστυχώς, τίποτα δεν έρχεται χωρίς κόστος. Αν και η ταχεία βιομηχανική ανάπτυξη έχει ωφελήσει την ανθρωπότητα με διάφορους τρόπους, έχει γίνει επίσης σημαντικός παράγοντας στην παγκόσμια περιβαλλοντική ρύπανση. Οι κύριοι τύποι περιβαλλοντικής ρύπανσης περιλαμβάνουν τη ρύπανση του εδάφους, του αέρα και των υδάτων, με πολλές διαφορετικές βιομηχανίες να διαδραματίζουν καθοριστικό ρόλο στην επιδείνωση της κατάστασης. Μεταξύ αυτών, η ναυτιλιακή βιομηχανία συμβάλλει σημαντικά στην ατμοσφαιρική ρύπανση και στο φαινόμενο του θερμοκηπίου μέσω της εκπομπής αέριων ρύπων και σωματιδίων.

Με το φαινόμενο αυτό να εντείνεται σημαντικά τα τελευταία χρόνια, η ανάγκη για απανθρακοποίηση και η μετάβαση σε συστήματα καθαρότερης ενέργειας βρίσκονται στο κατώφλι της ναυτιλιακής αγοράς. Αν και είναι ένα δύσκολο εγχείρημα, είναι ζωτικής σημασίας για τον ναυτιλιακό τομέα να προσαρμοστεί στα νέα δεδομένα και να βασίζεται λιγότερο στα ορυκτά καύσιμα σε μια προσπάθεια μετριασμού των ρύπων και των εκπομπών που βλάπτουν το περιβάλλον. Οι διεθνείς και περιφερειακοί κανονισμοί, προερχόμενοι είτε από τον IMO είτε από την ΕΕ, έχουν επικεντρωθεί όλο και περισσότερο στη μείωση του ανθρακικού αποτυπώματος των ναυτιλιακών δραστηριοτήτων. Δεδομένου ότι η Μεσόγειος Θάλασσα θα χαρακτηριστεί ως SECA την 1η Ιανουαρίου 2025 και λαμβάνοντας υπόψη τα πολλά επιβατηγά πλοία RoRo που πλέουν στα ύδατά της, αυτή η διπλωματική εργασία διερευνά τις δυνατότητες εναλλακτικών καυσίμων και στρατηγικών μείωσης ταχύτητας για τη μείωση του αποτυπώματος άνθρακα των πλοίων RoPax που πλέουν στην ελληνική επικράτεια. Παράλληλα, εκτός από τα περιβαλλοντικά, αξιολογούνται και τα οικονομικά οφέλη από την εφαρμογή των μέτρων αυτών στον υφιστάμενο στόλο.

Αυτή η μελέτη χωρίζεται σε έξι κεφάλαια και ρίχνει φως σε όλες τις πτυχές του θέματος. Αρχικά, παρουσιάζεται το θεωρητικό μέρος, παρέχοντας ουσιαστικές πληροφορίες για την καλύτερη κατανόηση της μελέτης. Πιο συγκεκριμένα, τα πρώτα κεφάλαια εμβαθύνουν στη ρύπανση του περιβάλλοντος, καθώς και στους κανόνες και τους κανονισμούς που θεσπίστηκαν λόγω της αυξανόμενης ρύπανσης τα τελευταία χρόνια. Επιπλέον, παρουσιάζονται διάφοροι τρόποι μετριασμού των ρύπων που εκπέμπονται από τον ναυτιλιακό κλάδο, όπως η χρήση εναλλακτικών καυσίμων, καινοτόμες τεχνολογίες και στρατηγικές μείωσης της ταχύτητας, μαζί με γενικές πληροφορίες για τους τύπους πλοίων που μελετώνται στην παρούσα διατριβή. Μετά το θεωρητικό μέρος, ακολουθούν αναλυτικότερες πληροφορίες σχετικά με τη μελέτη, συμπεριλαμβανομένων των παραδοχών που έγιναν για τους υπολογισμούς, της μεθοδολογίας που ακολουθήθηκε και των προσομοιώσεων. Τέλος, συζητούνται τα συμπεράσματα που βασίζονται στους υπολογισμούς, γίνεται ο σχολιασμός των τελικών αποτελεσμάτων και προτείνονται μελλοντικές εργασίες, ειδικά με την επικείμενη θέσπιση αυστηρότερων κανονισμών.

Introduction

From the early ages, shipping played a crucial part to the global economy. It was the most effective way of transferring goods and continues to do so until today. Maritime trade is what made all the famous civilizations flourish. Starting from Mesopotamia at 3,000 BC, it helped the evolution of the societies located in this area, with people like the Babylonians and the Egyptians. The trade then kept expanding through the Mediterranean to the west shores of Europe and finally, it crossed the Atlantic and the Pacific oceans. Throughout this 5,000-year period, the centre of the sea commerce changed a lot of times, but it was always moving on top of an imaginary line called westline [1].

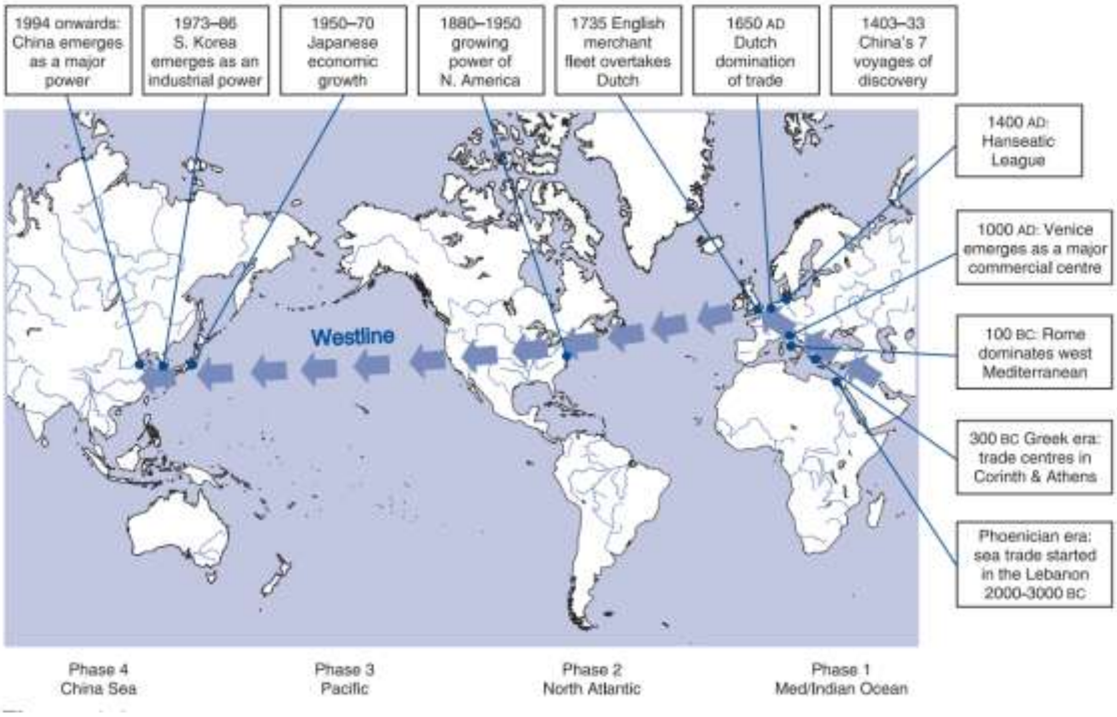

Figure 1: The westline: 5,000 years of maritime trading centres [1]

After watching closely for approximately the past 200 years, someone can notice that there has been a dramatic change, when it comes to the propulsion system. Given the fact that both the increase of distance for the voyages and the need of transportation of even greater cargo had emerged, people sought out different and more efficient ways to produce thrust for the ship's movement. The notable transformation of the propulsion systems started in the early 19th century, when the steam engine was implemented into ships. Shifting from ships with sail rigs, the coal-fired steamships started appearing, having a puddle wheel usually in the middle of the length of the vessel. That change of the propulsion system led to the first iron steamship to go to sea, named 'Aaron Manby' in 1822 [2]. Five years later, in 1827, the first ship propeller was invented and after about a decade, the first ever steamship, driven by a screw propeller, was SS Archimedes in 1838. Many years later, in 1876, the combustion engine was designed and pointed towards the future, which was a path to most fuel-driven vehicles. Due to the high price of the petrol, ships could not afford such an engine. That problem was solved when Rudolf Diesel invented the diesel engine in 1892, a much more viable and efficient 2-stroke engine and, by extension, much more suitable for ships. With the end of World War 2, the number of steamships was greatly reduced, as many of them were destroyed in the fight, letting the diesel engine take over, as most diesel-engine ships were built after 1940. In 1959, the LNG ships made their way to the list of the feasible options, as the 'Methane Pioneer' started sailing cargo, with the number of LNG ships now, either referring to existing ones or newbuildings, exceeding 200. This is mainly the chart of ship propulsion until this day, if we also add the green or the electric ships, which are mostly in the first phase of a project, aiming to assess and identify the value of ‘green shipping’ [3].

These days, maritime shipping is responsible for the transport of the majority of raw materials and products in general, throughout the whole world. It is considered to be efficient and relatively low-cost, given the amount of goods they transport. As it is mentioned by an article in Britannica, in the first quarter of the 21st century, the global fleet of container ships, tankers and dry bulk ships shoulder 80% of the world trade volume and about 70% of the trade value. A huge problem, deriving from the change of the propulsion systems of the world’s fleet, is the environmental pollution. In order for the ships to transport vast amounts of materials in every corner of the globe, nearly all the commercial ones run on fossil fuels. That has as an outcome, the global shipping industry to be considered as a major contributor to the greenhouse gas effect and the climate change [4].

The International Maritime Organization (IMO) has made a noticeable breakthrough when it comes to marine pollution. As it is a specialised agency of the United Nations, responsible for regulating shipping, the assumption that the protocols and the conventions developed by the IMO refer to various aspects of shipping, is quite rational for someone to make [5]. Despite the fact that IMO was focusing on safety at sea, which was its principal responsibility, it tried to solve the emerging problem of pollution with the International Convention for the Prevention of Pollution from Ships (MARPOL) in 1973. Fifty years later, there have been set regulations, stricter and more complex every time, so that the pollution due to ships can be prevented. Some of them refer to ship emissions, aim to tackle the climate crisis and regulate the greenhouse gases emitted from ships, making, fortunately, the whole shipping industry seek the way to decarbonisation and the appliance of sustainable energy to ships [6].

Chapter 1: Pollution of the environment

The rapid evolution of technology the past years has been beneficial and helped the human race in a lot of aspects of their life. Contrary to its vitally important contribution to the improvement of various sectors of our lives, it unfortunately paved the way for the burst of environmental pollution, which imposes heavy burdens on human life and well-being and can be divided into three major types. According to National Geographic, that would be air, water and land pollution [7].

1.1 Climate change and Greenhouse gas effect

Nowadays, the tactic of exploiting fossil fuels (like gas, coal and oil), in order to overcome the obstacle of the huge increase of demand for energy, is more than usual. But nothing comes without a cost and in our case, the cost is the air pollution due to the burning of fossil fuels, which critically affect the environment and, by extension, the human life itself [8].

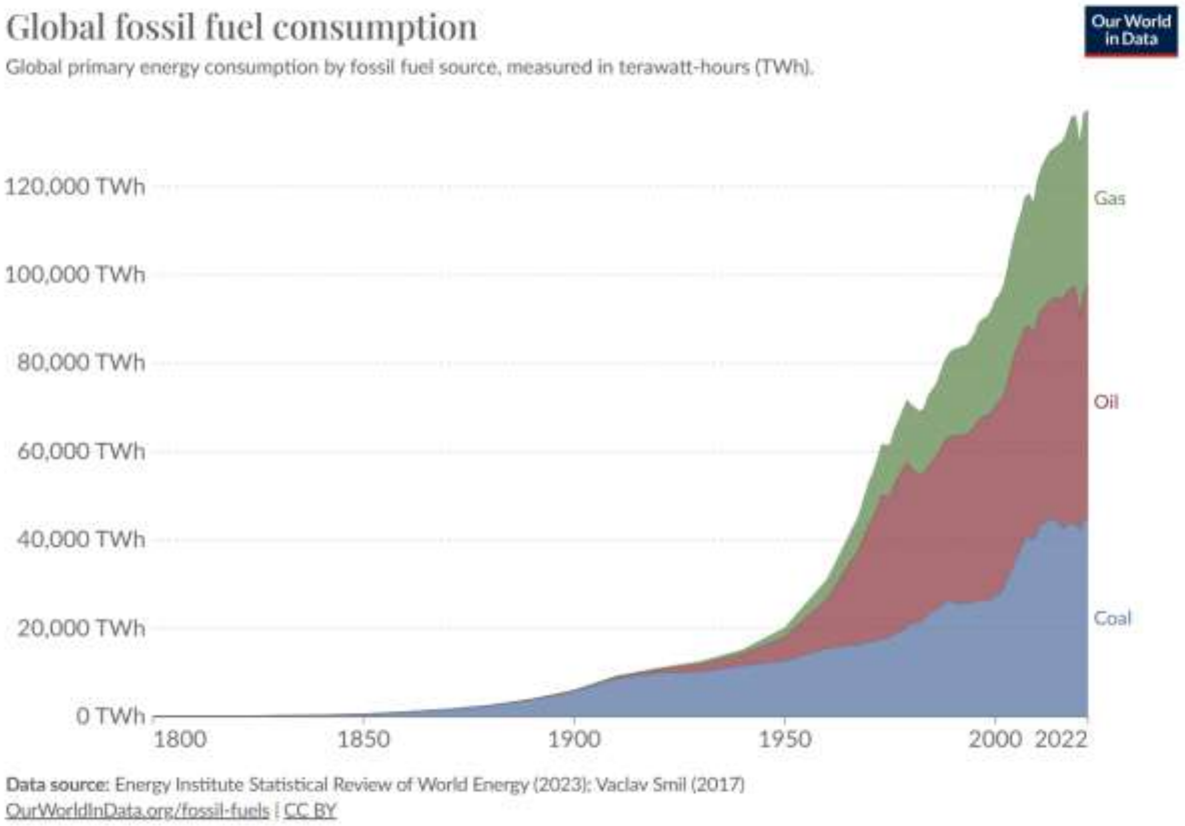

Figure 2: Global fossil fuel consumption by OurWorldInData [7]

Gases emitted mainly from the consumption of the fossil fuels that trap heat in the atmosphere are called Greenhouse Gases (GHG), lead to Greenhouse effect and take the major part of the blame, when it comes to global warming. More in detail, these gases have the ability to absorb infrared radiation (net heat energy) emitted from the Earth’s surface and reradiate it back to Earth [9]. Emissions like these tend to increase more and more the past years, making their mitigation through certain policies of imperative need, given the fact that it is essential to keep the temperature of the Earth in the current standards.

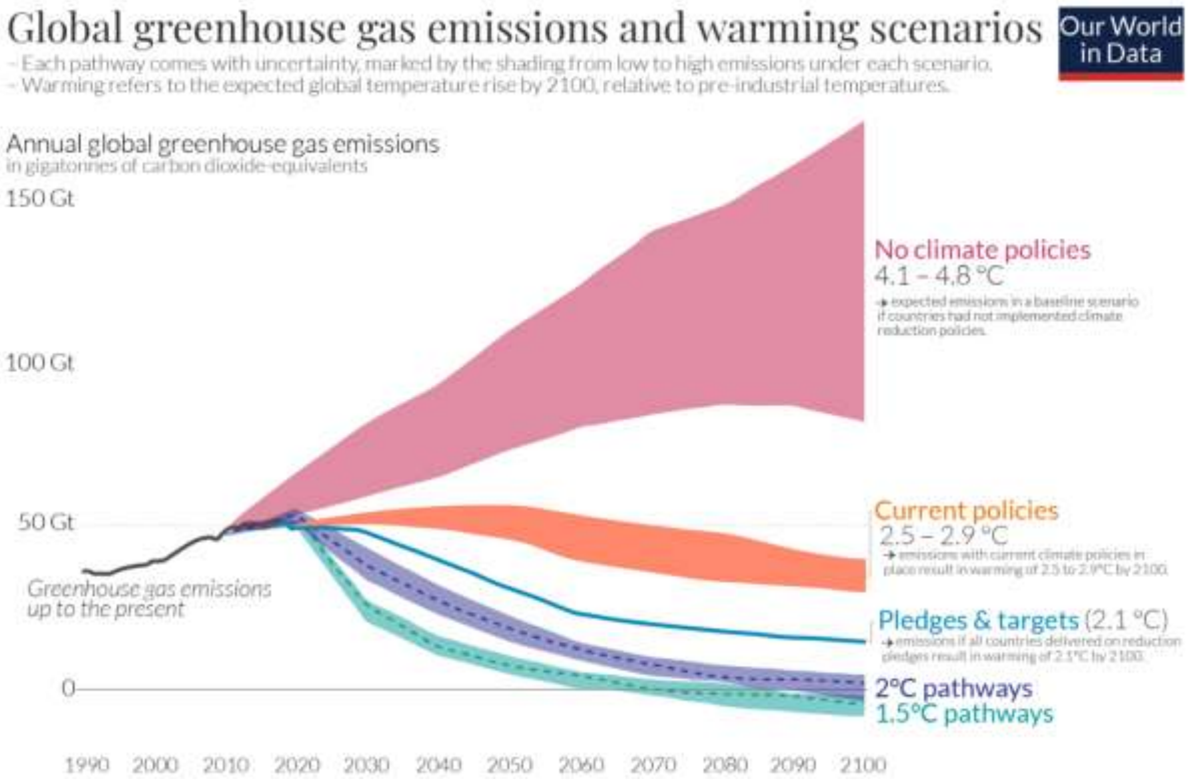

Figure 3: GHG emissions globally by OurWorldinData [10]

According to EDGAR data [11], global GHG emissions in 2022 have reached 53.8 Gt CO_{2eq}, representing the highest level ever recorded, 1.4% or 730Mt CO_{2eq} higher than the previous year. The figure above projects each scenario to the future, up to 2100. It presents the scenario of no climate policies, with the enormous inclination of the temperature following it, the current policies and the targets set by humanity for the future.

1.2 Overview of GHG emissions

The main GHG emitted by human activity are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases (F-gases). A brief overview of these gases is presented below, according to EPA [12]:

- ***Carbon dioxide (CO_2)***: The largest contributor to human-caused climate change is the release of CO_2 from activities like burning fossil fuels for energy and transportation. That release can also be the result of certain chemical reactions like cement production.
- ***Methane (CH_4)***: Methane is the most dominant component of natural gas, emitting during the production of natural gas and oil. Methane emissions also result from livestock and other agricultural practices, land use, and by the decay of organic waste in municipal solid waste landfills.
- ***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***: fluorinated gases are synthetic, powerful greenhouse gases that are emitted from a variety of household, commercial and industrial applications, and processes. Although they are usually emitted in small quantities, they are sometimes referred to as high global warming potential gases.

Table 1: Amount of GHG gases per year [11]

Greenhouse gases by gas globally [Mt CO_2 eq/yr]	
CO_2	38522
CH_4	11294.03
N_2O	2571.117
F-GASES	1398.895
TOTAL	53786.04

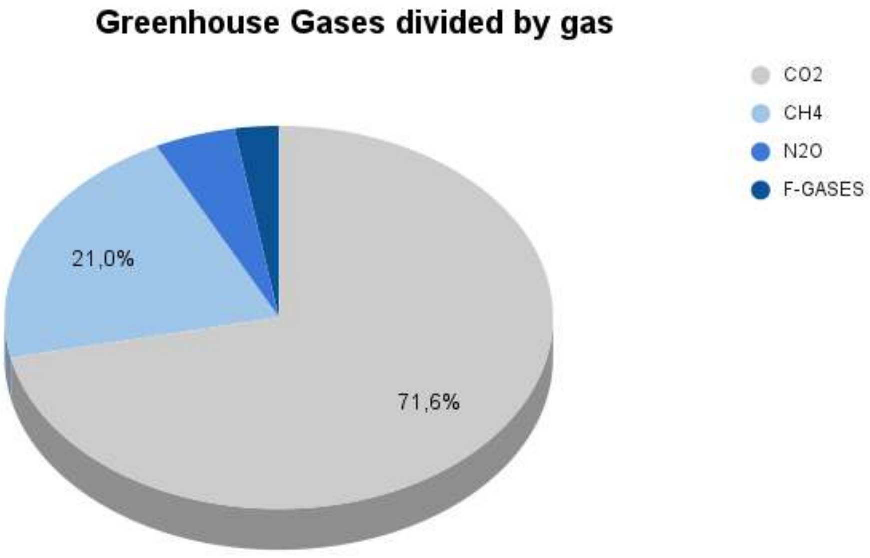

Figure 4: GHG divided to gases (Data by EDGAR) [11]

1.3 Sources of GHG emissions

Human activities are responsible for the escalated increase of greenhouse gases in the atmosphere within the last 150 years. The greatest amount of GHG emissions comes from the fossil fuel burning procedure for transportation, electricity, heat, and other human needs. As reported by EDGAR, the main sources of greenhouse gas emissions are presented as follows:

- **Agriculture**: It is a rather big portion of the pie, including livestock, agricultural soils (fertilisers, direct soil emissions) and field burning of agricultural residues.

- **Buildings**: This sector stands for the small scale, non-industrial, stationary combustion.

- **Fuel exploitation**: It represents the processes of fuel extraction and transformation and the refinery activities, including venting and flaring.

- **Industrial combustion**: Referring to the combustion for industrial manufacturing like the production of iron and steel, cement and aluminium.

- **Power industry**: It claims the biggest portion of the pie, accounting to power and heat generation plants.

- **Processes**: Referring to industrial processes like iron, steel, cement, aluminium and chemicals.

- **Transport**: Representing the second highest percentage of the whole, accounting road and non-road transport and in addition to that, the domestic and international aviation and shipping.

- **Waste**: The smallest but still countable portion, calculated by solid waste disposed on land and waste incineration.

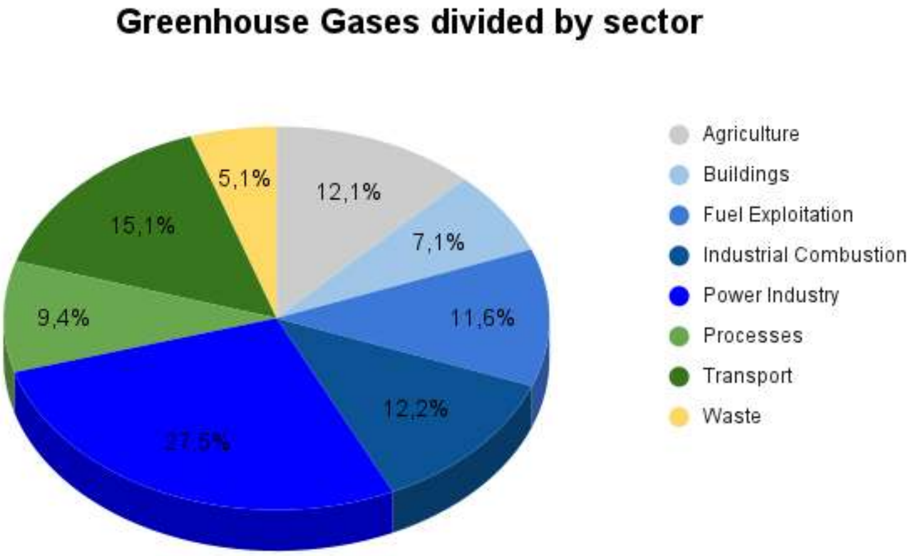

Figure 5: GHG by sectors [11]

1.4 Pollution of the environment due to shipping

As mentioned in the previous paragraphs, maritime transport shoulders over 80% of the world's trade volume. This sector has seen its GHG emissions rise through the roof the past decade, as the increase of these gases reaches out to the rate of 20%. The main reason for such a rapid increase is the fact that almost the entire world fleet, about 98.8% of it, runs on fossil fuels. The silver lining when it comes to this dreadful situation with the use of fossil fuels by ships is that 21% of the ships on order will operate on cleaner fuels, like LNG, methanol and hybrid technologies [13].

Assessing the current situation, this enormous reliance on fossil fuels helps to the conclusion that shipping accounts for 7% of the global fuel consumption and 3% of the energy demand and also releases many pollutants to the atmosphere [14]. The main pollutant shipping produces is first and foremost the Carbon Dioxide (CO_2), which is emitted in much greater amounts, than the rest of the air polluters. Following the most prolific pollutant emitted due to shipping, there are Nitrogen Oxides (NO_x), Sulphur Oxides (SO_x) and Particulate Matter (PM). Although they can be found in much smaller amounts, the consequences can be devastating. According to the European Environment Agency (EEA), international maritime transport was responsible for 9.4% of SO_x emissions, 6.75 % and 3.56% for PM2.5 and PM1 emissions respectively, worldwide, back in the year 2017 [15].

1.4.1 Carbon Dioxide (CO_2):

Carbon dioxide is a gas chemical compound that can be found in the atmosphere of the earth. When it is in small quantities, it remains colourless and odourless. The sources of CO_2 can be the burn of any matter, organic or not, from fossil fuels to plastic and wood. Although its presence is completely natural to the environment, while it helps regulate and maintain the temperature of the earth, it can pose an imminent threat to the planet in time. That can happen due to global warming, due to human activity.

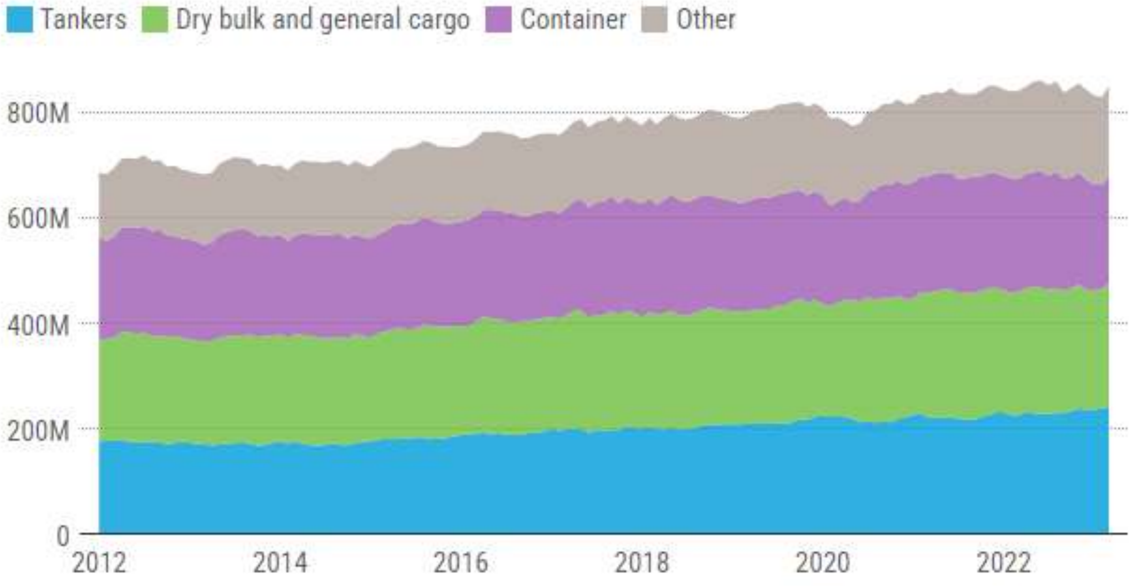

Figure 6: CO2 emissions by main vessel types[1], [12]

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[1] The group 'other' includes vehicles and Ro-Ro, passenger, offshore and service and miscellaneous ships.

1.4.2 Nitrogen Oxides (NO_X):

Nitrogen oxides are a set of gaseous pollutants resulting from the various mixtures of oxygen and nitrogen. These oxides can be produced during the ignition of fuel matter, or during photochemical reactions that occur in the atmosphere.

The two main oxides of nitrogen are nitrogen dioxide (NO_2) and nitric monoxide (NO).

Nitric oxide is a colourless gas and the origin of tropospheric ozone and nitric acid. Its main source of emission is the combustion of fossil fuels (ships, aeroplanes, cars, refineries, etc.), biomass and the photochemical reactions.

Nitrogen dioxide is a reddish-brown, pungent gas that gives smog (urban cloud) its characteristic brown colour. This is a very active chemical component, strongly corrosive and belongs to the category of oxidants, which means it has the ability to remove electrons from molecules. The effects of nitrogen dioxide can be spotted both on the ecosystem and the human health, as it reduces plant growth and conduces to the acid rain, and causes many problems to the respiratory system, respectively. The main sources of nitrogen oxides can be divided into natural and human-caused sources. The burning of fossil fuels in power generation facilities and factories, as well as by means of transport, can be considered as human activity, while the natural sources can be forest fires or volcanic activity.

1.4.3 Sulphur Oxides (SO_X)

Sulphur oxides are chemical compounds of oxygen with sulphur, with the most dangerous oxide of sulphur being the dioxide. Sulphur dioxide is a colourless gas that at high concentrations has a pungent irritating odour. Due to its ability to react with oxidants or particles found in the atmosphere, it becomes quite dangerous, as the products of these chemical reactions, such as sulphides and acid particles of sulphur are more dangerous than dioxide itself. The main sources of sulphur dioxide are the burning of fossil fuels, as well as the processing of fossil ores. These pollutants are extremely harmful to health. Short-term exposure to large concentrations can cause problems to the respiratory system, such as asthmatic episodes. In terms of environmental impact, the most important are due to the transformation of sulphur dioxide into sulphuric acid and its deposition as acid rain. Acid rain can create soil erosion, change the composition of the atmosphere, alter the local climate and affect the balance of flora and fauna. Sulphur dioxide has been associated with steel corrosion, breakdown of zinc and other protective coatings, wear and tear of building materials (concrete and limestone) such as also the degradation of the quality of paper, leather goods, and works and monuments of historical interest.

1.4.4 Particulate Matter (PM)

The term suspended particles characterises the mixture of different liquid droplets or solid particles found in the air. They are one of the most dangerous pollutants because they contain carcinogenic substances and at the same time they aggravate the consequences of other pollutants. Their properties differ according to their type particles, while their danger depends on their diameter. The smallest particles are more harmful as they are inhaled deeper into the lungs damaging the sensitive tissues while at the same time facilitating the realisation of chemical reactions due to large free surface area allowing toxic substances to attach more easily. Even due to their light weight they can remain in the atmosphere for a long time and be transported long distances by air. The largest particles mainly come from mining, construction activities, fires and atmospheric dust. They are deposited faster than small particles and therefore they are a hazard mainly close to their source. They can also be divided into particles that are large or dark enough to be seen with the naked eye, such as dust or smoke, and the ones that don’t get detected by the naked eye, making the existence of an electron microscope essential. The main source of emission of particulate matter is industrial activities and construction sites, while the means of transport also have an important contribution to these emissions. When it comes to the consequences PM has, they also refer to both health and environment. The exposure to these pollutants in a long term can cause damage to the lung tissues leading to chronic respiratory disease, cancer, mainly of the lung, premature disease and death. Thus the environmental consequences are also serious, as these particles lead to impaired visibility. Due to their union with sulphur dioxide and nitric oxide, acidic particles are created, which are transported to the soil through the acid rain, making freshwater lakes and streams acidic. In conclusion, heavy pollution can have a huge impact on the wildlife and the ecosystems of the earth.

Chapter 2: Regulations for the pollution of the environment

Setting regulations is one of the most effective ways to mitigate environmental pollution. In order to contribute to this global effort, both UNFCCC and IMO can be called forth. Although they share the same cause, regarding environmental sustainability, each one may focus on a different aspect of the problem or even follow a different path. The common denominator is the support that is being provided to the UN Sustainable Development Goal 13, regarding the urgent action for the fight against climate change [16].

2.1 UNFCCC Actions

The international community started worrying about climate change and environmental pollution, only after the threats of global warming fell into scientist's perception. The concentration of CO_2 in the atmosphere increased during the 1970s, but it was not before 1990 that the first assessment report was issued by the Intergovernmental Panel on Climate Change (IPCC), lighting the spark for the quest for solutions to the environmental crisis. This urged the governments to create the United Nations Framework Convention on Climate Change (UNFCCC), or more popularly known as "Earth Summit", in 1992.

The first agreement aiming at the reduction of GHG emissions was linked to the UNFCCC and it was named the **Kyoto Protocol**, in 1997. Its main feature was to set targets for 37 industrialised countries and the European community [17]. The successor of the Kyoto Protocol was the **Paris Agreement**, adopted at the Conference of Parties (COP 21) in 2015 and entered into force in 2016. As mentioned by EPA, it was ratified by 195 parties, who collectively aim to have a stronger response to the danger of climate crisis, through:

- holding the average temperature increase to well below 2^oC above pre-industrial levels, while trying to limit it to 1.5^oC.
- increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and encourage the development of low GHG emissions.
- making finance flows resistant, creating a pathway to lower GHG emission and climate-resilient development thus enabling transition and transformation to take place [18].

The Paris Agreement is considered a significant step in the global fight against climate change, as it marks a shift towards a more cooperative and coordinated approach to reduce greenhouse gas emissions. In contrast with the Kyoto Protocol, the distinction between developed and developing countries is blurred, in order for the latter to submit plans for emission reduction.

2.2 IMO Actions

Following the path carved by the UN, IMO is constantly making efforts to protect the environment. Understanding and assessing correctly the situation, it sets more specific regulations, when it comes to the emissions of ships. MARPOL Annex VI, adopted in 1997, but entered into force on 19 May 2005, specifically addresses air pollution from ships. It refers to the set of limits on sulphur oxide and nitrogen oxide emissions from ships exhausts, while simultaneously prohibits deliberate emissions of ozone depleting substances [19].

The first notable action, after Annex VI of MARPOL entered into force, was the introduction of **Emissions Control Areas (ECAs)** and **Sulphur Emission Control Areas (SECAs)**. An ECA is defined as a sea area, in which stricter controls are established, in order to minimise the airborne emissions from ships. Initially, this regulation was aiming to reduce sulphur oxides, but it was extended to include nitrogen oxides for several areas. The ECAs, where the only restrictions that are applied are on SO_x, are referred to as SECAs. So far, the ECAs, determined by the regulation 14 in the MARPOL Annex VI, are the following [20]:

- Baltic Sea Area
- North Sea Area
- North American Area West
- North America Area East
- Hawaii Area
- United States Caribbean Area

Figure 7: ECAs worldwide [21]

On December 6, 2022, MEPC 79 adopted the Mediterranean Sea Emission Control Area for Sulphur Oxides and Particulate Matter. This historic milestone will be taken into effect from 1 May 2025, in the general context of the endeavour for greener shipping [22].

In addition, it is worth noting that the sulphur content limits for fuels in both ECAs and SECAs have became much stricter during the last couple of years with the rule known as “IMO 2020” coming into force. That action led to the use of very low sulphur fuel oil when sailing in those waters, interrupting the extensive use of heavy fuel oil. The reason for that is simply because of the much higher sulphur content of the latter one, which is a quite rational, given the fact that it derives as a residue from crude oil distillation [23].

2.3 Commitment to energy efficiency

Realising that environmental pollution and energy efficiency are interrelated, IMO has tried to make ships as efficient as possible, starting from the past decade. The main indexes contributing to that effort are EEDI, EEXI and CII. The timeline starts in 2011, when the first of a series of regulations concerning energy efficiency was adopted. Apart from EEDI, MEPC 62 made ***SEEMP*** mandatory for new ships as well, in July 2011. (MEPC.203 (62)) The Ship Energy Efficiency Management Plan is an operational measure that establishes a mechanism to improve the energy efficiency of a ship, in a cost-effective manner. Also, it provides an approach of shipping companies to manage ships and fleet efficiency performance over time using various monitoring tools, like Energy Efficiency Operational Index, which is a voluntary measure. The following year, four important guidelines were adopted by the MEPC 63 (resolutions MEPC.212 (63), MEPC.213 (63), MEPC.214 (63) and MEPC.215 (63)), which assisted the implementation of the mandatory regulations on energy efficiency for ships in MARPOL Annex VI [24].

The next regulation, assisting the previous ones, was the ***MRV*** for the EU. In April 2015, regulation 2015/757 was adopted, referring to Monitoring, Reporting and Verification of carbon dioxide emissions from maritime transport and applicable for ships above 5,000 GT on EU related voyages. In accordance with the EU MRV regulation, the vessel must have a monitoring plan which describes its installed combustion machinery, kind of fuels used, monitoring methods applied and eventually must be verified by an independent and accredited verifier. After monitoring, the vessel must report the voyage data, which must be verified [25]. In addition, trying to inform further the measures regarding the mitigation of the GHG emissions, the IMO DCS was adopted by resolution MEPC.278 (70). It consisted of requirements for ships to record and report their fuel oil consumption in order to provide the data for the calculation of the indexes regarding energy efficiency. The regulation came into force on the 1st of January 2019 and was addressed to ships of 5,000 GT and above, which produce about 85% of the total CO_2 emissions in international shipping [26].

Along with these regulations, IMO enacted the ***Initial GHG Strategy*** (MEPC.304 (72)) in 2018 and started setting more specific targets, aiming to reduce the Greenhouse Phenomenon. First, the CO_2 emissions per transport work released by ships should be reduced by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008. Simultaneously, IMO is aiming to reduce the total annual GHG emissions by at least 50% by 2050, also compared to 2008 [27].

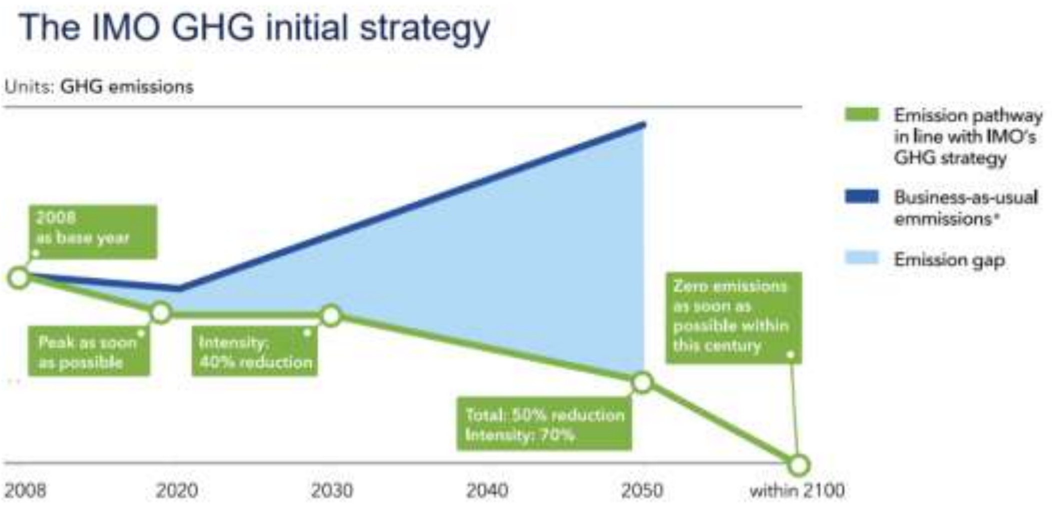


Figure 8: IMO GHG Initial Strategy

According to this strategy, the way humanity is going to achieve these ambitious goals, regarding CO_2 emissions, is by following a wide list of possible measures. These measures are divided into short-term, mid-term and long-term and should be consistent with the following timeline:

- Possible short-term measures could be measures finalized and agreed by the Committee between 2018 and 2023.
- Possible mid-term measures could be measures finalized and agreed by the Committee between 2023 and 2030.
- Possible mid-term measures could be measures finalized and agreed by the Committee beyond 2030.

In addition, based on the Initial Strategy, a brief but quite comprehensive list of these possible measures is presented below:

- **Short-term measures:**
    - Further improvement of the existing energy efficiency framework with a focus on the EEDI and SEEMP
    - Develop technical and operational energy efficiency measures for both new and existing vessels, including consideration of indicators in line with the three-step approach that can be utilized to indicate and enhance energy efficiency performance of shipping, such as the Annual efficiency Ratio (AER) and the Individual Ship Performance Indicator (ISPI)
    - Establishment of Existing Fleet Improvement Program
    - Consider and analyse the use of speed optimization and speed reduction as a measure, taking into account safety issues, distance travelled, distortion of the market or trade and that such measure does not impact on shipping's capability to serve remote geographic areas
    - Initiate research and development activities addressing marine propulsion, alternative low-carbon and zero-carbon fuels, and innovative technologies to further enhance the energy efficiency of ships and establish an International Maritime Research Board to coordinate and oversee these R&D efforts
- **Mid-term measures:**
    - Implementation program for the effective uptake of alternative low-carbon and zero-carbon fuels, including uptake of national actions plans to specifically consider such fuels
    - Operational energy saving measures for both new and existing vessels, including indicators in line with the three-step approach that can be utilized to indicate and enhance energy efficiency performance of shipping
    - New/Innovative emission reduction mechanisms, possibly including Market-based Measures (MBMs), to incentivize GHG emission reduction
- **Long-term measures:**
    - Pursue the development and provision of zero-carbon and fossil-free fuels to enable the shipping sector to assess and consider decarbonization in the second half of the century
    - Encourage and facilitate the general adoption of other possible new/innovative emission reduction mechanisms

The revised IMO GHG Strategy is the successor of the initial one, appearing in 2023 and including an enhanced common ambition to reach net-zero GHG emissions from international shipping close to 2050. This enhancement is a commitment to ensure an uptake of alternative zero or near-zero GHG fuels by 2030. (MEPC.377 (80))

2.3.1 Energy Efficiency Design Index (EEDI)

As mentioned previously, EEDI first introduced itself in 2011 with the adoption of MEPC.203 (62) and entered into force 2 years later, in 2013. It is a rate that applies to ships of 400 gross tonnage and above and estimates the energy efficiency of new vessels built from 2013, it is measured in gr-CO_2/t*nm. According to the IMO, the main purpose of the EEDI is to provide a fair basis for comparison, while simultaneously tries to support the development of more innovative, energy efficient vessels. In addition, the regulation sets a minimum efficiency level of new ships, based on size and type and building on that, it also established the reference lines for each ship type. There are 3 targets set, known as phases, that progressively require the reduction of carbon intensity and they are presented below:

- **Phase 0:** ships built between 2013-2015 are required to have a design efficiency at least equal to the baseline, which is the average efficiency of ships built between 1999-2009.
- **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 [28].

According to some new sustainability and climate-focused amendments made for the EEDI, phase 3 began on April 1, 2022, instead of 2025, for certain type of vessels. This change was applicable for containerships, general cargo hips, refrigerated cargo carriers, combination carriers, gas carriers, LNG carriers and cruise ships [29].

The energy efficiency of a vessel increases when the attained EEDI value decreases, giving ship owners a competitive advantage, as ships that comply with the corresponding demands are more likely to sign a more profitable chartering contract. This measure is based on technical design parameters for a given ship and is calculated by the following formula:

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

Figure 9: Formula for calculation of EEDI

According to the resolution MEPC.364 (79), adopted in 2022, the parameters applied to the formula are explained in the paragraph 2.2 as follows:

C_F: Conversion factor between fuel consumption and CO_2 emissions

V_{ref}: Ship speed

P: Power of main and auxiliary engines

$P_{ME(i)}$: Power of main engines

$P_{PTO(i)}$: Shaft generator

$P_{PTI(i)}$: Shaft motor

$P_{eff(i)}$: Innovative mechanical energy-efficient technology for main engine

P_{AEeff}: Innovative mechanical energy-efficient technology for auxiliary engine

P_{AE}: Auxiliary engine power

SFC: Certified specific fuel consumption

f_j: Ship-specific design elements

f_w: Factor for speed reduction at sea

$f_{eff(i)}$: Factor of each innovative energy efficiency technology

f_i: Capacity factor for technical/regulatory limitation on capacity

f_c: Cubic capacity correction factor

f_l: Factor for general cargo ships equipped with cranes and cargo-related gear

f_m: Factor for ice-classed ships having AI Super and IA

The compliance of a ship with the EEDI regulation is accomplished when:

$$\boldsymbol{Attained\ EEDI \leq Required\ EEDI}$$

$$\boldsymbol{Required\ EEDI = \frac{1 - X}{100} \times Reference}$$

X: Reduction factor based on the phase

$Reference = a \times b^{-c}$, with a, b and c given by the following table:

Table 2: Constants for the calculation of the EEDI reference line

Ship type in regulation 2	a	b	c
2.25 Bulk carrier	961.79	DWT of ship	0.477
2.26 Gas carrier	1120.00	DWT of ship	0.456
2.27 Tanker	1218.80	DWT of ship	0.488
2.28 Container ship	174.22	DWT of ship	0.201
2.29 General cargo ship	107.48	DWT of ship	0.216
2.30 Refrigerated cargo carrier	227.01	DWT of ship	0.244
2.31 Combination carrier	1219.00	DWT of ship	0.488

2.3.2 Energy Efficiency Existing Ship Index (EEXI)

In June 2021, the IMO’s MEPC 76 adopted amendments to MARPOL Annex VI, introducing regulations 23 and 25, referring to the upcoming EEXI. It is a regulatory measure aiming to enhance the energy efficiency of existing ships and mitigate the greenhouse gas emissions. Its main purpose is to establish a standardized method for assessing the energy efficiency of vessels in operation, thereby encouraging the shipping industry to adopt measures that reduce fuel consumption and environmental impact. By requiring existing ships to meet specified targets regarding efficiency, EEXI aims to drive the implementation of technological upgrades, new practices and operational improvements. Along with other IMO measures, it forms a crucial part of the industry’s commitment to reducing the carbon footprint and aligning with the global efforts to tackle climate change.

This index must be calculated for ships of 400 GT and above, in accordance with the different values set for ship types and size categories. Like the EEDI, the attained EEXI value for each individual vessel must be below the required EEXI, to ensure the ship meets a minimum energy efficiency standard [30]. The required

EEXI is calculated using the capacity and some factors depending on the type of the ship, while the attained EEXI is calculated by the following formula:

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

Figure 10: Formula for calculation of EEXI

This formula is the same as the one used for the calculation of EEDI and follows the guidelines indicated by resolution MEPC.350 (78).

When ships fail to meet the specified EEXI requirements, there are potential consequences that can impact both ship-owners and the broader maritime industry. Non-compliance may lead to increased operational costs, resulting in higher expenses and a larger carbon footprint. In addition, regulatory penalties and sanctions could be imposed on those ships, a fact that urged ship-owners to seek solutions to the problem. The technological upgrades geared towards enhancing the energy efficiency of ships target different facets of a vessel's design and operational functionality. These encompass not only advancements in propulsion systems, like engine power limitation, but also hull optimization, energy recovery systems and data monitoring and analytics. By adopting these innovations, ship-owners can not only ensure compliance with EEXI, but also contribute to sustainability goals and enhance operational efficiency [31]. According to ClassNK, the following diagram shows the timeline of the EEXI regulation, starting from its adoption in 2021.

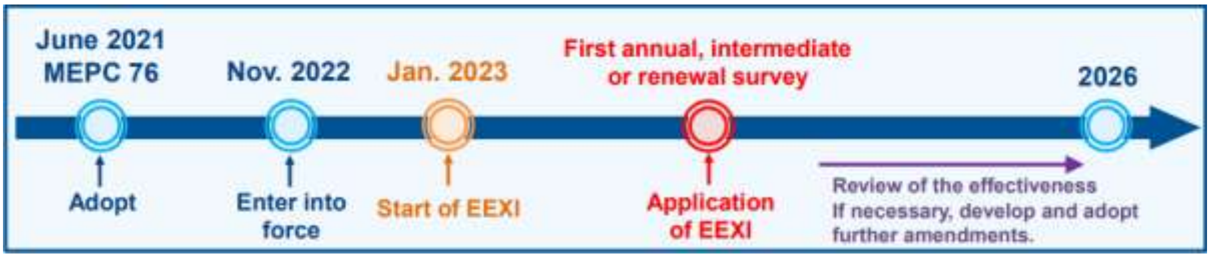


Figure 11: Timeline of EEXI regulation [32]

2.3.3 Carbon Intensity Index (CII)

As mentioned in previous chapters, regulatory bodies make constant efforts to mitigate climate change and reduce GHG emissions. Both IMO and the UN adopt regulations addressing that matter. The latest of them and the one this thesis is trying to calculate is the Carbon Intensity Index (CII). This index is a mandatory measure that came into force on 1st January 2023 and it serves as a vital tool for quantifying and benchmarking the carbon intensity and footprint of a ship. Represented by regulation 28 of MARPOL Annex IV, it addresses to all ship with gross tonnage greater than 5,000 tonnes and it is an operational measure for ship's energy efficiency, given in "CO_2 emitted per cargo–carrying capacity and nautical mile", whereby cargo capacity is either deadweight or gross tonnage depending on ship type. The first year of the attained annual operational CII verification will be 2024 for the operation in calendar year 2023. Vessels, based on their performance, will receive an environmental rating, meaning they will be assigned a ranking label from the five grades (A, B, C, D, E) based on the attained annual operational carbon intensity indicator, indicating a major, minor superior, moderate, minor inferior or inferior performance level respectively, with the rating thresholds becoming increasingly stringent towards 2030. If a ship has rating D for 3 consecutive years or E, the company must develop an approved plan for achieving rating C or better (Regulation 28.7) and the revised SEEMP shall be submitted for verification within 1 month after reporting the attained annual CII (Regulation 28.8). To enhance this effort, administrations, ports and other stakeholders are encouraged to provide incentives to ships rated as A or B (Regulation 28.10).

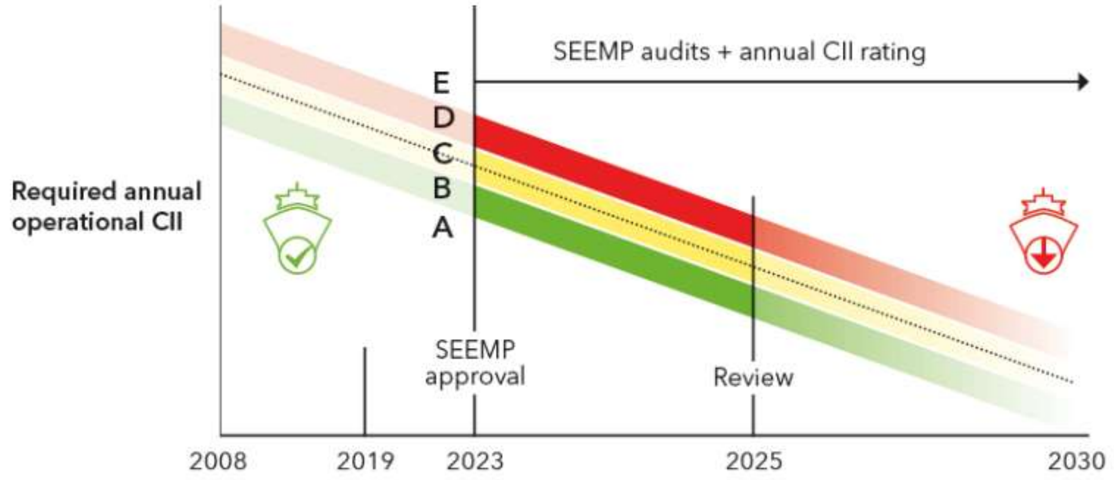


Figure 12: CII ratings [33]

In addition, to cater for special design and operational circumstances, the correction factors and voyage adjustments can be applied to the basic CII calculations for the purposes of determining the rating [33].

Figure 13: Simplified attained annual CII formula [33]

According to MEPC.352(78), published in 2022, the attained annual operational CII of individual ships is calculated as the ratio of the total mass of CO_2 (M) emitted to the total transport work (W) undertaken in a given calendar year, as follows:

$$\boldsymbol{Attained\ CII_{ship}} = \frac{\boldsymbol{M}}{\boldsymbol{W}}$$

Mass of CO_2 emissions (M)

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

$$\boldsymbol{M = FC_j \times C_{Fj}}$$

Where:

- j is the fuel oil type;
- FC_j is the total mass (in grams) of consumed fuel oil of type j in the calendar year, as reported under IMO DCS;
- C_{Fj} represents the fuel oil mass to CO_2 mass conversion factor for fuel oil type j, in line with those specified in the *2018 Guidelines on the method of calculation of the attained Energy Efficiency Design Index (EEDI) for new ships (resolution MEPC.308(73)),* as may be further amended. In case the type of the fuel is not covered by the guidelines, the conversion factor should be obtained from the fuel oil supplier supported by documentary evidence.

Transport work (W)

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

$$\boldsymbol{W_s = c \times D_t}$$

Where:

- C represents the ship's capacity:
    - For bulk carriers, container ships, gas carriers, LNG carriers, general cargo ships, cargo carrier and combination carriers, deadweight tonnage (DWT) should be used as Capacity.
    - For cruise passenger ships, ro-ro cargo ships (vehicles carriers), ro-ro cargo ships 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.

In general, according to the regulation, the value of CII of a ship must not exceed a specific value associated with the type of that ship.

$$\boldsymbol{Attained\ CII \leq Required\ annual\ operational\ CII}$$

In accordance with regulation 28 of MARPOL Annex IV, the required annual operational cII for a ship is calculated as follows:

$$\boldsymbol{Required\ annual\ operational\ CII = \frac{1 - Z}{100} \times CII_R}$$

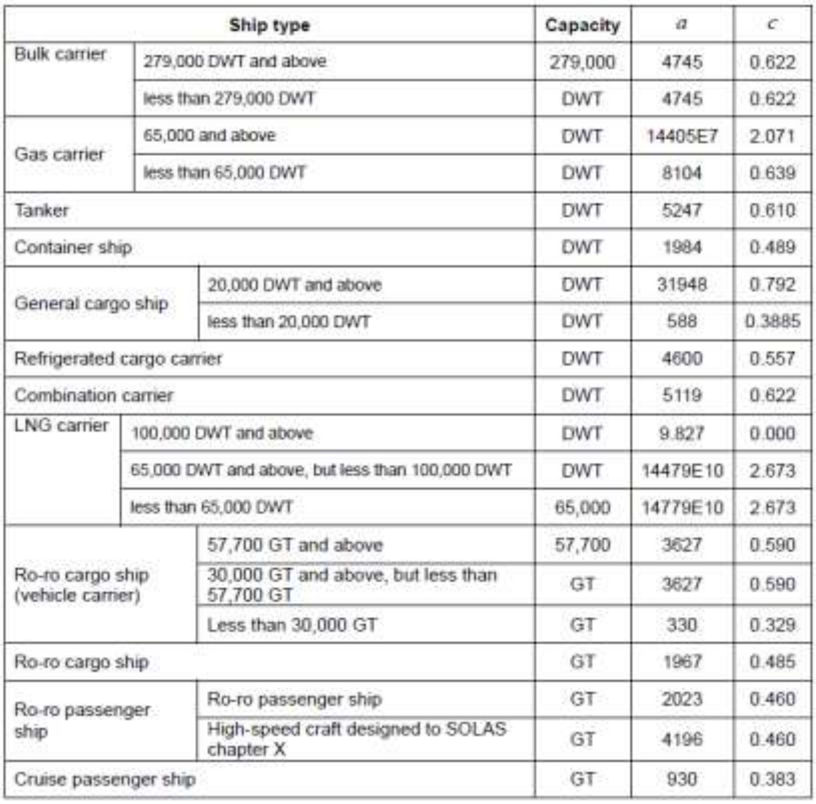
Where:

- CII_R is the reference value in year 2019 as defined in *the Guidelines on the reference lines for use with operational carbon intensity indicators (G2)* MEPC.353(78)

$$\boldsymbol{CII_R = a \times Capacity^{-c}}$$

Where the parameters are specified as follows:

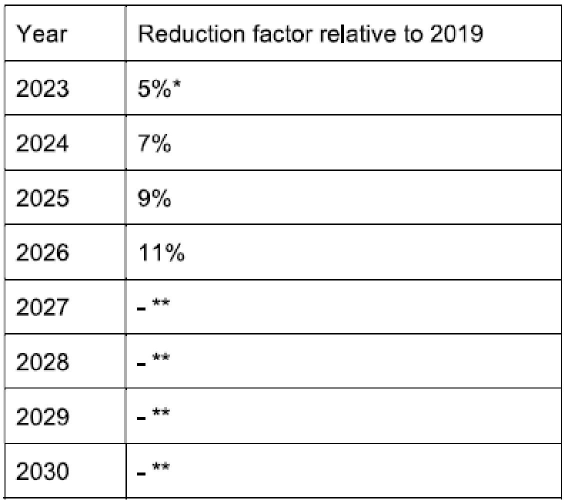
Table 3: Parameters for determining the 2019 ship type specific reference lines



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	5119	0.622
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	14779E10	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

- Z is a general reference to the reduction factors for the required annual operational CII of ship types from year 2023 to 2030, as specified in resolution MEPC.338(76):

Table 4: Reduction factors (Z%) for CII relative to the 2019 reference value[2]



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

In addition, according to MEPC.354 (78), the boundaries between the CII ratings can be determined by the required annual operational CII in conjunction with the vectors "dd", as illustrated in the following figure:

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[2] There will be conducted a review by 1 January 2026 (Regulation 28.11) that will determine the Z factors for 2027-2030

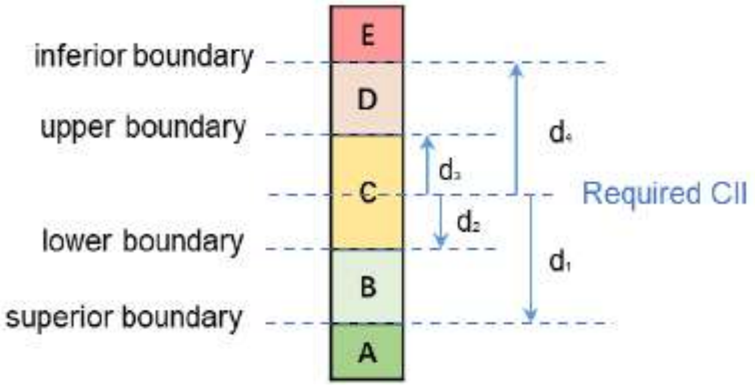


Figure 14: dd vectors and rating bands

- The middle 30% of the fleet assigned C
- The upper and lower 20% assigned rating D and B respectively
- Further upper and lower 15% assigned rating E and A respectively

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

Table 5: dd vector for determining the rating boundaries of ship types

Ship type		Capacity in CII calculation	*dd* vectors (after exponential transformation)			
			exp(d1)	exp(d2)	exp(d3)	exp(d4)
Bulk carrier		DWT	0.86	0.94	1.06	1.18
Gas carrier	65,000 DWT and above	DWT	0.81	0.91	1.12	1.44
	less than 65,000 DWT	DWT	0.85	0.95	1.06	1.25
Tanker		DWT	0.82	0.93	1.08	1.28
Container ship		DWT	0.83	0.94	1.07	1.19
General cargo ship		DWT	0.83	0.94	1.06	1.19
Refrigerated cargo carrier		DWT	0.78	0.91	1.07	1.20
Combination carrier		DWT	0.87	0.96	1.06	1.14
LNG carrier	100,000 DWT and above	DWT	0.89	0.98	1.06	1.13
	less than 100,000 DWT		0.78	0.92	1.10	1.37
Ro-ro cargo ship (vehicle carrier)		GT	0.86	0.94	1.06	1.16
Ro-ro cargo ship		GT	0.76	0.89	1.08	1.27
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

In order to have the final rating of the ship, the ratio that has to be calculated is the following:

$$\frac{\boldsymbol{Attained\ CII}}{\boldsymbol{Required\ CII}}$$

Starting in 2024, the CII must be calculated and reported to the Data Collection System (DCS) verifier together with the aggregated DCS data for the previous year, including any correction factors and voyage adjustments. Deadline for DCS and CII submission remains unchanged - no later than 31 March each year. The following figure by DNV shows the timeline of CII:

Figure 15: CII timeline

2.4 EU actions

In parallel with global efforts, the European Union (EU) has been proactive in implementing robust measures to address climate change within its borders and has been actively engaged with international entities such as the UN and the IMO. In alignment with the commitment to global cooperation, a strategy addressing environmental issues has been set up, introducing the "**Fit for 55**" package. It is a set of proposals to revise and update EU legislation and implement new initiatives with the aim of ensuring that EU policies are in line with the climate goals agreed by the council and the European parliament. This package is acting as an intermediate step towards climate neutrality, with the EU raising its 2030 climate ambition, committing to cutting emissions by at least 55% by 2030.

Figure 16: Main goals of Fit for 55 package [34]

Some of the main goals that this package has are listed right below:

- Reach climate goals in the land use and forestry sectors
- Reduce emissions from transport, buildings, agriculture and waste
- A more energy efficient EU
- Boost of renewable energy
- Revise energy taxation
- Increase uptake of greener fuels

More in detail, this bundle is going to set a new course for the shipping industry. This change has as its centrepiece the EU Emissions Trading System (EU ETS), a “cap and trade” program designed to curb greenhouse gas emissions from major industries. Since 2005, when the system first made its appearance, it has helped reduce emissions consisting of not only CO_2, but also N_2O and PFCs, from power and industry plants by 37%. It is worth mentioning that it is the world’s first major carbon market and remains the biggest one until today. The deduction based on the piece of information presented above is that this system establishes a clear economic incentive for industries to reduce their carbon footprint, fostering a transition towards cleaner and more sustainable practices [35]. According to DNV, the EU’s legislative bodies have reached an agreement on including shipping in its Emission Trade System from 2024. Subject to final adoption, ships above 5,000 GT transporting cargo or passengers for commercial purposes in the EU will be required to acquire and surrender emissions allowances for their CO_2 emissions. More in detail, the emission in scope for surrendering allowances will be gradually phased-in, starting with 40% for 2024, increasing to 70% for 2025 and to 100% for 2026 onwards [36].

Before moving to the next important regulation of the bundle, it is important to explain the approach of “well-to-wake” emissions. It is a critical step to assess lifecycle GHG emissions from marine fuels, which refers to the entire process of fuel production, delivery and use onboard ships and all emissions produced therein, and it can be divided into two parts, the “well-to-tank” (WtT) and the “tank-to-wake” (TtW) emissions. The first phase is used to describe the emissions that take place during the production and the extraction stage of the fuel, while the later refers to the emissions due to burning the fuel or converting the energy into another form, including amounts of energy lost [37].

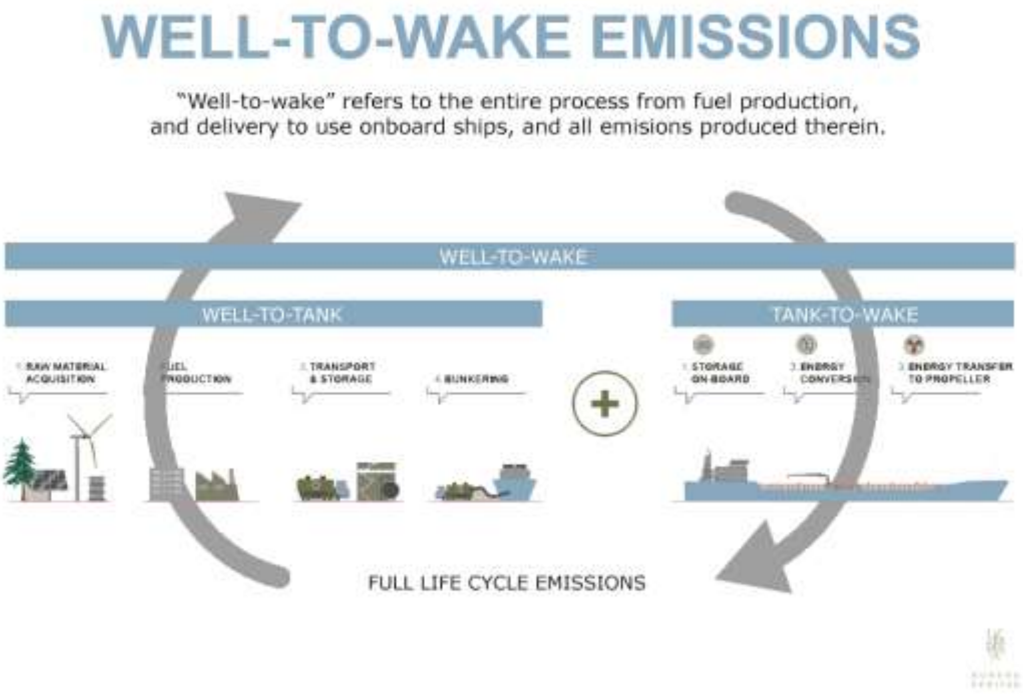


Figure 17: "Well-to-wake" approach [37]

Now that well-to-wake approach is clear, it is time to highlight another regulation introduced by Fit for 55. It is **FuelEU Maritime** regulation, also known as FuelEU Maritime initiative, which aims to support decarbonisation of the shipping industry. One of its main objectives is to put maritime on the trajectory of the EU's climate targets for 2030 and 2050 and to promote the use of sustainable alternative fuels, as it focuses on reducing the carbon intensity of maritime fuels. According to a press release of the council of the EU on 25 July 2023, the new law was adopted later in 2023 and will enter into force from 1 January 2025. In general, this regulation sets well-to-wake greenhouse gas emission intensity requirements on energy used on ships trading in the EU from 2025 and also supports the uptake of the so-called renewable fuels of non biological origin (RFNBO) with a high decarbonisation potential. Thus, it renders as an obligation for passenger and container ships to use on-shore power supply for all electricity needs while moored at the quayside in the major EU ports as of 2030. From 2035, the requirement applies to all ports where shore power is available, with a view to mitigating air pollution in ports, which are often near densely populated areas [38]. When it comes to GHG intensity requirements, it is worth mentioning that the percentage of the energy used on voyages differs, depending on the route. As DNV states, these requirements apply to 100% of energy used on voyages and port calls within the EU or EEA and 50% of energy used on voyages into or out of the EU or EEA [39].

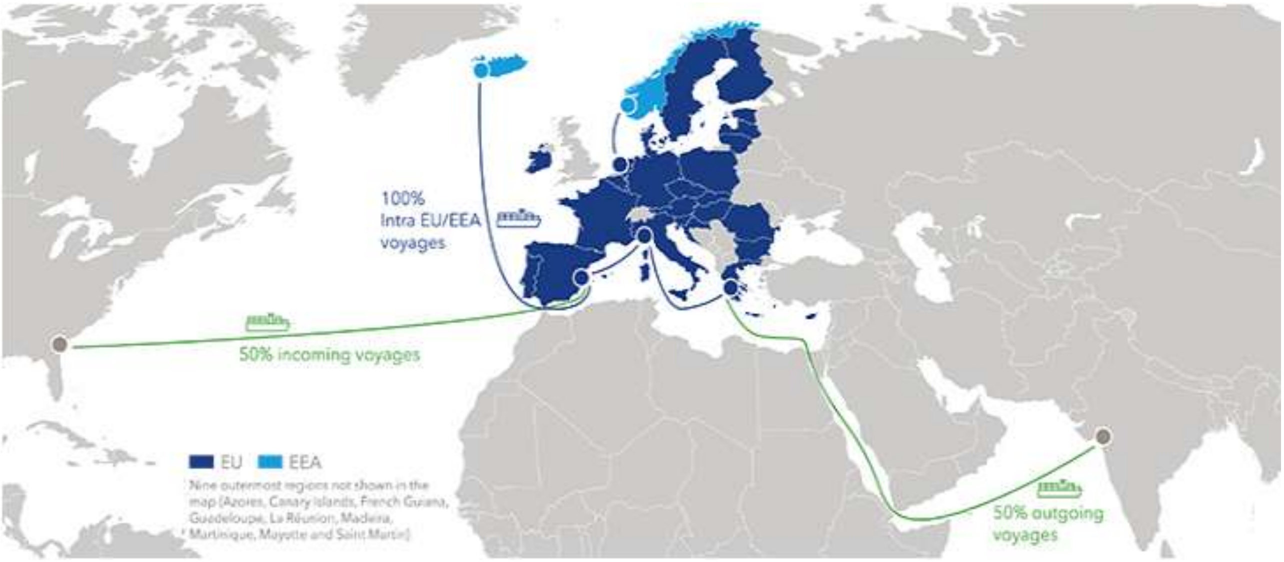


Figure 18: FuelEU Maritime requirements based on percentage of energy used on voyages [39]

Chapter 3: Fuels

The sea trade has always been a vitally important element to the flourishing of the global economy. The change of ship's propulsion system and its turn towards fossil fuels came to enhance this perspective, as it led to the transportation of even greater cargo. Nevertheless, the downside that balanced the scales to the situation caused by the previous action is the global warming and the pollution of the environment. The rise of CO_2 emissions each year, reaching up to 38.522 billion tones in 2022 [11], is a continuous deteriorating phenomenon, the solution of which is of imperative need. With this being said, technologies have been developed and regulations have been set that possess a vital role to the mitigation of this phenomenon. In tandem with that, people turned to cleaner fuels, like LNG and LPG and alternative fuels, like Ammonia and Hydrogen, having as the ultimate target the decarbonization of shipping. Given the fact that the industry is in a transition phase, with many potential options emerging alongside conventional fuels, it is a fair deduction that important breakthroughs will be noticed in the following years [40].

In an effort to give an overview of the type of fuels used in shipping, DNV AFI (Alternative Fuels Insight) provides some very useful data that will be presented below [41] .

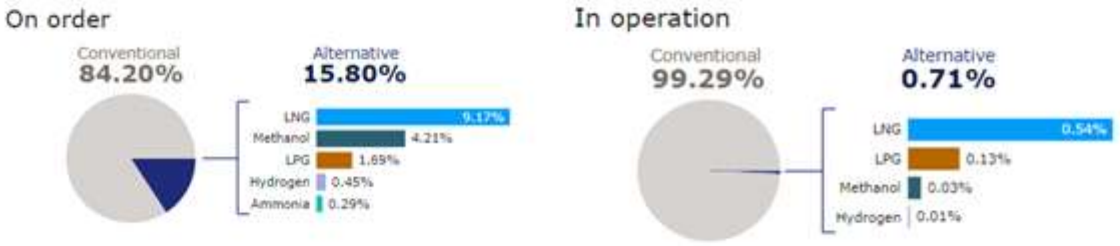


Figure 19: Percent of fleet using conventional vs. alternative fuels

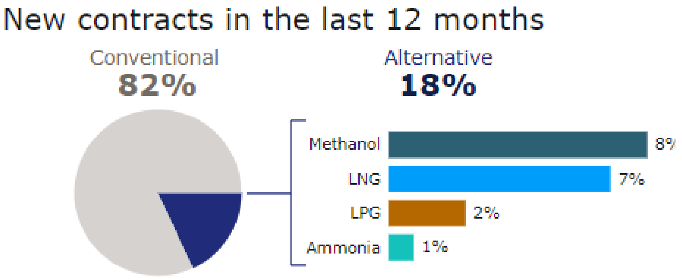


Figure 20: New contracts in the last 12 months

According to these diagrams, despite the fact that almost the entire maritime fleet runs on conventional fuels, the orders made for newbuildings have a strong element of alternative fuels, compared to the current situation. In addition, it is getting clear that mainly methanol and LNG mark the transition to a more sustainable future of the maritime sector.

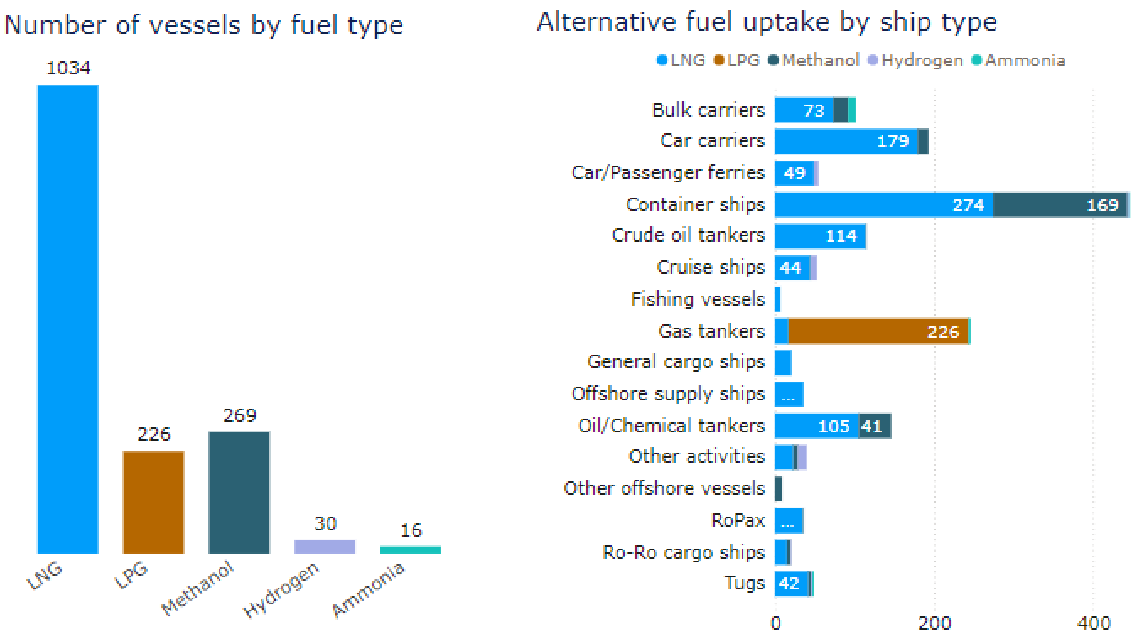


Figure 21: Distribution of alternative fuel fleet (In operation and on order)

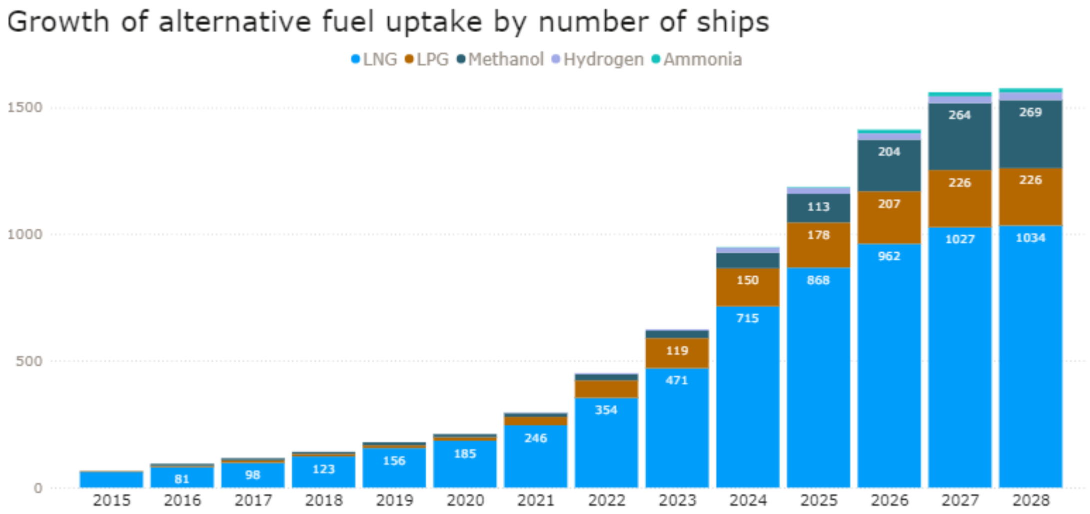


Figure 22: Growth of alternative fuel uptake by number of ships

Moreover, the supremacy of LNG versus the other alternative fuels at the moment is obvious, as besides the large number of ships using it, it is versatile when it comes to the ship type. This is something that does not happen with LPG or methanol the time being, with the first fuel being found almost exclusively on gas carriers, while the second mainly in container ships and a few bulk carriers, car carriers and tankers.

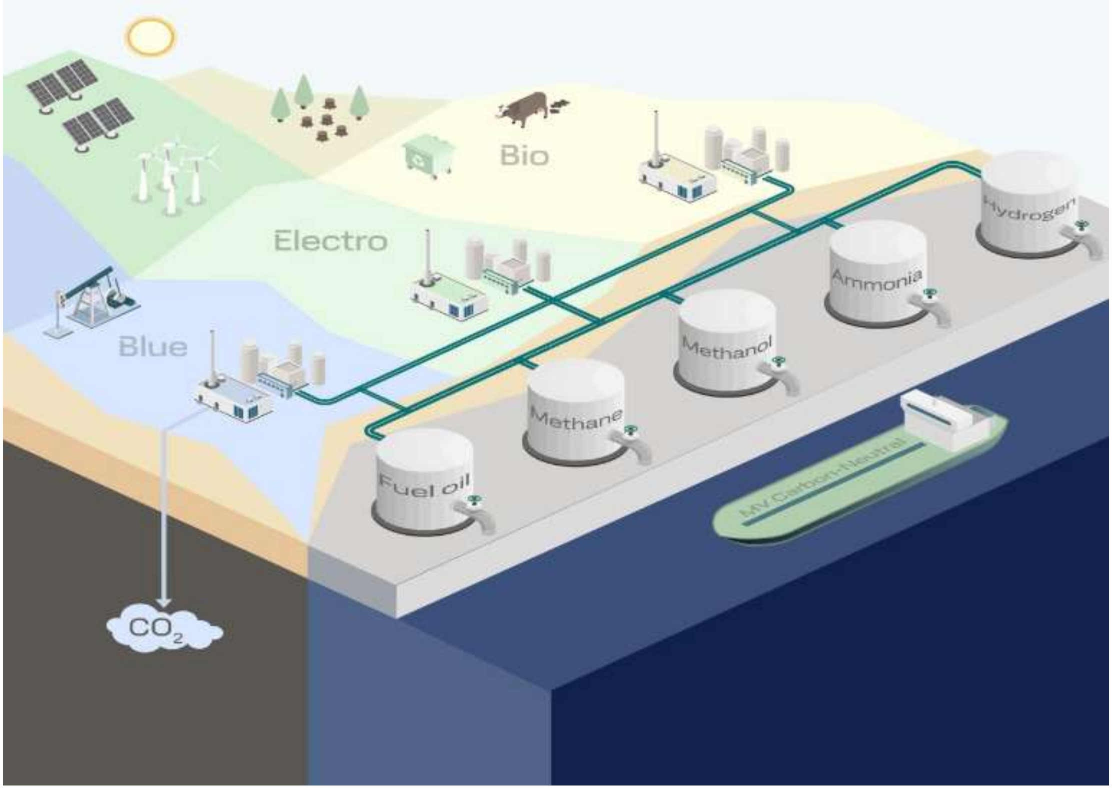


Figure 23: Blue, green and biofuels

On top of all this, it is quite important to understand that critical variations may be noticed, even though the basic fuel remains the same. Escalating on that topic, there are two distinct approaches to enhance the effort of decarbonizing shipping, e-fuels, also known as synthetic fuels, and biofuels. E-fuels are produced using electricity to convert CO_2 and water into liquid or gaseous fuels, with potential of achieving net-zero. This category is divided into two, as we have blue and green fuels. During the phase of their production, the first are coupled with CCS technology to reduce emissions, while the later are coupled with renewable energy sources. On the other hand, biofuels are derived from biomass feedstock. At the end of the day, the efforts for securing a sustainable future for the shipping sector are obvious, given the fact that marine fuels are moving towards carbon neutrality.

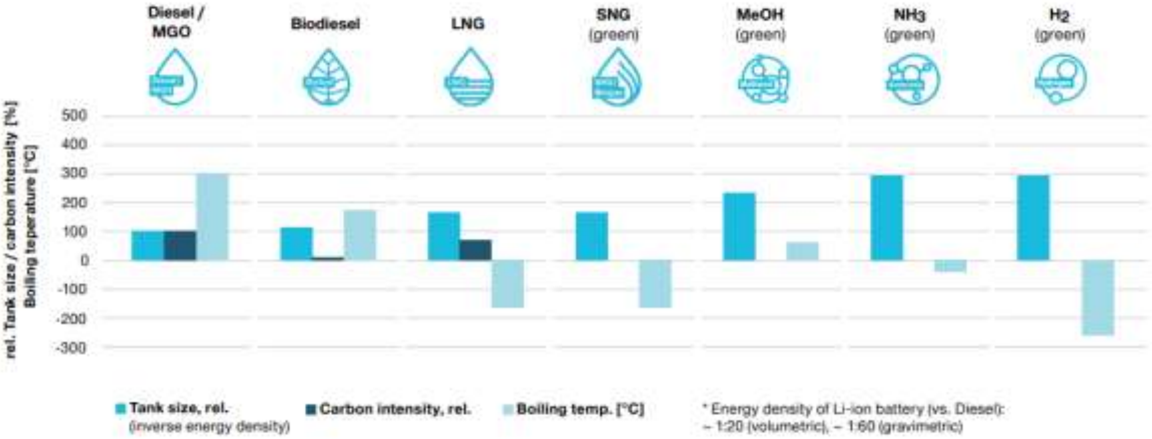


Figure 24: Marine fuels towards carbon neutrality [42]

3.1 Conventional fuels

Nowadays, the most common fuels used in shipping are heavy residual fuels (residual oil) and light crude oil distillates (marine gas oil – marine diesel oil). Their quality can vary depending on numerous factors, like the starting crude oil and its refining process. This quality variation can lead to different characteristics, such as viscosity (resistance to flow), density, flash point, sulphur and water content. The pre-refining, the blending with lighter products and the transportation methods can be added to the list of the factors, which contribute to the creation of different fuel quality. In general, fuels are categorized as intermediate fuel oil (IFO) types based on their viscosity at 50 °C.

Table 6: Classification of fuels into IFO categories

IFO category	Viscosity [cSt/50°C]	Viscosity [Redwood I/100°F]
30	30	100
40	40	178
60	60	439
80	80	610
100	100	780
120	120	950
150	150	1250
180	180	1500
240	240	2100
320	320	2900
380	380	3550

Marine diesel engines can run on various types of fuels. However, the manufacturer provides guidance on the recommended fuel and its quality, so that the optimum performance and consumption can be achieved. Refineries and oil trading companies instead of stocking all types of fuel suitable for ships, they produce 3 main products: MDO, IFO 180 and IFO 380 and by blending these products with specific proportions, they can produce every type of fuel they want.

Despite the fact that there are quite a few international organizations involved in the set of fuel specifications, like Society of Automotive Engineers (SAE), American Society for Tests and Materials (ASTM) and Institute of Petroleum (IP), the biggest portion of the fuel suppliers follows the specifications set by the ISO. The current ISO 8217 standard covers 15 different fuel grades:

- Marine Gas Oil (DMX)
- Marine Diesel Oil (DMA, DMB, DMZ)
- Residual Fuels (RMA10, RMB30, RMD80, RME180, RMG180, RMG380, RMG500, RMG700, RMK380, RMK500, RMK700)

The IMO limits on fuels sulfur content influence the types of fuels that can be selected for use on a ship, and thus it helps us understand the maximum/minimum values of sulfur content and viscosity for the standard fuels. The following table provides a list of fuels based on IMO Resolution MEPC.320 (74), along with other relevant data.

Table 7: Typical Parameters of Marine Fuel [43]

Fuel Types	ISO Category	Viscosity		Sulfur Mass (%)
		Minimum	Maximum	
Distillate Marine Fuels (DM)	DMX	1.4	5.5	1.0
	DMA, DFA	2.0	6.0	1.0
	DMZ, DFZ	3.0	6.0	1.0
	DMB, DFB	2.0	11.0	1.5
Residual Marine Fuels (RM)	RMA, RMB, RMD RME, RMG, RMK	-	10-700	-
Ultra-low Sulfur Fuel Oil (ULSFO-DM)	DMA, DMX	1.4[2]	6.0[2]	≤0.10
Ultra-low Sulfur Fuel Oil (ULSFO-RM)	Mixed fuel with RM	8	60[3]	≤0.10
Very low Sulfur Fuel Oil (VLSFO-DM)	DMA, DMX	1.4[2]	6.0[2]	≤0.50
Very low Sulfur Fuel Oil (VLSFO-RM)	Mixed fuel with RM	-	80[3]	≤0.10
High Sulfur Heavy Fuel Oil (HSHFO)	RMA, RMB, RMD RME, RMG, RMK	-	10-700	≤0.50

The final overview of the fuels mostly used for marine engines consists of Marine Gas Oil, light and heavy Marine Diesel Oil, Heavy Fuel Oil and Light Fuel Oil. The first one has characteristics similar to diesel, making its usage the safest and most stable for marine transportation. When it comes to MDO, the light one has a small life cycle but is considered to be one of the finest fuels with low viscosity and dark color. On the other side, the heavy one is mostly used for ships designed to burn heavier petroleum fractions, as it consists mostly of light MDO (about 80-90%), mixed up with residual fuels. It is noteworthy that none of these types of fuels require preheating before usage. Passing on to residual fuels, HFO is heavy by-product/residue of the extraction of crude oil, with a high sulfur concentration and viscosity, while LFO is produced from the mixing of HFO and crude oil or other crude oil products, in order to reduce its viscosity. Contrary to MGO and MDO, for both HFO and LFO, preheating is necessary before using it.

3.2 Cleaner and alternative fuels

In the wake of growing environmental concerns, the maritime industry is compelled to chart a course towards cleaner and more sustainable fuel options. After examining the detrimental effects of the reliance on traditional fuels on air quality, marine ecosystems and global climate, people have started to explore a spectrum of cleaner alternatives, which could reshape the future of marine propulsion once and for all. As an outcome of this exploration, a diverse array of cleaner fuel options has emerged, each offering unique advantages in terms of emissions reduction and operational efficiency. Apart from the embracing of cleaner and alternative fuels, from LNG and LPG to hydrogen and ammonia, people should work collectively and encompass technological innovation in order to achieve important breakthroughs regarding decarbonisation of shipping.

3.2.1 LNG

LNG is a mixture of several gases in liquid form, principally composed of methane (CH_4), with a concentration that can vary from 70 to 99% by mass, depending on the origin of the natural gas. Other hydrocarbon constituents commonly found in this mixture are ethane (C_2H_5), propane (C_3H_8), butane (C_4H_{10}) and also nitrogen (N_2) can be observed in small amounts. LNG is produced by cooling natural gas under pressure under conditions such that flashing to slightly above atmospheric pressure generates a cryogenic liquid boiling at < -160°C. Liquefaction is an action that facilitates the transportation and storage of the fuel, as it greatly reduced its volume, given the fact that 1 liter of LNG is approximately equivalent to 600 liters of natural gas at ambient conditions. According to an article published in the 2nd International Conference on the Sustainable Energy and Environmental Development, there are three types of LNG, light LNG with dominant fraction of methane (above 95%), heavy LNG with summary molar fraction of ethane, propane and butanes about 10%, and LNG with higher content of nitrogen (about 2-3%) [44].

In addition, there are two distinct types of gas made from LNG, depending on how it is extracted:

- Natural boil-off gas, which is taken off the top of the LNG tanks above the liquid and will have high methane content. Analysis shows values typically around 100 methane number and low calorific value between 33-35 MJ/nm^3.
- Forced boil-off gas, which is LNG extracted from down in the tanks and evaporated separately. This gas will contain a mixture of all hydrocarbons. The difference with the previous type is that the methane number drops in between 70 and 80 and the low calorific value is higher, around 38-39 MJ/nm^3, making it quite stable and very popular as fuel for general shipping.

Both of these gases are produced due to the evaporation of LNG during the loading and storage process and are either being consumed by the engines or are re-liquefied in order to maintain the LNG tank pressure within acceptable limits. Liquefied natural gas is often considered a transition fuel towards a low greenhouse gas economy, as it is a relatively mature low-carbon fuel. Its carbon to hydrogen ratio offers a reduction in CO_2 emissions of up to 20% compared to baseline heavy fuel oil.

The liquefaction of natural gas and its drastic volume reduction is enhancing the transportability and storage capabilities of the fuel. This transformative process enables LNG to be efficiently transported across vast distances via specialized vessels, constituting a crucial component of the global energy supply chain. A **typical LNG supply chain** is composed of gas production, liquefaction, shipping, regasification and pipeline delivery. According to the International Gas Union, global LNG trade grew by an impressive 6.8% last year, reaching a new record of 401.5 million tons (MT), with a network connecting 20 exporting markets with 48 importing ones. Since the conflict between Russia and Ukraine broke out, spiking LNG demand from Europe and a lack of growth in global LNG supplies resulted in soaring gas prices in 2022 amidst a tight market, leading more than 10 European markets to initiate new regasification terminal construction plans. Although prices moderated closer to historically average levels at the start of 2023, they remain elevated with an ongoing risk of a return to 2022 conditions [45].

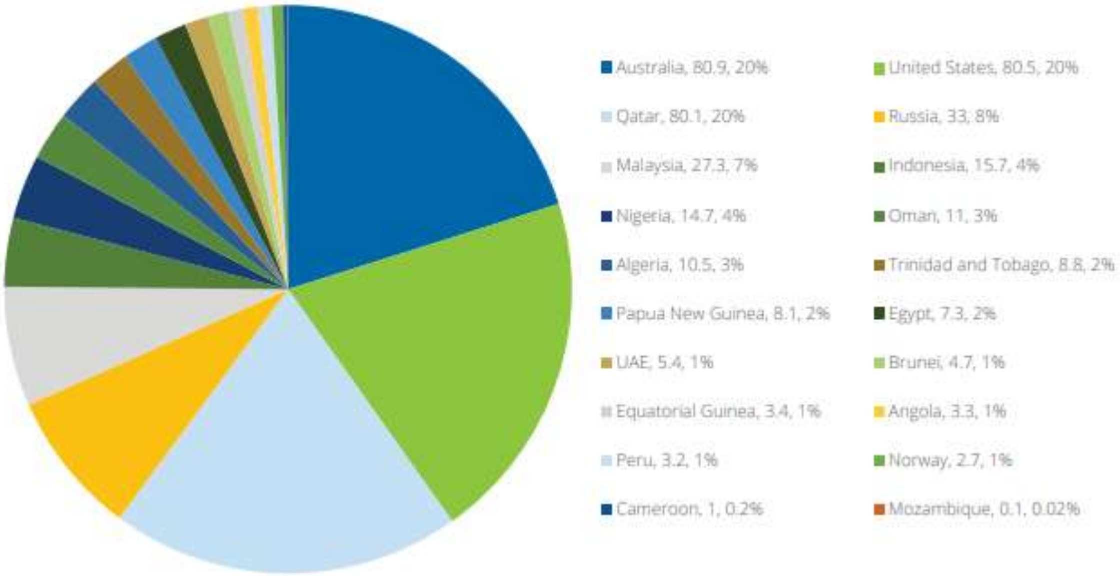


Figure 25: 2022 LNG exports and market share by export market (MT) [45]

From the data presented above, it is worth mentioning that only the first four countries leading in LNG exports (Australia, United States, Qatar and Russia) represent more than half of the total exports, with the percentage reaching up to 68%. Natural gas liquefaction processes for onshore and offshore plants come right after the production, forming the first part of the supply chain. These plants can be divided into three categories: large-scale on shore plants, small-scale onshore plants and offshore processes, with the value of one million tons LNG per annum (MTPA) being the borderline between small and large-scale plants. The next crucial aspect of the LNG supply chain is the LNG transportation via shipping. Once LNG is produced at liquefaction plants, it is loaded onto specialized LNG carriers for transport to import terminals around the world. These LNG carriers are purpose-built vessels equipped with advanced insulation and containment systems to maintain the LNG at its cryogenic temperature throughout the voyage. Also, they can be divided into two categories, self-supporting systems and membrane systems, with the later one offering a thinner and lighter containment system, better fuel and space efficiency. The shipping sector plays a pivotal role in facilitating the global trade of LNG, ensuring its delivery from production hubs to consumption centres efficiently and reliably. Last year, the global LNG carrier fleet consisted of 668 active vessels, representing a 4% increase of the fleet and a 2.7% growth of the LNG carriers' voyages [45].

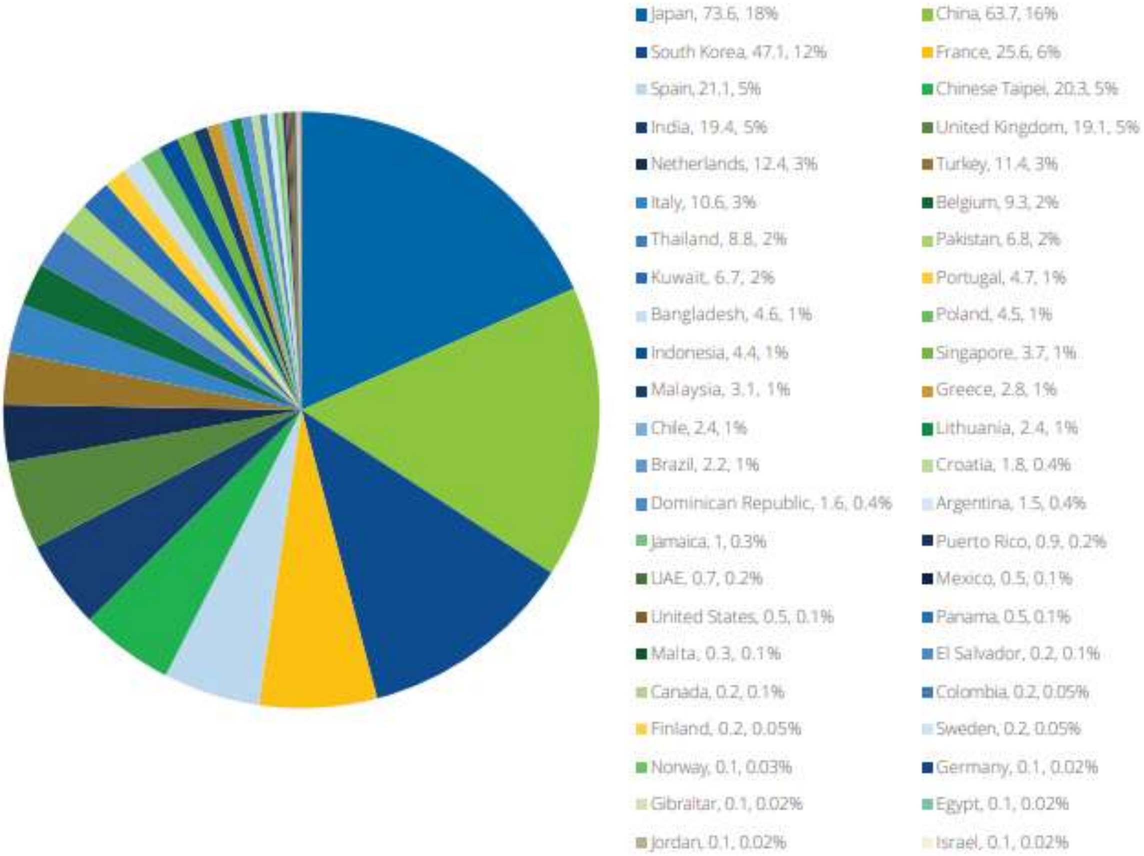


Figure 26: 2022 LNG imports and market share by market (MT) [45]

Just like the export market, a similar situation can be noticed when it comes to the imports, with Japan, China, South Korea and France importing 52% of the total imports of LNG. Upon arriving to import terminals and simultaneously entering the last stage of the supply chain, LNG is heated up to ambient temperature in order to be converted back into its gaseous state, before being distributed to end-users. This is accomplished using special heat exchangers fed with high-pressure pumps for achieving the final gas pressure, with the most commonly used system being the open rack vaporizers (ORV). They are heat exchangers that utilise sea water as the heat energy source in a direct heat system to vaporise LNG. In addition, offshore terminals, which receive LNG from LNG carriers, regasify it and deliver the natural gas to customers via pipeline, are distinguished into two fundamental concepts. These are Gravity Based Structure (GBS) and Floating Storage and Regasification Units (FSRU). They are floating structures, either moored to the seabed or tethered to a jetty in a port area, with the FSRU actually being a ship designed or modified to include a regasification facility [46].

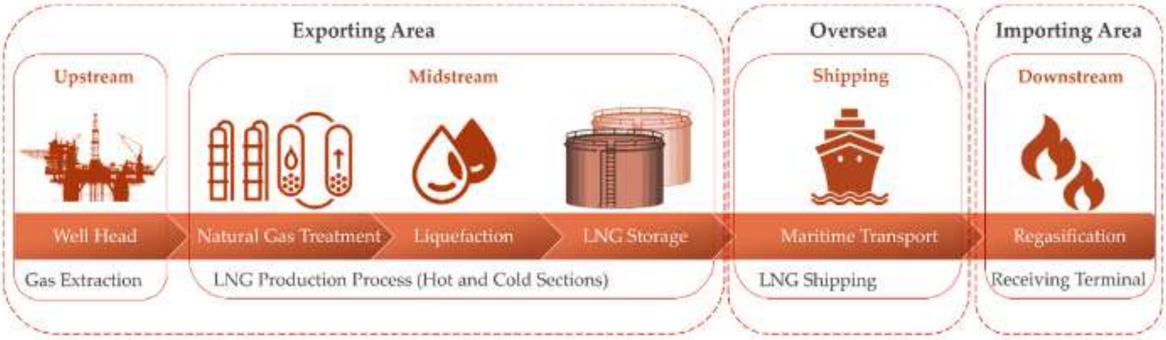


Figure 27: Typical LNG supply chain [47]

During the phase of storage and transportation via shipping, there are some noticeable phenomena taking place. One of them is the production of two distinct types of gas made from LNG, depending on how it is extracted:

- Natural boil-off gas, which is taken off the top of the LNG tanks above the liquid and will have high methane content. Analysis shows values typically around 100 methane number and low calorific value between 33-35 MJ/nm^3.
- Forced boil-off gas, which is LNG extracted from down in the tanks and evaporated separately. This gas will contain a mixture of all hydrocarbons. The difference with the previous type is that the methane number drops in between 70 and 80 and the low calorific value is higher, around 38-39 MJ/nm^3, making it quite stable and very popular as fuel for general shipping.

The other one is the methane slip, which is considered to be the main drawback of the switch of marine engines from oil to LNG or synthetic natural gas (SNG). The reason why it needs to be tightly controlled is the fact that methane has a greenhouse effect roughly about 28 times as strong as an equivalent amount of CO_2. According to MAN, methane slip depends on the type of the engine. For two-stroke engines, a process called direct gas injection can be used where, instead of mixing gas with air before it goes into the combustion chamber, it is injected directly. This process allows for an extremely small amount of methane to escape, between 0.2 and 0.3 g/kWh. When it comes to four-stroke gas engines running on Otto cycle technology are in higher need of reductions, MAN has been addressing methane slip in these engines since it introduced them in the mid-2000s and has halved methane slip over the past ten years to respectively low figures [48] .

3.2.2 LPG

LPG (stands for Liquefied Petroleum Gas) is a hydrocarbon gas that exists in a liquefied form. It is a colourless, low carbon and highly efficient fuel, coming into a mixture of two chemical compounds, propane (C_3H_8) and butane (C_4H_{10}). This fuel is extracted from natural gas by absorption and, unlike diesel, can be stored almost infinitely without any degradation. Although it is known to the wide public for its common use as a domestic gas for cooking and heating, its largest proportion is used for commercial and industrial applications.

Despite these many different uses of LPG, it is also used in shipping, contributing to the great effort of the industry for sustainability and decarbonisation. During April’s Maritime Decarbonisation Conference in Asia, Mr. Constantinos Chaelis, Lloyd’s Register Global gas markets & technology lead, shared data by the classification society to back up his statement that “LPG from a well-to-tank and well-to-wake perspective has the lowest carbon emission factors”. According to that data, using MGO as the measurement baseline, LPG yielded CO2e savings of 17% — better than LNG (Diesel-cycle dual-fuel engine) at 16% or LNG (Otto-cycle, dual-fuel engine), 5%. He also stated that due to its compelling well-to-wake (WtW) carbon emissions profile, it has emerged as the de facto fuel choice for VLGC newbuildings, with more than 90% of dual-fuel LPGs being very large gas carriers [49].

Like all possible options for decarbonisation in shipping, LPG shows advantages and disadvantages. When it comes to the benefits, the most important one is that it contains close to zero sulphur. That makes it possible for these ships to meet the requirements of SECAs, while simultaneously CO_2 and PM emissions are lowered significantly. Thus it has a high energy density, high availability, it is relatively easy to store compared to cryogenic gases and the two-stroke engine technology already exists. Coming to add up on all these, by using LPG cargo as a fuel source allows for significant cost savings for the owners or charterers which also includes reduced time and fees for the bunkering and can take advantage of fluctuating fuel prices. On the contrary, there are some challenges rising regarding LPG as a marine fuel. First and foremost, it is the infrastructure**.** Despite its global presence, the infrastructure for LPG bunkering in ports is not in the scale needed and continues to grow. In addition, great disadvantages are both safety concerns and regulatory framework. As an explanation for the first, LPG is highly flammable and requires careful handling to provide some protection on board and comprehensive safety measures and training for individual employees are critical to mitigating risks, while for the later, the regulatory framework governing its use in harsh marine environments requires further development and standardization to ensure compliance on and protected [50].

3.2.3 Methanol

Methanol is a quite promising solution to the urgent problem of fuel transition from conventional to cleaner ones, as it offers a compelling blend of environmental benefits, operational versatility and technological feasibility. Methanol, also known as CH_3OH and MeOH, is a colourless water-soluble liquid with a mild alcoholic odour and occurs naturally in fruits, vegetables, fermented food and beverages, the atmosphere and even in space. It is one of the four critical basic chemicals alongside ethylene, propylene and ammonia and it is used to produce any other chemical products, such as acetic acid and plastics. Also it is used for gasoline blending (octane booster) and for the production of biodiesel and dimethyl ether. It is worth noticing that it has the highest hydrogen-to-carbon ratio of any liquid fuel at regular ambient conditions [51].

Delving into its characteristics, advantages and challenges, we explore its potential to mitigate environmental impact and propel the industry towards a more sustainable future. The first main **benefit** of methanol is its storage. Methanol provides one clear advantage over other types of alternative fuels, which is the fact that it can be stored under ambient pressure. This ensures a higher volumetric weight and generally less operational restrictions.

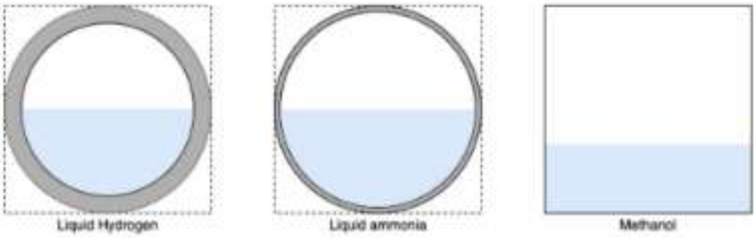


Figure 28 : Storage of methanol [52]

Going deeper into this fuel, someone can underline the following benefits:

- Lower local emissions due to the smaller carbon factor when compared with conventional fuels
- CII: ~ 2 years compliance lifetime increase
- Lower GHG emissions on well-to-wake basis when green MeOH is used
- Mature production processes (industrial scale)
- Advanced bunkering infrastructure
- Already proven engine technology (since 2016, 40 two-stroke MAN engines with more than 110,000 running hours on methanol have been sold) [42]
- Easy to handle, stable with indefinite shelf life (BOG management not required)
- Lower investment costs compared with other alternative fuels
- Water soluble, readily biodegradable (spills and leaks less impactful for seas)
- High octane number (RON 109, high efficiency)
- High flame velocity (less knocking behaviour)
- Low flame temperature (les NO_x produced during combustion)

Unfortunately, despite all these benefits that indicate methanol as the next step of the journey of decarbonisation, there are some drawbacks that make the whole situation much more complicated. The major **drawbacks** that tackle its effort to ascend to the top of the alternative fuels at the moment are 2: the very limited availability of green methanol and the lower energy content. The first one is based on grey's methanol negative effect on well-to-wake basis and the second one on the extremely lower calorific value than MDO (e.g. 40% of diesel) that can cause compromise for cargo tanks, as the tanks for methanol can be 2-2.5 x MDO. Some more downsides of methanol are presented below:

- High fuel costs
- Competition for renewable feedstock
- Toxic and can be lethal if ingested
- High flammable
- Safety system more complex than conventional fuels
- Low viscosity
- Corrosive behaviour
- Less ignitable

Along with those advantages and disadvantages, there are some characteristics of the ships' running on methanol that are presented below:

Fuel delivery system: Given the fact that safety for technicians carrying out maintenance or repairs is very important, methanol engines are equipped with double-walled fuel distribution systems, similar to LNG vessels. Methanol vapour is heavier than air and it will therefore move downwards, hence the placement of gas detectors and ventilation at lower elevations is essential. In addition, the whole system, including the engine itself is designed to be purged with nitrogen ensuring operators can work safely. A significant difference with the HFO is that the fuel has no need to be preheated; on the contrary sometimes it needs to be cooled before injection.

Combustion: Lubrication requirements presented by the use of methanol are quite different than those of conventional fuels, due to significantly greater engine wear compared to fuel oil. Also for engine retrofitting, fuel injection has to be modified to achieve higher injection pressure in order to ignite methanol. A property being shared with LNG is the low cetane number and the need of a cetane enhancer in order to ignite. That makes pilot fuel inevitable for these types of engines.

Efficiency: Wärtsilä tests indicate that the fuel efficiency is the same or better when running on methanol (1-2% from Stena's experience) [52].

The first RoPax ship converted to a methanol powered vessel was Stena Geranica in 2015 that could run on both diesel and methanol and it was a co-operation between Methanex Corporation, Stena Line, Wärtsilä, the Port of Gothenburg, and the Port of Kiel [53].

Figure 29: First methanol powered Ropax "Stena Germanica" [53]

In conclusion, methanol is trending, with clear benefit on environmental indices (EEDI, EEXI, CII) and with larger vessels leading this trend, most of them being container ships. For local emissions, we can assume a TtW reduction of 99% SO_X, 60% NO_X, and 95% PM respectively, when compared with fuel oil. For GHG emissions, on a TtW basis we see a 5% reduction, but on a WtW basis, it depends on the feedstock and production pathway. When methanol is coming from fossil sources it will have a significantly worse footprint, but when referring to biogenic or synthetic methanol, there can be achieved GHG savings up to 90%. With all that being said, it is clear that in order to reduce GHG emissions, shipping needs to aim for synthetic (green) methanol, with blue or hybrids like low-carbon methanol being the intermediate step. Our current production pathway, consisting mostly of methanol from natural gas (gray) and coal (brown) will definitely not get us there [51].

3.2.4 Bio-fuels

In the quest of cleaner and more sustainable energy sources, biofuels have emerged as a promising solution that leverages the power of nature to reduce GHG emissions and mitigate environmental impact. Derived from renewable organic materials like plant biomass, agricultural residues and waste oils, they offer a renewable and carbon-neutral alternative to traditional fossil fuels. Throughout the years, the development of biofuel technology has undergone significant evolution, progressing from first-generation biofuels to more advanced ones, with improved efficiency, sustainability and environmental performance. First-generation ones, such as corn-based ethanol and biodiesel from food crops grown on arable soil, paved the way for the commercialization of biofuels, demonstrated their feasibility as alternative fuels and are currently 99% of today's biofuels. After that, there are the second-generation, which are fuels made on the basis of lignocelluloses, wood biomass, agriculture residues and public oils. Lastly, the third-generation biofuels derive from microalgae cultivation. However, most efforts to produce fuel from algae have been abandoned.

According to MAN energy solutions, biofuels cover a range of fuels, such as **bioethanol** and **biodiesel.** Biodiesel is used interchangeably with **FAME** (fatty acid methylester) which is the generic chemical term for a bio-based component from soya oil, used cooking oils and animal fats/tallow. Thus, **HVO** (hydrotreated vegetable oil) is referred to as a biofuel produced via hydroprocessing of oils and fats, where **DME** (dimethyl ether) can be synthesized from biomass feedstock through a gasification process. Their main advantages are that they can be fully renewable and nearly 100% CO_2 neutral, while simultaneously their transport, storage and handling are unusually simple. [54] Along with these fuels, biogas, or also known as **LBG** (liquefied biogas) and **SNG** (synthetic natural gas) are other solutions, with the first one being produced from biomass and waste products and the later being the product of fossil fuels and biomas via gasification and methanation processes. Their main benefit compared to LNG is that although they have the same low NO_X, SO_X and PM emissions, they can be CO_2 neutral depending on the feedstock and conversion energy source. Also they have "drop-in" properties, which mean they can be blended with LNG to gradually reduce the CO_2 footprint. [55] The huge challenge existing at the moment for all of these kinds of biofuels is mainly that they are unscalable. Despite the fact that 2022 was a record-breaking year for consumption of biofuels, it accounted for just 0.1% of the maritime energy mix. According to DNV's Business Development Manager Christos Chryssakis, "Demand for biofuels is high from other industries and supply is limited. Therefore, it currently seems quite unlikely that biofuels will be a magic bullet for decarburizing the entire existing maritime fleet." [56].

Figure 30: In operation makers of biofuels [41]

According to the figure above, the biggest part of the biofuel production is located in northern Europe, with another 19 production centers being under construction at the moment.

3.2.5 Ammonia

Figure 31: Molecule of ammonia [57]

Staring into the future for searching for another solution for decarbonize shipping, ammonia will be one of the first fuels anyone can see, which will maybe have a critical role in the effort of mitigating greenhouse gases. Ammonia is a synthetic product obtained from fossil fuels, biomass or renewable sources. It can be stored under pressure at atmospheric temperature or in a refrigerated state. The figure below shows the different types of ammonia, based on the way they are produced.

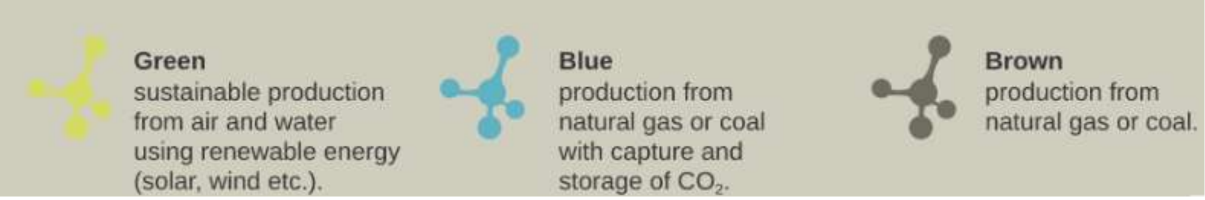


Figure 32: Types of ammonia [57]

Its major advantage as a fuel is that its chemical composition, NH_3, contains no carbon and hence no CO_2 is formed during its combustion. In addition, it is already produced and transported in significant quantities on a large scale (for example as feedstock for fertilizers), which has driven safe handling well established. The first orders of ammonia fuelled ships have already been placed. This is a fact that pushes for further evolution of the technology, as the 1st ammonia engine is to be delivered in 2025. On top of all these benefits, simple storage, as ammonia liquefies at only -33 °C and its less flammability from hydrogen can be added to the list. Last but not least, it is quite important that it has a pungent smell, meaning that it gives an ample warning of its presence, which may help to avoid extremely dangerous incidents.

With all these advantages gained from ammonia come great challenges for the maritime industry. Its lower density makes the need of very big fuel tanks inevitable and specifically, the fuel tanks must be around 3-4 times bigger than the ones of conventional fuels. In addition, ammonia production is not green yet, enhancing the problem of the well-to-wake approach carbon footprint, which is negative. The most common method at the moment for producing green ammonia is via the Haber-Bosch process, converting green hydrogen and nitrogen into ammonia. Other ways are electrochemical nitrogen reduction are under development, but will take time to mature and become industrialized. [57] Once a viable way of production of green ammonia is found, then the targets set from the Paris Agreement will be much easier to be accomplished, as green ammonia produces almost 90% less emissions. Another important problem emerging from that fuel is the possible formation of nitrous oxide (N_2O, “laughing gas”), an issue that needs to be resolved. The reason for that is because N_2O is a GHG with a factor of 270 compared to CO_2 and the potent release of that gas is obvious that will make the global efforts for decarbonisation go down the drain [58].

3.2.6 Hydrogen

Hydrogen has emerged as a versatile and sustainable fuel option for maritime transport, offering a zero-emissions propulsion solution that aligns with the ambitious decarbonisation goals. According to MAN Energy Solutions, hydrogen-powered engines, amongst other systems, will play a crucial role on the path of sustainability. As a future fuel type, it offers great potential as it contains no carbon, with that potential growing even stronger as the production of green hydrogen is reaching a more mature level. Hydrogen does not exist naturally, neither in elemental nor molecular form. Instead, it has to be extracted from other compounds. It is the simplest and most basic renewable fuel generated from electrolysis and it has considerable potential as a storage medium for renewable electricity [59] .

According to an article published in February 2023, there are several different ways to produce hydrogen. The most common ones are mentioned below:

- Coal gasification: chemical and thermal processes to convert solid coal into a gaseous mixture, consisting of hydrogen, carbon monoxide, methane and other hydrocarbons. The problem emerging by this approach is the extravagant amount of greenhouse gases, and especially CO_2 emissions, which is being released into the atmosphere
- Biomass gasification: the process of burning biomass such as plant crops and wood wastes at high temperature in the presence of oxygen and steam

- Water electrolysis: the process of decomposing the chemical elements in salt water by passing electric current through the two electrodes immersed in the electrolyte. The outcome is clean and of high purity hydrogen
- Steam reforming by using natural gas: extracting hydrogen by the two main components of natural gas, methane and ethane by going through steam reforming processes
- Photochemical water-splitting: light energy from sunlight is utilized to produce hydrogen and oxygen from water. It is a completely sustainable energy solution, as it is based on the use of free solar energy, offering zero emissions [60]

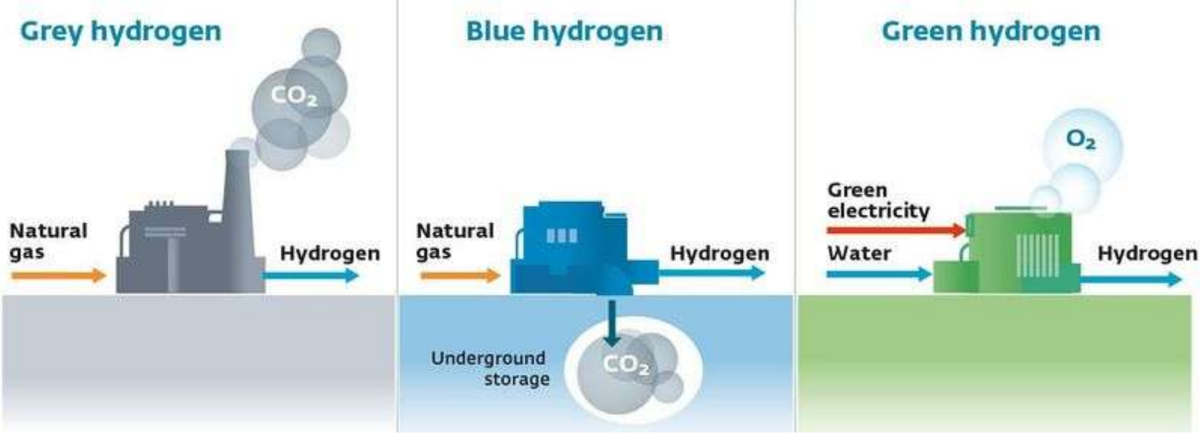


Figure 33: Different types of hydrogen [61]

The fact that grey hydrogen accounts for roughly 95% of the hydrogen produced in the world today is quite notable. As MAN mentions, currently, green hydrogen is more expensive than blue hydrogen, at around 3-8 USD/kg compared to 1.5-4 USD/kg. Without subsidies, this is unattractive in terms of price at the moment. It is predicted that, with decreasing renewable costs and electrolysis costs, as well as the increase of carbon price, the costs of green and blue hydrogen will be equal in 2030 at 2 USD/kg in most regions [62].

Figure 34: Hydrogen molecule [63]

Taking a closer look at hydrogen, something really curious and paradox emerges due to its nature. It is both familiar and different from anything else in the energy system. As with electricity, it is an energy carrier that can be used to "charge" batteries. Like a fossil fuel, it is explosive and produces heat when combusted, while simultaneously it can be extracted by hydrocarbons, held in tanks, moved through pipeline and be transformed between gaseous and liquid states. These properties make it a fascinating prospect, but also create barriers to its adoption in terms of safety, commercial viability and infrastructure. Escalating on that, it is the most abundant element in the universe, but on earth it is found as part of a compound. Thus it is the lightest element, with high energy density compared to weight, but seems very low when compared to other fuels. This brings it into the table as a viable solution for heavy road transport but at the same time more difficult when it comes to its feasibility at aviation or shipping, at least in its gaseous form, as there is difficulty in storage and transport. Also, liquid hydrogen and derivatives like ammonia can overcome various limitations in terms of transport, but conversion is generally inefficient and can be extremely costly. It is noteworthy to say that it has to be either compressed to 700 bars or at the temperature of -253 °C when in the forms of gas or liquid respectively.

According to DNV's hydrogen forecast, the global hydrogen uptake is very low and late relative to Paris Agreement requirements, reaching 0.5% of global final energy mix in 2030 and 5% in 2050, while the total amount of money spent globally on producing hydrogen from now until 2050 will be USD 6.8trn, with an additional USD 180bn spent on hydrogen pipelines [63].

Despite the fact that hydrogen as a marine fuel is still in an early phase of its evolution, there have already been witnessed ships running on hydrogen. In 2018, Norled AS won a tender released by the Norwegian Public Administration for a zero-emission passenger and car ferry. Working with DNV and some other project partners, they succeeded to establish the first hydrogen propulsion regulation for the industry and in March 2023, “MF Hydra” embarked on its maiden journey [64].

Figure 35: MS Hydra [64]

3.2.7 Full electric ships

Full electric vessels are the final category when it comes to different propulsion than the traditional conventional fuels. These vessels get all their power from batteries, both for propulsion and for auxiliaries. They are becoming more and more common, with the capabilities increasing fast and combining the battery power onboard and charging infrastructure onshore, they can enable zero emissions operations. The most important attribute of full electric ships is the fact that they don’t have a combustion engine. As batteries are heavy, these ships are more suitable for shorter distances, usually passenger ferries, while in longer one there can be used hybrid ships. They resemble a plug-in hybrid car in that it will charge its battery using shore power, and it also has a conventional engine onboard [65]. The potential electric ships have when it comes to decarbonisation of shipping is huge, as they have zero carbon footprint during their operation. But this green solution has some drawbacks and a more mature technology is needed so that they can be overcome. Apart from the cost of energy (cost per kilowatt-hour) and the challenges of weight and size that were mentioned before, the current battery capacity is relatively low. In addition, questions are raised about battery recharging and disposal, as they have to be recharged solely by green energy and after they reach 80% of their initial capacity, they are turned over for scrap [66] .

The world’s first fully electric container ship set sail in Norway. Developed by chemical company Yara International, ‘Yara Birkeland” is the world’s first zero emission, autonomous cargo ship. It is capable of carrying 103 containers and with a top speed of 13 knots, it will use a 7 MWh battery [67]. This ship cost about 25 million dollars, about three times a “conventional ship price”, but will nonetheless cut the OPEX for Yara by 90% [68].

Figure 36: First full electric autonomous cargo ship [67]

3.3 Innovative technologies

It is made clear from the previous paragraphs that in the pursuit of sustainable maritime practices, the maritime industry has embarked on a quest to mitigate environmental impacts through not only the adoption of alternative fuels, but also of innovative technologies. Among all these solutions, cold ironing, also known as shore power and CCS (Carbon capture storage) stand out as groundbreaking advancement, having a pivotal role in promoting sustainability, with both having crucial benefits and challenges.

3.3.1 Cold ironing

Cold ironing is the process during which electrical power from shore is provided to a ship while being at berth, letting its main and auxiliary engines turn off. To seek the origin of its name, someone will have to go way back into shipping’s past, when all ships used coal-fired engines. When a ship stopped at a port, it did not have to continue feeding the fire, having as a result the iron engine to cool down and go totally cold. Nowadays however, it is not that simple to turn off the engines and have everything shut down, as ships need to support some basic functions while being at port, like lighting, communications systems, HVAC systems, refrigeration, security and fire detection and suppression. That is done by using their onboard generators to produce electricity for the vessel, but along with that comes the cost of the environmental pollution. Not only SO_X, NO_X, CO_2 and PM are generated during ship’s stay at port, which are substances that enhance climate change and the greenhouse gas phenomenon, but also noise and vibration comes to make the problem even greater. Given the fact that there are residential areas near ports, the situation is deteriorating even more, as the disruption of the tranquillity and respiratory health problems due to the exposure to more and more air pollutants will come to their doorstep. With the application of cold ironing, the ship turns off the engines and plugs into an onshore power source, letting its power load get transferred to the shore-side power supply without disrupting onboard services [69]. The shutdown of the engines and the generators is reducing the amount of fuel consumed by ships, especially those which stay in ports for more than 2 hours, like passenger ships. Based on this reduction of the fuel consumed, the mitigation of ship's emissions while at berth is a reasonable assumption for someone to make and by extension, the improvements regarding energy efficiency indexes like CII, EEDI and EEXI. Besides, according to an article of Professor Ioannis Prousalidis, ports supply ships with electric energy which comes from environmentally friendly sources and to a significant extent, from renewable energy sources, with a zero environmental footprint [70].

It has been calculated that cold ironing reduces total shipping related greenhouse gases by less than 0.5%; though of greater importance are the benefits related to SO_X, NO_X and PM reductions and improvements of the local air [71]. According to an article of the Maritime Executive in 2020, European and North American ports were preparing for cold ironing. They were aiming to cruise ships in order to reduce emissions and enhance the region's environmental performance. First the port of Kiel, Germany illuminated its new power supply plant, empowered to supply Stena Lines ferries with eco-power, an action that started from 2021. In addition, Stockholm and Baltic Sea ports Copenhagen/Malmö, Aarhus, and Helsinki all invested in providing onshore power to cruise ships, with the project being complete in 2024 [72]. According to a case study, in Gothenburg, Sweden, an actual reduction of 10% of CO_2 emissions from RoRo and ferry ships was reported [73]. Some large ports that offer cold ironing around the world are:

- Port of Los Angeles
- Port of Long Beach
- Port of Rotterdam
- Port of Hamburg
- Port of Seattle
- Port of Antwerp
- Port of Gothenburg
- Port of Stockholm
- Port of Southampton
- Port of Kiel
- Port of Bergen

It is worth mentioning that the first shore power supply in the East Mediterranean is located at Greece's port of Killini, with "Fior Di Levante" being the first ship plugged into the region' power facility on 20 December 2018. This application was implemented within the European project EL.E.MED.(Electrification in the Eastern Mediterranean), co-financed by the European commission Innovation and Networks Executive Agency (INEA) and the cohesion fund [74] .

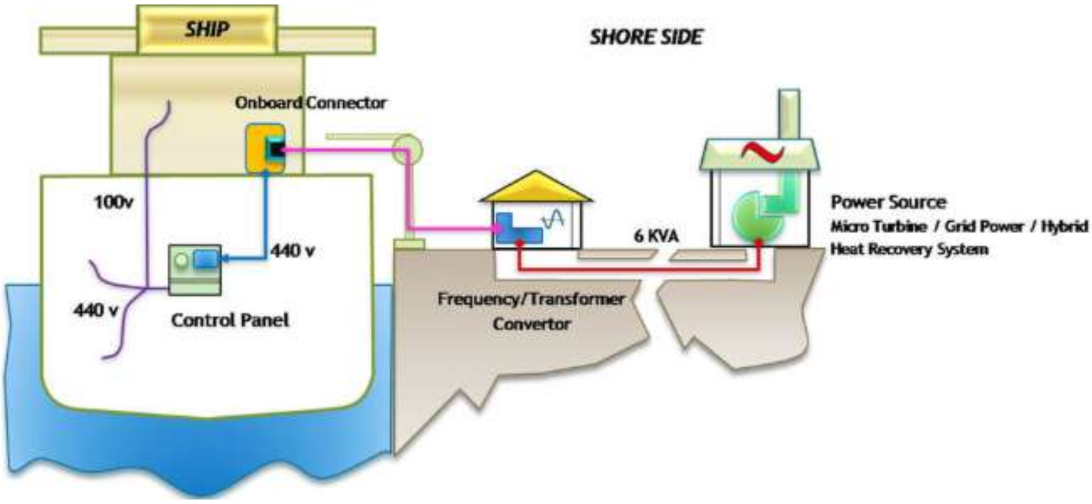


Figure 37: Plan of shore-to-ship electrical supply connection

Every shore power connection must meet the specifications of the international standard IEC/IEEE 80005-1/2/3. According to a feasibility study made by Holland Marine Equipment BV, the shore power installation consists of the basic elements mentioned below [75]:

- Net (main) connection
- Cable connections
- Distribution transformers
- Local main distribution board (high voltage installation)
- Substation parking area
- Transformer to adjust the grid voltage and vessel voltage at the input/output voltage of the converter
- Frequency converter
- Depending which type converter is used, a 10 kV sub distribution board is needed
- 10kV/6.6kV sub distribution board
- Substations vessel area
- Shore power connection box

At the same time, the ship needs to have some specific items to plug in:

- Low voltage switchboard
- Switch board control panel
- Cable routing
- High voltage cable
- Isolator cabinet
- Shore side connection

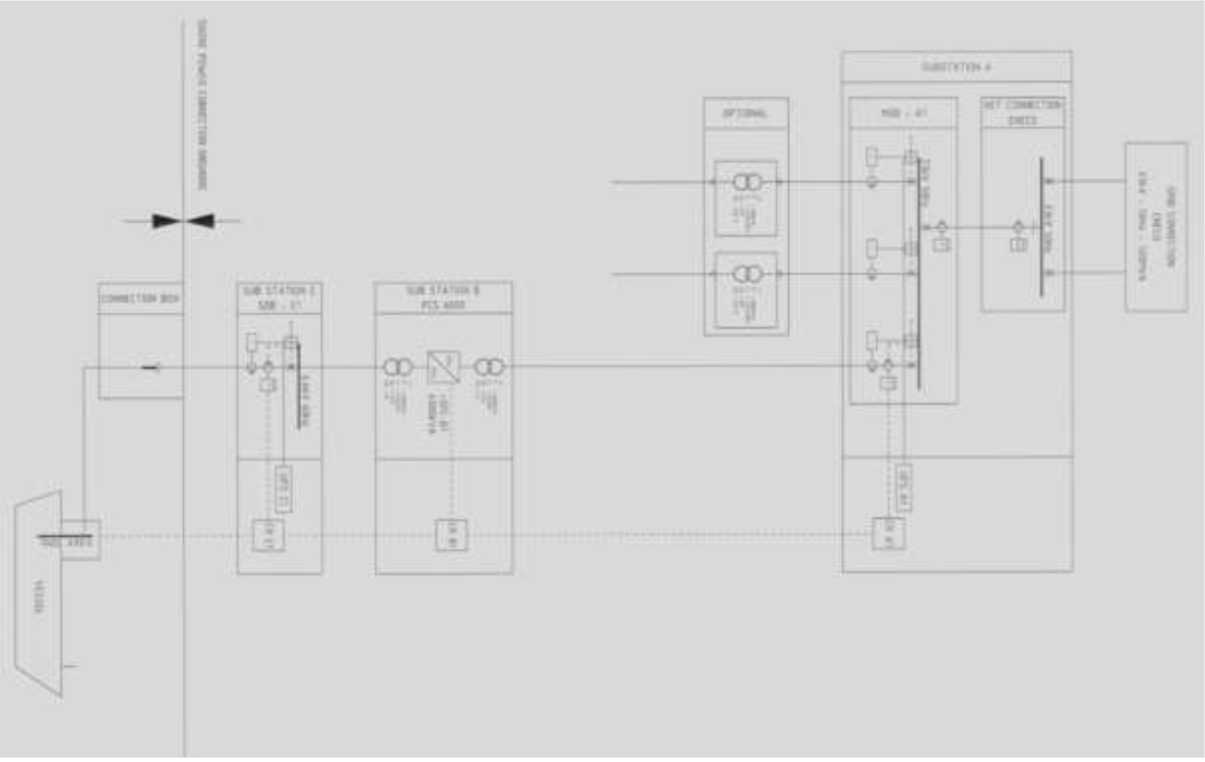


Figure 38: Basic elements of a ship's shore side connection [75]

3.3.2 Carbon capture and storage

CCS technology offers a multifaceted approach on the mitigation of CO_2 emissions by capturing them from various industrial processes and power generation facilities, preventing their escape to the atmosphere. Given the maturity of land-CCS systems, there is a growing need to explore the potential of maritime CCS technology, so that the emissions produced by the shipping sector can be reduced drastically, in the effort to achieve the decarbonization goals until 2050. While its implementation can be challenging, its popularity and recognition as a potential key player to the tackle of greenhouse gas emissions and climate change continues to grow rapidly. A quick look into the CCS market will help to better understand the importance of this technology. In 2023, the global CCS institute stated that the total CO_2 capacity of CCS projects in development, construction and operation was 361 Mtpa, an increase almost 50% compared to the previous year's Global status of CCS report [76].

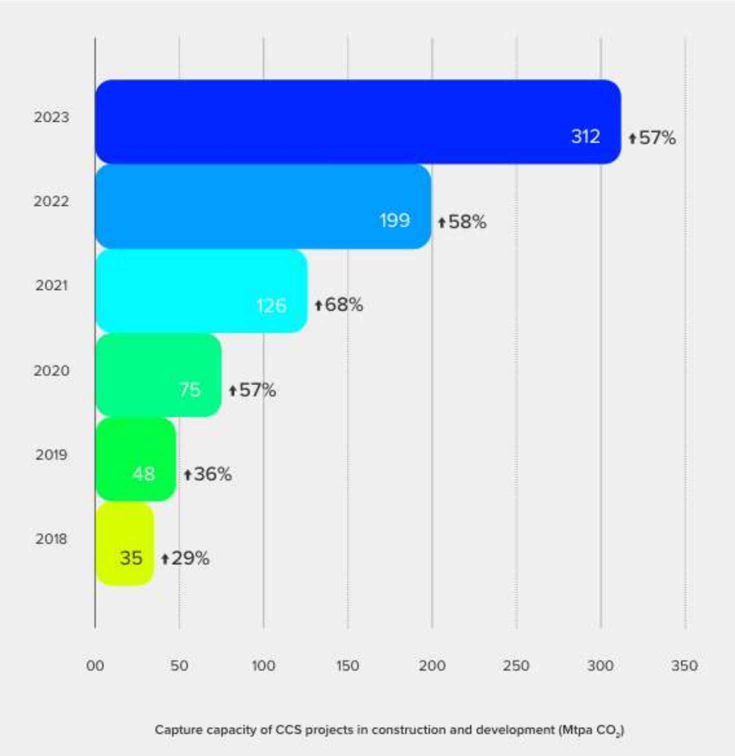


Figure 39: Year-on-year growth of CCS capacity [76]

These are all encouraging indicators of progress. However, authoritative analysis by the International Energy Agency, the Intergovernmental Panel on Climate Change, and others consistently indicates that achieving global climate targets will require annual CO2 storage rates of approximately 1 Gtpa by 2030, growing to around 10 Gtpa by 2050. Despite the fact that it is a promising solution, there is no doubt that CCS is facing some important challenges. The most important one to CCS deployment is commercial, as it requires investment in capital-intensive long-lived assets. As the global status of CCS report of 2021 states, between USD$655 billion and USD$1,280 billion in capital investment is needed by 2050 [77].

Delving into this technology, according to MAN Energy Solution [78], the harness of carbon dioxide can be achieved in three steps:

a) ***Capture and purify***

There are multiple methods to capture CO_2, with the 3 main of them being **post-combustion**, **oxy-fuel combustion** and **pre-combustion** capture. Starting from the first one, it requires the separation of CO_2 from flue gases after the burn of fossil fuels. After treatment, most of the carbon dioxide is separated and stored in a tank, while the rest of the gases are released into the atmosphere. Analyzing the second method, it indicates that pure oxygen mixed with recycled exhaust gas is used for combustion, instead of air. After combustion, water and combustion residues are relatively easy to separate. Last but not least, the pre-combustion capture technology removes CO_2 before combustion happens. Here, steam methane reforming or gasification of fuels as coal or biomass produces syngas. The syngas then undergoes a water-gas shift reaction that converts carbon monoxide and water to hydrogen and CO_2, with the concentration of the later one being high and able to be separated, leaving hydrogen as fuel. This is the first step in producing blue hydrogen from coal or natural gas.

b) Aggregate and transport
Once captured, CO_2 begins its journey to industrial users or sequestration sites.

c) Use or sequester
Regarding the utilization of CO_2, fertilizer and oil and gas industry are the main shareholders, with food and beverage production, mineral carbonation, metal fabrication, chemical manufacturing and water treatment coming to significantly raise the demand of CO_2.

As DNV implies, onboard CCS is an innovative solution, as such systems may be established to any vessel, even to a non-technological advanced one. The best candidates regarding the method followed fro CCS in maritime are post-combustion ones, such as liquid absorption, absorption, membrane separation, combination and variants, electro-separation and cryogenic separation [79].

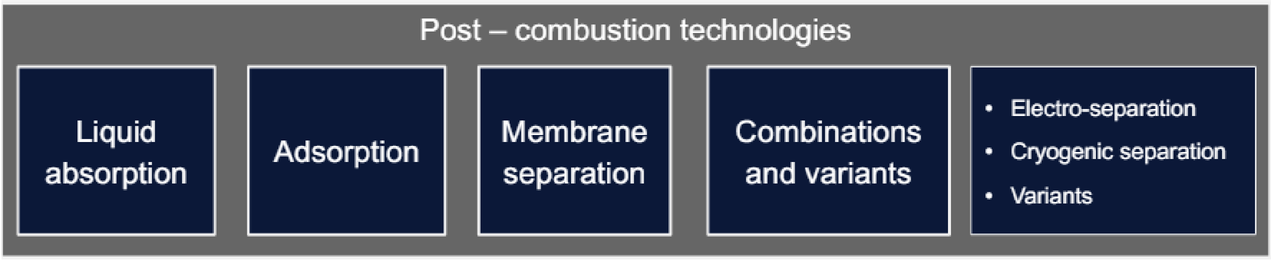


Figure 40: Candidate CCS technologies in maritime [79]

In conclusion, CCS technology holds significant promise as a vital tool in the global efforts to combat climate change and contributes to energy security and economic stability during the transition to a low-carbon future. However, its widespread deployment faces several challenges, including high costs, technological uncertainties, and regulatory hurdles, issues that may be resolved in the future.

Chapter 4: Passenger ships

Delving into environmental pollution due to the maritime industry, in order to estimate the carbon intensity of ships, it is essential to see at first the big picture regarding the world fleet. With that being said, it is vitally important to study the composition of the fleet, depending on size and type and highlight the Ro-ro passenger ships, as it is the type of ship the calculations of this study are referring to.

4.1 Fleet overview

As of 31 December 2022, the size of the merchant fleet has been reported to be 105,000 vessels worldwide and has reached a carrying capacity of 2.3 billion dead weight tons (dwt), 70 million dwt more than a year ago. Although oil tankers, bulk carriers and container ships account for approximately one quarter of the total number of ships worldwide, they hold the outstanding share of three quarters of the total capacity in gross tonnage. The following map indicates the countries which lead the way in ship building, recycling, ownership and registration.

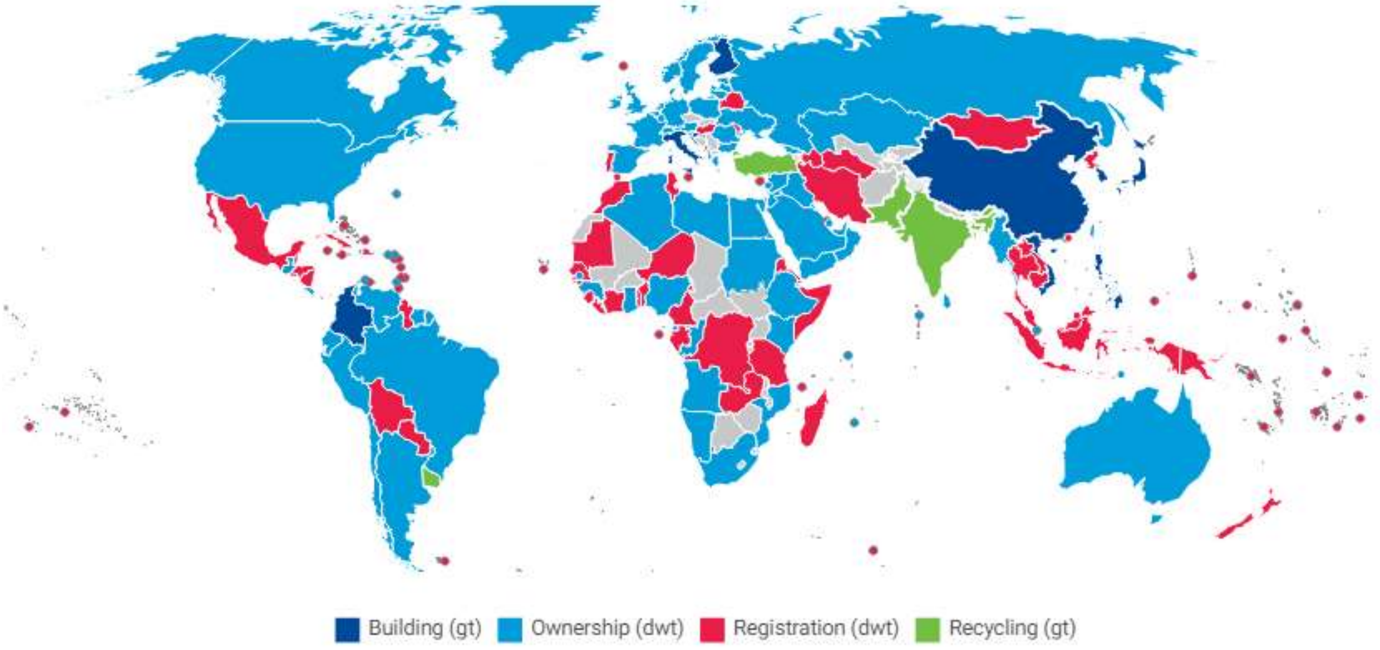


Figure 41: World map overview for shipping industry [80]

Given the fact that 93% of shipbuilding by gross tons occurred in China, Republic of Korea and Japan, the conclusion that Europe is struggling to keep up with the fast pace ships are built in Asia is rational for someone to make. Nonetheless, Europe still contributes to a point in the global production, mainly through Italy and Scandinavia, with the most ships built there being large cruise and ro-ro passenger ships. Although China and Japan are indicated as major shipbuilding powers by the map above, it is essential to state that they are also major ship owners. In fact, in 2023 China beat Greece to become the world's largest ship owning nation by gross tonnage. In addition, the fleet is divided into the categories mentioned at the figure below.

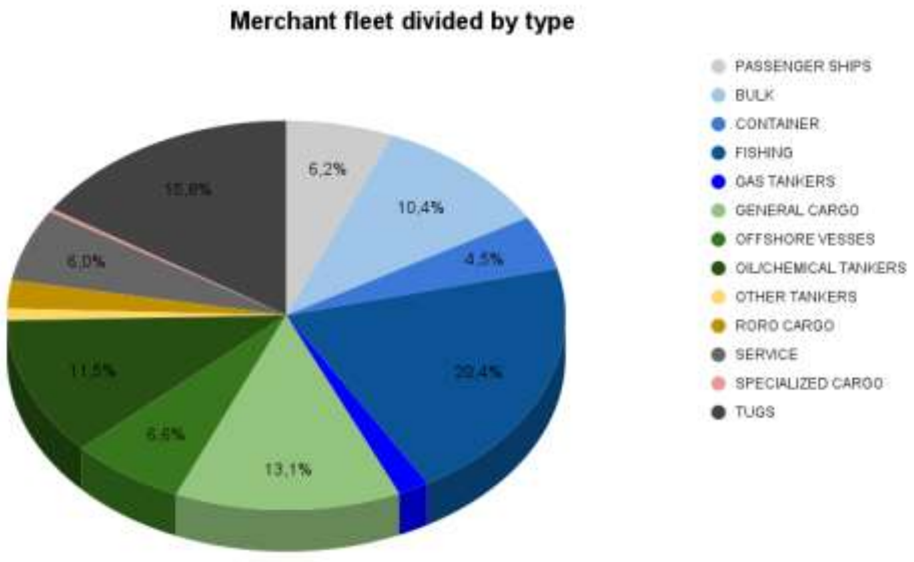


Figure 42: Merchant fleet according to 2022 World Fleet Report [81]

Commenting on this, it is evident that if fishing vessels and tugs are excluded, the prevailing types of ships are general cargo ships, oil and chemical tankers, and bulk carriers. Passenger ships follow, comprising only 6.2% of the merchant fleet, which translates to a total of 7,866 vessels.

4.2 Ro-ro passenger ships

Ro-ro stands for "roll-on/roll-off" and refers to ships carrying wheeled cargo, such as cars, motorcycles and trucks. This kind of ship has ramps or ferry slips, in order to allow the cargo to be efficiently rolled on and off the vessel when in port. When speaking for ro-ro passenger ships (RoPax), a huge advantage over the ro-ro cargo ships is underlined, which is the versatility these ships have. That is because they combine the functionality of both passenger ferries and cargo carriers, offering a seamless transportation solution for both passengers and freight. In order for them to be able to provide such versatility, it is essential to have unique design features. Escalating on that, RoPax ships have dedicated spaces for cars and other wheeled cargo, with multiple decks equipped with ramps for efficient loading and unloading procedures. In addition, most of these ships use 4-stroke engines, in contrast with most commercial ships that use 2-stroke. The reasons for such a selection of engine are the following [82]:

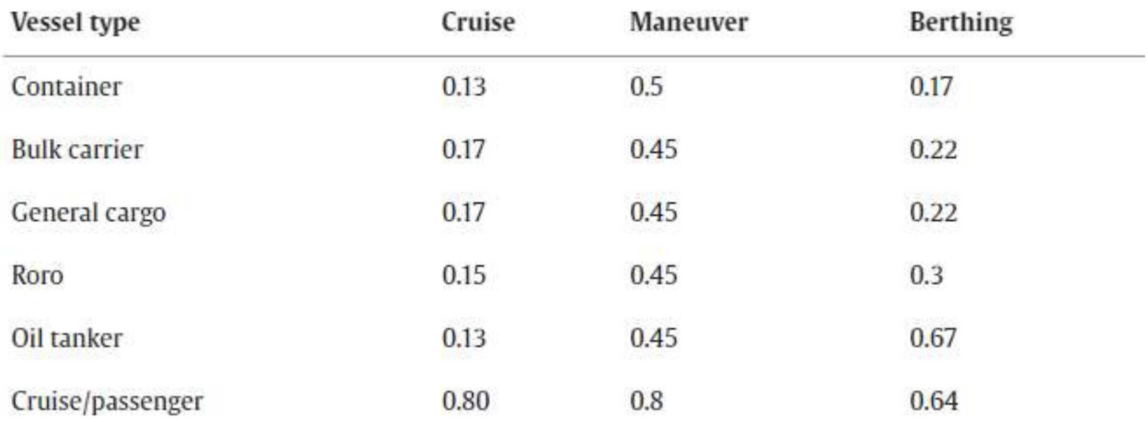
- **Lower emissions:** 4-stroke engines generally have lower emissions of pollutants (SO_X, NO_X, PM) compared to 2-stroke engines, a fact extremely important as RoPax ships often operate in environmentally sensitive areas such as coastal regions and ports.

- **Size and speed:** 4-stroke engine offers like the compact size of the plant, much more RPM or speed

- **Improved manoeuvrability:** 4-stroke engines offer better manoeuvrability and responsiveness compared to 2-stroke engines, especially at low speeds and during docking and berthing operations.

- **Reduced costs:** the initial cost of installation of a two stroke propulsion plant is also much higher than the running and maintenance cost of a 4 stroke engine.

Thus, the operational profile of these ships is quite different from tankers, bulk carriers or containerships. When referring to RoPax ferries, they operate on short to medium distance routes, connecting ports with a region or along coastal areas. Their most common use is for commuter transport and tourism, as they provide essential links between islands, coastal communities and mainland ports and they operate on frequent schedules, with multiple daily sailings and relatively short turnaround times in port, maximizing their utilization and efficiency. On the other hand, there are large cruise ships that are generally way larger and bigger in terms of gross tonnage, may operate on larger routes and have much fewer port calls than the RoPax ships. With either of the two types mentioned before, the much greater amount of power needed for the period these ships are in port, compared to other ship types, is a fact. According to a study of 2023 [83], the load factor for the auxiliary generators can be found in the following table:



Vessel type	Cruise	Maneuver	Berthing
Container	0.13	0.5	0.17
Bulk carrier	0.17	0.45	0.22
General cargo	0.17	0.45	0.22
Roro	0.15	0.45	0.3
Oil tanker	0.13	0.45	0.67
Cruise/passenger	0.80	0.8	0.64

Table 8: Load factors for auxiliary engines [83]

The huge increase of the load factor for cruise ships is easily explained due to multiple functions that need to be supported while either at port or at sea. Transporting a large number of passengers makes functions like lighting, HVAC systems and refrigeration of imperative need, a fact that also makes the large amount of power generated from the diesel generators reasonable.

Last but not least, another big difference can be stated between RoPax ships and other types, like bulk carriers and tankers. This difference is no other than the lifetime of these ships. While most of the merchant ships have an average lifetime of 20 years, RoPax ships generally surpass that limit and extend it for another 10 years. As displayed by the figure below, about 60% of the global passenger fleet is aged 25 years old and above, making clear the fact that the life span is quite different, compared to the rest of the fleet.

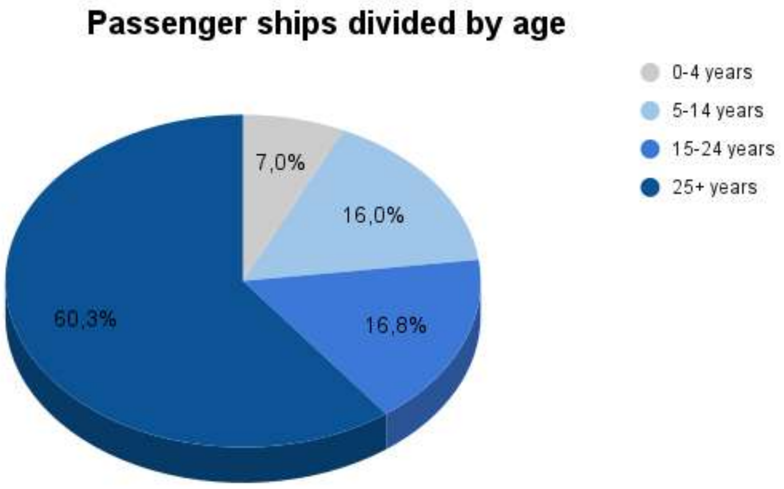


Figure 43: Passenger ships categorized by age [81]

4.3 Ro-ro passenger ships in Greek territory

Despite the fact that passenger ships stand for a small part of the fleet, it is quite interesting to investigate their carbon intensity index and how it reacts to different technologies. Especially in the Mediterranean Sea, the big number of passenger ships sailing there, in conjunction with the decision of the IMO to turn this area into an ECA from January 1st 2025 makes this investigation even more important.

Searching through platforms like Seaweb, Marine traffic and Vessel finder, a fleet of 317 passenger ships sailing in Greek territory was recorded. Out of these 317 vessels, 211 were ro-ro passenger ships, with the rest of them being small, strictly passenger and cruise ships. Something worth mentioning is the size of the fleet. About 80% of the fleet is consisted of ships with gross tonnage smaller than 5,000 tonnes, making them of no use to the study, as CII refers to ships with gross tonnage greater than 5,000 tonnes. According to the approach of this study, the categories are displayed at the chart below with different colours for each one. First there are the routes at the Ionian Sea, which are displayed with grey colour and have as final destination either a Greek island or an Italian city (Bari, Ancona or Venice). Next, there are the ones at Argosaronic and Sporades, indicated in purple and yellow respectively, where almost every ship sailing there is a relatively small high speed vessel. Thus, most of the routes are located at the Aegean Sea. There are few connecting the port of Piraeus with Crete at either Chania or Heraklion (blue) and the ones that go through Cyclades and Dodecanese indicated in green, which are the routes that connect the most Greek islands not only with Piraeus, but with each other. Last but not least, indicated in red, there are the routes at the North Aegean Sea, where several islands are connected either to Piraeus or Alexandroupoli and Kavala.

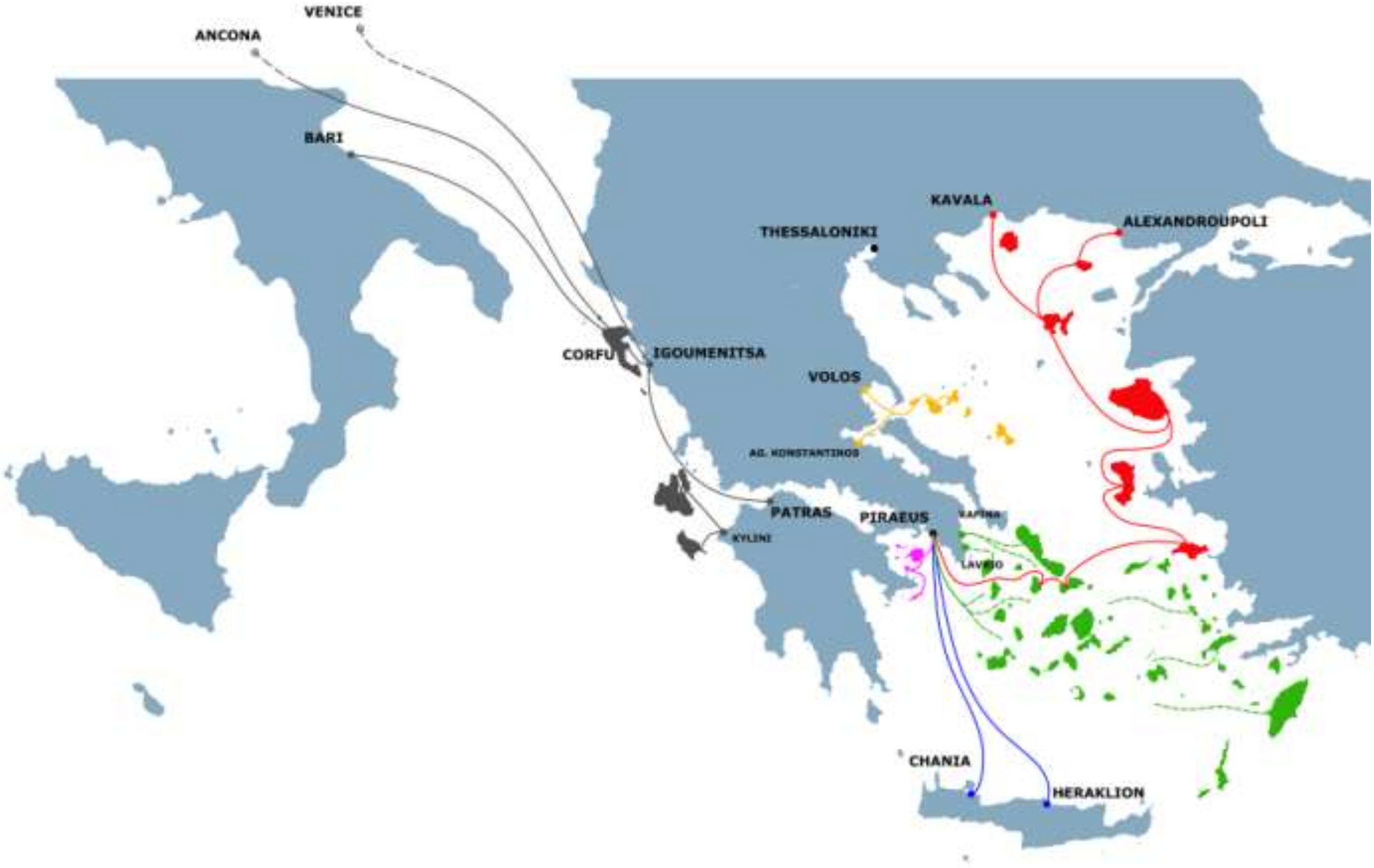


Figure 44: Routes of RoPax ships in Greek territory

Chapter 5: Case study for Ro/Ro passenger ship – methodology

The scope of the present thesis is to explore the impact of alternative fuels and innovative technologies on the Carbon Intensity Index (CII) for RoRo passenger ships operating in Greek territory. To achieve this, the study is divided into two phases. In the first phase, there is no alteration in the operational profile of each ship, while in the second phase, there is a significant change due to speed reduction in a portion of the fleet. More in detail, the questions that are going to be answered are the following:

- How do CII ratings fluctuate for the upcoming 3 years, when a RoRo Passenger ship uses conventional fuel?
- How do CII ratings fluctuate for the upcoming 3 years, when a RoRo Passenger ship uses alternative/cleaner fuels?
- How do CII ratings fluctuate for the upcoming 3 years, when some RoRo Passenger ships use alternative/cleaner fuels, in conjunction with a speed reduction of 10%, 15% or 20%?
- If a ship switches to alternative/cleaner fuels, what are the environmental (CO_2 emissions) and economical (EU ETS) benefits?

In order to carry out this research, a fleet of 28 vessels, consisting of high speed crafts and RoRo Passenger ships of different sizes and trading routes was included in the study and can be found in the Appendix (Table 12). Operational and technical data have been used for the necessary calculation, including total annual fuel consumption, distance sailed and total time spent at port, which were collected from the publicly available database of EMSA THETIS-MRV. The scenarios for both phases of the study for the fleet were the following:

i. Engines running on conventional fuels
ii. Application of cold ironing while at berth
iii. Engines retrofitted so that they can run on LNG, with MDO as the pilot fuel
iv. Engines retrofitted so that they can run on methanol, with MDO as the pilot fuel
v. Application of cold ironing with running on LNG
vi. Application of cold ironing with running on methanol

5.1 Assumptions

In order to successfully conduct the case study, certain assumptions were made regarding all scenarios. More precisely, they are listed below:

- **For the calculation of CII:**
    - G5 is not taken into consideration as the study refers to RoRo passenger ships.
    - According to MEPC.353 (78), Gross Tonnage accounts for the capacity value for Passenger and Ro-Ro vessels.
    - CII values are estimated for three consecutive years, starting from 2024.
    - For the first phase of the study, data of each ship collected by THETIS-MRV (consumption and distance) is assumed to remain the same for each year and equal to those reported in the first one (2022).
    - All calculations are performed for annual service of each ship included.
    - One ship of the fleet is already using cold ironing, so it is excluded from the scenarios ii, iv and vi.
    - For conventional fuel scenario, main and auxiliary engines are supposed to burn either HFO or MDO.

  - For ships where no data exists on the fitting of scrubbers, it is assumed that main and auxiliary engines run on HFO and MDO respectively.
- **For the alternative fuels scenarios:**
  - The new fuel thermal energy is equal to the case of conventional fuels. Thus, the new specific fuel oil consumption (SFOC), changes according to the Lower Calorific Value (LCV).
  - In each scenario, each retrofit is considered feasible.
  - Engine power output is assumed the same as the case of conventional fuel.
  - For SFOC, MAN engines with a wide range of power output have been used to create 19 models that calculate the SFOC at the appropriate load
- **For the LNG scenario:**
  - The engines that are used are 4-stroke, with MDO as pilot fuel and without taking into consideration the methane slip.
  - The amount of pilot fuel consumed accounts to 5% of the total energy produced by the engine
- **For auxiliary engines:**
  - For the load of the Diesel Generators, load factors of 0.64 at port and 0.8 at sea are used, referring to the total capacity of the generators working at each state [83].
  - Operation of two Diesel Generators is considered for both sea and port operation.
  - The application of cold ironing can cover the total power need of the vessel at port, leading to the turn off of all the generators.
- **For the methanol scenario:**
  - The engines that are used are 4-stroke, with MDO as pilot fuel.
  - It is assumed that 5% of the total fuel consumed if the engine runs on MDO is used as pilot fuel.
- **For both phases of the study:**
  - If scrubbers are fitted, SFOC value is corrected with new LCV, as these diagrams refer to ISO conditions.
  - For EU ETS penalty, 100% of the CO_2 emissions is used, as the routes are entirely between EU ports
  - The price of carbon permits settle at 68.52 € at the time this study is written (April 30th).
- **For the second phase of the study:**
  - SFOC of each main engine is calculated based on figure 69 and the value of SFOC at 100% load that can be found in the manual of each model.
  - If all four engines are in use while speed is reduced, power may drop below the alleged value at idle speed condition.
  - The appropriate configuration exists, with clutches and reduction gearbox, so that the ship can operate two main engines instead of four.

5.2 Methodology

The methodology followed for this study is divided into two phases. Both phases aim primarily at improving the carbon footprint of the fleet through the CII ratings. The major difference between the two phases lies in the operational profile of the ships. In the first phase, there will be no changes to the operational profile of the fleet. In the second phase, only a portion of the fleet with the worst performance in terms of CII ratings will be examined and will undergo testing for all the scenarios from the previous phase, in conjunction with a speed reduction.

5.2.1 Phase one

For the first phase of the study, the publicly available database of EMSA THETIS-MRV was filtered to include only RoPax ships sailing in Greek territory. Only ships with a gross tonnage greater than 5,000 were considered for the final dataset, in accordance with regulation 28. Consequently, ships built before 1996 were excluded due to their relatively old age. As a result, a fleet of 28 ships was compiled and divided into three categories based on data collected from Seaweb:

i. Category 1: Ships belonging to this category have scrubbers fitted, indicating that they use only HFO for both main and auxiliary engines.
ii. Category 2: Ships belonging to this category are high speed crafts that consume only MDO for both main and auxiliary engines.
iii. Category 3: Ships belonging to this category use HFO for the main engine and MDO for the auxiliary engines.

Since the carbon factor of HFO is different from that of MDO, it is essential to estimate the proportion of these fuels in the total fuel consumption recorded by MRV. With that in mind, the following steps lead to the calculation of CII for scenario i:

a. ***<u>For the duration a vessel operates in port and at sea:</u>***

Time spent at sea is collected by MRV for every vessel of the fleet and time spent at port is calculated as follows:

$$\boldsymbol{Time\ at\ port = 360 \times 24 - Time\ at\ sea}$$

b. ***<u>For the consumption of the auxiliary engines:</u>***

Diesel generators' power and frequency is collected from Seaweb and study [84], while the number of the generators and the load percentage in use in port and at sea are 2, 64% and 80% respectively, based on [83], while taking SUPERFAST II's ELA as an example to confirm the validity of the assumption. When it comes to SFOC, 19 models (Figure 70) have been designed based on MAN typical generator sets for the range 450-3150 kW and on [85] for values below 450 kW. Depending on each generator's power and frequency, an optimal SFOC is selected between all the models that match the specifications of every vessel separately. Only in case of scrubbers fitted, the SFOC is corrected using the LCV of HFO, as the fuel burnt by the auxiliary engines is HFO, while the diagrams refer to ISO conditions. The formula used for that is the following:

$$\boldsymbol{SFOC_{CORR} = SFOC_{CALC} \times \frac{LCV_{HFO}}{LCV_{MDO}}}$$

After that, fuel consumed at port and at sea by the diesel generators is calculated as follows:

$$\boldsymbol{FC_{at\ port} = Time\ spent\ at\ port \times P_{generator} \times load\ factor_{at\ port} \times SFOC_{64\%\ LOAD} \times 10^{-3}}$$

$$FC_{at\,sea} = Time\ spent\ at\ sea \times P_{generator} \times load\ factor_{at\,sea} \times SFOC_{80\%\,LOAD} \times 10^{-3}$$

The amount of fuel burnt by diesel generators is distinguished by the amount recorded by MRV with a simple deduction:

$$FC_{ME} = FC_{MRV} - FC_{AE} = FC_{MRV} - FC_{at\,port} - FC_{at\,sea}$$

If the vessel belongs to category 1 or 3, FC_{ME} is HFO, else it is MDO.

c. <u>For distance travelled:</u>

Distance travelled by each vessel is calculated by the following formula, based on data provided by MRV:

$$Distance\ travelled = \frac{Total\ annual\ fuel\ consumption}{Annual\ average\ fuel\ consumpton\ per\ distance}\left[\frac{m\ tonnes}{kg/nm}\right] \times 10^{3}$$

Bringing together all these pieces of information, CO_2 emissions, reference, attained and required CII, as well as CII ratings for the upcoming 3 years were calculated as indicated by paragraph 2.3.3. For the CO_2 emissions, the maximum variation between the calculated and the reported by MRV values is 1.84%, with the full list of the fleet being presented in the Appendix (Table 16).

In order to move to the next scenarios, the fuel consumption of the two alternative fuels used for the case study must be estimated, through the following steps:

a. <u>For LNG scenario:</u>

Fuel consumed by the main engine is used to calculate the energy produced by the main engine, based on the type of fuel it runs on:

$$Energy_{ME} = FC_{ME} \times LCV_{i}$$

Where *i* stands for the type of fuel each vessel's main engine burns.

Since this energy remains the same for retrofitted engines that use different fuels, a small portion of the energy comes from pilot fuel responsible for the ignition. This portion is 5% of the total energy of the main engine [86]. After calculating all these values, LNG consumed for each ship is estimated:

$$LNG_{consumed} = \frac{0.95 \times Energy_{ME}}{LCV_{LNG}}$$

$$Pilot\ fuel_{consumed} = \frac{0.05 \times Energy_{ME}}{LCV_{pilot\,fuel}}$$

b. <u>For methanol scenario:</u>

Fuel flow on MCR on diesel and total diesel consumption has to be calculated first. The formulas used are the following:

$$Fuel\ flow = P_{MCR} \times LCV_{i}$$

$$Diesel\ consumption = fuel\ flow \times Time\ spent\ at\ sea \times 3600$$

A small portion of this diesel amount is the pilot fuel used for the ignition of the engine. This portion is 5% of diesel consumed in diesel mode [87]. The amount of methanol needed is calculated:

$$Methanol_{consumed} = \frac{Energy_{ME} - (0.05 \times diesel\ consumption)}{LCV_{methanol}}$$

c. ***For cold ironing application:***

For scenarios ii, iv and vi, where cold ironing is applied, $FC_{at\,port}$ is not taken into consideration for the calculation and the procedures of scenarios i, ii and v are repeated respectively.

After calculating CII ratings and CO_2 emissions for every ship, the taxation due to EU ETS is calculated. There is a p% of the total emissions that is taxable for each year. Given the fact that this percentage is 40% of CO_2 emissions in 2024, 70% in 2025 and 100% in 2026, the following formula is used to calculate the penalty:

$$\boldsymbol{PENALTY_{EU\,ETS} = price_{\,carbon\,permit} \times p\% \times CO_2emissions}$$

5.2.2 Phase two

For the **second phase** of the study, calculations were made for a portion the fleet with speed reduction of r%, with r taking the values of 10, 15 and 20. The only difference between the previous part of the methodology and the current one can be spotted in the initial amount of fuel burnt, because of the alternation of the operational profile.

First and foremost, the distance these ships have covered remains the same as reordered by MRV, despite their reduced speed. This assumption is realistic through shorter stays at ports, as voyage time will apparently increase due to lower speed. Additionally, speed reduction will cause power reduction of the main engines. Since the dataset of THETIS EMSA-MRV refers to ships operating at speeds lower than their service speed, further speed reduction may cause the power usage to drop far below 40% of the installed power. The fuel consumption of a 4-stroke main engine does not change significantly over a load range of 40-100%, so at typical CPP loads at very low pitch (30-40% load) the fuel consumption is high, but very little thrust is generated. For that reason, two options are examined. Given that the number of active main engines used for speed reduction scenarios is adaptable and that all vessels used in phase two have four main engines, the first option is to use all four engines, while the second one is to operate only half of them. The latter option comes with a significant advantage. When all main engines operate, load percentage can get too low after speed reduction, because the required power is distributed equally among all four engines. By turning off one of the two sets of main engines, the power needed for each ship is covered by the remaining set. As a result, the load percentage will be doubled, as the same power requirements must be met by half the number of engines and it is likely for load percentage to enter the range of 40-100%. Tables providing the exact number and the load percentage of the main engines in use for every speed reduction scenario can be found in the Appendix (Table 17 and Table 18). These new scenarios have been based on the calculations below:

$$\boldsymbol{V_{new} = (1 - r) \times V_{mrv}}$$

$$\boldsymbol{Time\ at\ sea_{new} = \frac{Distance\ travelled}{V_{new}}}$$

$$\boldsymbol{Time\ at\ port_{new} = 360 \times 24 - Time\ at\ sea_{new}}$$

$$\boldsymbol{P = c \times V^3}$$

$$\boldsymbol{FC = P \times Time\ at\ sea \times SFOC \times 10^{-6}}$$

Using the appropriate data for each operational profile, a set of two equations referring to main engines is established.

$$\boldsymbol{FC_{new(ME)} = P_{new} \times Time\ at\ sea_{new} \times SFOC_{new} \times 10^{-6}}\ \textbf{[1]}$$

$$\boldsymbol{FC_{ME} = P_{mrv} \times Time\ at\ sea_{mrv} \times SFOC_{mrv} \times 10^{-6}}\ \textbf{[2]}$$

For SFOC, a typical SFC contour plot was used for a 4-stroke marine engine, where the clean hull line was only taken into consideration, while at the same time power and engine speed axis were changed to dimensionless sizes and can be found in Appendix (Figure 75 and Figure 76).

By dividing [1]/[2], the new value of fuel consumed in scenario i can be calculated:

$$\boldsymbol{FC_{new} = FC_{mrv} \times \frac{P_{new}}{P_{mrv}} \times \frac{Time\ at\ sea_{new}}{Time\ at\ sea_{mrv}} \times \frac{SFOC_{new}}{SFOC_{mrv}}}$$

$$\boldsymbol{FC_{new} = FC_{mrv} \times \left(\frac{V_{new}}{V_{mrv}}\right)^{3} \times \frac{Time\ at\ sea_{new}}{Time\ at\ sea_{mrv}} \times \frac{SFOC_{new}}{SFOC_{mrv}}}$$

Using the new fuel consumption (FC_{new}) as a starting value, the calculations for the five remaining scenarios are performed in the same manner as in phase one.

5.3 Simulations

After following the methodology described in the previous section for every ship of the fleet, the results of the calculations are displayed in the following tables. The first one refers to all 28 ships of the fleet, indicating the CII rating of each one for all six scenarios, given that MRV data remains the same for the following two years. The remaining tables refer to a portion of the fleet with the worst ratings for the three-year period and show the new ratings after a speed reduction. The major difference is spotted at the number of main engines that operate during each voyage, as the second table refers to all four engines operating, while the third table refers to half of them.

Table 9: CII Ratings

Vessel	Conventional			Cold Ironing			LNG			LNG & CI			Methanol			Methanol & CI		
Vessel 1	D	D	E	D	D	D	C	C	C	C	C	C	D	D	D	C	C	D
Vessel 2	C	D	D	C	C	C	B	C	C	B	B	B	C	C	C	C	C	C
Vessel 3	D	D	D	C	D	D	C	C	C	B	B	C	C	D	D	C	C	C
Vessel 4	D	D	D	C	C	D	C	C	C	B	B	B	C	C	D	C	C	C
Vessel 5	D	D	D	C	C	D	C	C	C	B	B	B	C	C	D	C	C	C
Vessel 6	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Vessel 7	C	C	C	C	C	C	B	B	B	B	B	B	B	B	C	B	B	C
Vessel 8	E	E	E	E	E	E	C	D	D	C	C	C	D	E	E	D	D	D
Vessel 9	E	E	E	D	D	E	D	D	D	C	C	C	E	E	E	D	D	D
Vessel 10	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Vessel 11	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Vessel 12	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Vessel 13	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Vessel 14	D	D	D	C	D	D	C	C	C	B	B	C	C	C	D	C	C	C
Vessel 15	D	D	D	C	C	C	C	C	C	B	B	B	C	C	C	C	C	C
Vessel 16	C	C	C	C	C	C	B	B	B	B	B	B	C	C	C	C	C	C
Vessel 17	C	C	C	C	C	C	B	B	B	B	B	B	C	C	C	B	C	C
Vessel 18	D	D	D	D	D	D	C	C	C	B	C	C	C	D	D	C	C	C
Vessel 19	E	E	E	E	E	E	D	D	D	C	D	D	E	E	E	E	E	E
Vessel 20	E	E	E	E	E	E	C	C	D	C	C	C	D	D	E	D	D	D
Vessel 21	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Vessel 22	E	E	E	E	E	E	D	D	D	D	D	D	E	E	E	E	E	E
Vessel 23	E	E	E	E	E	E	C	C	D	C	C	C	D	E	E	D	D	D
Vessel 24	E	E	E	D	D	D	C	C	C	C	C	C	D	D	D	C	C	C
Vessel 25	C	C	C	C	C	C	B	B	B	A	B	B	C	C	C	B	B	B
Vessel 26	E	E	E	D	D	D	D	D	D	C	C	C	E	E	E	C	D	D
Vessel 27	E	E	E	D	D	D	D	D	D	C	C	C	E	E	E	C	C	C
Vessel 28	E	E	E	D	D	D	D	D	D	C	C	C	E	E	E	C	C	D

Table 10: CII ratings with speed reduction with 4/4 main engines in use

Vessel		Conventional			Cold Ironing			LNG			LNG & CI			Methanol			Methanol & CI		
Vessel 8	10% speed reduction	D	E	E	D	D	D	C	C	C	C	C	C	D	D	D	C	C	D
Vessel 9		E	E	E	D	D	D	C	C	D	B	C	C	D	D	D	C	C	C
Vessel 10		E	E	E	E	E	E	E	E	E	D	D	D	E	E	E	E	E	E
Vessel 11		E	E	E	E	E	E	E	E	E	D	D	D	E	E	E	E	E	E
Vessel 12		E	E	E	E	E	E	E	E	E	D	D	E	E	E	E	E	E	E
Vessel 13		E	E	E	E	E	E	D	E	E	D	D	D	E	E	E	E	E	E
Vessel 19		E	E	E	E	E	E	C	C	D	C	C	C	D	D	E	D	D	D
Vessel 21		E	E	E	E	E	E	E	E	E	D	D	D	E	E	E	E	E	E
Vessel 22		E	E	E	E	E	E	C	C	D	C	C	C	D	E	E	D	D	E
Vessel 23		D	E	E	D	D	D	C	C	C	C	C	C	D	D	D	C	D	D
Vessel 8	15% speed reduction	D	D	D	D	D	D	C	C	C	C	C	C	D	D	D	C	C	C
Vessel 9		D	E	E	C	C	D	C	C	C	B	B	C	D	D	D	C	C	C
Vessel 10		E	E	E	E	E	E	E	E	E	D	D	D	E	E	E	E	E	E
Vessel 11		E	E	E	E	E	E	D	D	E	D	D	D	E	E	E	E	E	E
Vessel 12		E	E	E	E	E	E	D	D	E	D	D	D	E	E	E	E	E	E
Vessel 13		E	E	E	E	E	E	D	D	D	D	D	D	E	E	E	E	E	E
Vessel 19		E	E	E	E	E	E	C	C	D	C	C	C	D	D	E	D	D	D
Vessel 21		E	E	E	E	E	E	E	E	E	D	D	D	E	E	E	E	E	E
Vessel 22		E	E	E	E	E	E	C	C	D	C	C	C	D	E	E	D	D	E
Vessel 23		D	D	E	D	D	D	C	C	C	C	C	C	D	D	D	C	D	D
Vessel 8	20% speed reduction	D	D	D	D	D	D	C	C	C	C	C	C	C	C	D	C	C	C
Vessel 9		D	D	D	C	C	C	C	C	C	B	B	B	D	D	D	C	C	C
Vessel 10		E	E	E	E	E	E	D	D	E	D	D	D	E	E	E	E	E	E
Vessel 11		E	E	E	E	E	E	D	D	D	D	D	D	E	E	E	E	E	E
Vessel 12		E	E	E	E	E	E	D	D	D	C	D	D	E	E	E	E	E	E
Vessel 13		E	E	E	E	E	E	D	D	D	C	D	D	E	E	E	D	E	E
Vessel 19		E	E	E	D	D	E	C	C	C	C	C	C	D	D	D	D	D	D
Vessel 21		E	E	E	E	E	E	D	D	E	D	D	D	E	E	E	E	E	E
Vessel 22		E	E	E	E	E	E	C	C	C	C	C	C	D	D	D	D	D	D
Vessel 23		D	D	D	D	D	D	C	C	C	C	C	C	C	C	D	C	C	C

Table 11: CII ratings with speed reduction with 2/4 main engines in use

Vessel		Conventional			Cold Ironing			LNG			LNG & CI			Methanol			Methanol & CI		
Vessel 8	10% speed reduction	C	D	D	C	C	C	C	C	C	B	B	B	C	C	C	C	C	C
Vessel 9		D	D	D	C	C	C	C	C	C	B	B	B	C	D	D	C	C	C
Vessel 10		E	E	E	E	E	E	D	D	D	C	C	C	E	E	E	D	D	D
Vessel 11		E	E	E	E	E	E	D	D	D	C	D	D	E	E	E	E	E	E
Vessel 12		E	E	E	E	E	E	D	D	E	D	D	D	E	E	E	E	E	E
Vessel 13		E	E	E	E	E	E	D	D	D	C	C	D	E	E	E	D	E	E
Vessel 19		D	D	D	D	D	D	C	C	C	B	C	C	C	D	D	C	C	C
Vessel 21		E	E	E	E	E	E	D	D	D	C	D	D	E	E	E	D	E	E
Vessel 22		D	D	D	D	D	D	C	C	C	C	C	C	C	D	D	C	C	C
Vessel 23		C	D	D	C	C	D	B	C	C	B	B	B	C	C	C	C	C	C
Vessel 8	15% speed reduction	C	C	C	C	C	C	B	B	B	B	B	B	C	C	C	C	C	C
Vessel 9		D	D	D	C	C	C	C	C	C	B	B	B	C	C	C	B	B	C
Vessel 10		E	E	E	D	D	E	C	D	D	C	C	C	D	E	E	D	D	D
Vessel 11		E	E	E	E	E	E	C	C	D	C	C	C	D	E	E	D	D	D
Vessel 12		E	E	E	E	E	E	C	D	D	C	C	C	D	E	E	D	D	D
Vessel 13		E	E	E	D	E	E	C	C	C	C	C	C	D	D	D	D	D	D
Vessel 19		D	D	D	C	D	D	C	C	C	B	B	B	C	C	D	C	C	C
Vessel 21		E	E	E	E	E	E	D	D	D	C	C	C	E	E	E	D	D	E
Vessel 22		D	D	D	D	D	D	C	C	C	B	B	C	C	C	C	C	C	C
Vessel 23		C	C	C	C	C	C	B	B	B	B	B	B	C	C	C	C	C	C
Vessel 8	20% speed reduction	C	C	C	C	C	C	B	B	B	B	B	B	C	C	C	B	B	C
Vessel 9		C	C	C	B	C	C	B	C	C	A	B	B	C	C	C	B	B	B
Vessel 10		E	E	E	D	D	D	C	C	C	C	C	C	D	D	D	C	C	C
Vessel 11		D	E	E	D	D	D	C	C	C	C	C	C	D	D	D	C	D	D
Vessel 12		E	E	E	D	D	D	C	C	C	C	C	C	D	D	D	C	D	D
Vessel 13		D	D	D	D	D	D	C	C	C	C	C	C	C	D	D	C	C	C
Vessel 19		C	C	D	C	C	C	B	B	C	B	B	B	C	C	C	C	C	C
Vessel 21		E	E	E	D	E	E	C	C	C	C	C	C	D	D	D	D	D	D
Vessel 22		C	C	D	C	C	C	B	B	B	B	B	B	C	C	C	C	C	C
Vessel 23		C	C	C	C	C	C	B	B	B	B	B	B	C	C	C	B	B	C

Chapter 6: Conclusion

In this chapter, the results presented above, based on the methodology breakdown in chapter 5.2, are further explained and analysed. These results are reviewed from various points of view, such as the CII values and ratings, the amount of fuel consumed, the CO_2 emissions emitted and the EU ETS taxation for the upcoming three years.

6.1 Carbon Intensity Index

Based on the results of this study, the initial scenario of ships running on **conventional fuels** indicates really poor performances in terms of CII ratings. More than half of the ships of the fleet score grade E, with only high speed crafts scoring D and few RoPax ships sailing to the Ionian Sea scoring either D or C. This poor performance can be explained both by the operational profile and the year of build. The first one is critical for the behaviour of a ship's CII rating, as it affects the distance travelled and the fuel consumption, while the later one is important if anyone take into consideration the EEDI phases. For example, when a ship is built before 2013, where EEDI was not implemented, it is obvious that the design of the ship in terms of efficiency would be completely different from one that is built in 2020. The fleet's newest ship was built in 2012, so the possible lack of compliance with EEDI is a sign that it may be a contributing factor of high carbon intensity and poor grades acquired by the fleet. The application of **cold ironing** barely improves the ratings, as it helps high speed crafts achieve grade C for a couple of years, or improves three consecutive years of E to three consecutive years of D for some ships over 30,000 gross tonnage sailing either to Crete or Italy. That is because these large RoPax ships present a relatively high power demand when at port, a demand which would be covered originally by onboard diesel generators, but according to the second scenario it is covered by shore power generation. On the other hand, it seems to have no effect on RoPax ships either small in terms of gross tonnage (between 10,000 and 20,000), that sail to Aegean Sea, or relatively big (near 30,000 gross tonnage), as the set of three consecutive years of grade E they score does not change.

It is quite easy for someone to see that the scenario indicating the use of **LNG** as main fuel of the main engine is a very beneficial option, in terms of CII ratings. Especially for high speed crafts with bad grades (D with conventional fuels), LNG helps 5 out of 6 to reach grade C. In addition, most ships sailing at the Ionian Sea acquire grades B and C, while the largest ships of the fleet sailing to Crete move from E to D. The use of LNG in conjunction with the application of cold ironing result to the best CII rating of all 6 scenarios, as it either helps the ships maintain the grade they acquire from LNG use, or it raises it even more, reaching up to a situation where even more ships score grade B, while simultaneously grade A appears for the first time, but only for the first year of service of a big RoPax. Last but not least, even though methanol is an alternative fuel, its use has minor effect on CII ratings as it may helps maintain D and C grades of some ships, but it is not able to change grade E of any ship. On the other hand, if methanol is used in conjunction with cold ironing, much greater results can be achieved.

Despite the fact that these scenarios really help reducing the environmental footprint of the fleet, there are some ships mainly operating in the Aegean Sea that, no matter what the scenario is, they are stuck on grade E for every one of the three following years. This happens because of the attained CII, which is far greater than the inferior boundary set by MEPC.354 (78) and the main reason for that is the operational profile of these ships. Especially the ones that operate in the Aegean Sea, connecting a lot of Greek islands with each other, Piraeus and the mainland, are scheduled to make frequent stops at ports. These stops and the increased waiting time at ports may contribute to the deterioration of the attained CII.

Apart from the CII ratings, there is much interest in the average CII acquired by the fleet. As indicated by the diagrams below, the maximum reduction of the average CII occurs at the scenario iv and leads the index below the average reference CII only at the categories of high speed crafts and RoPax ships with gross tonnage between 20,000-30,000 tonnes.

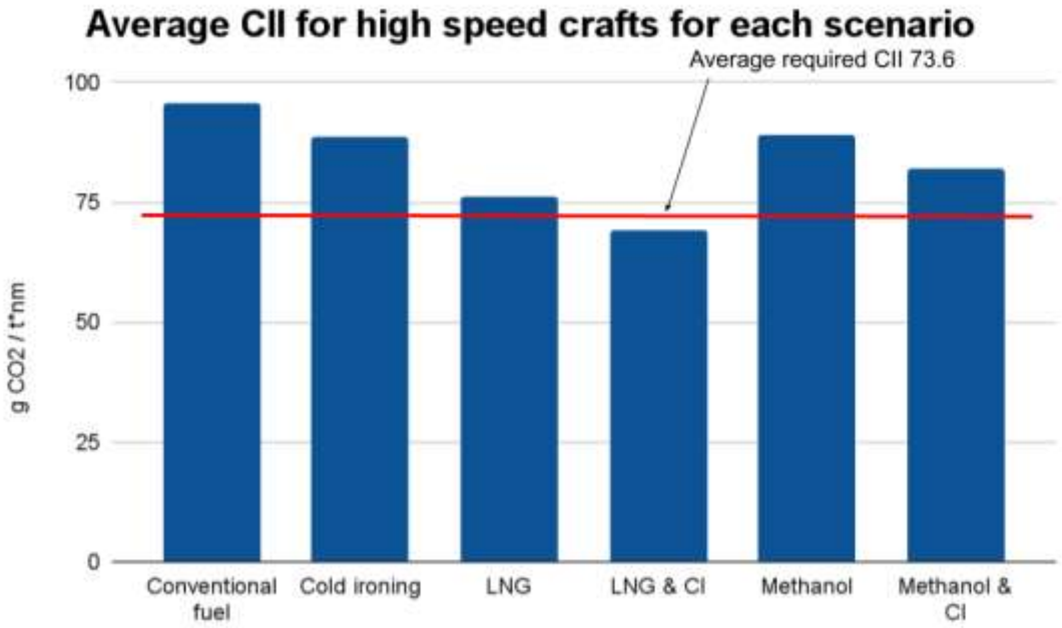


Figure 45: Average CII for high speed crafts for each scenario

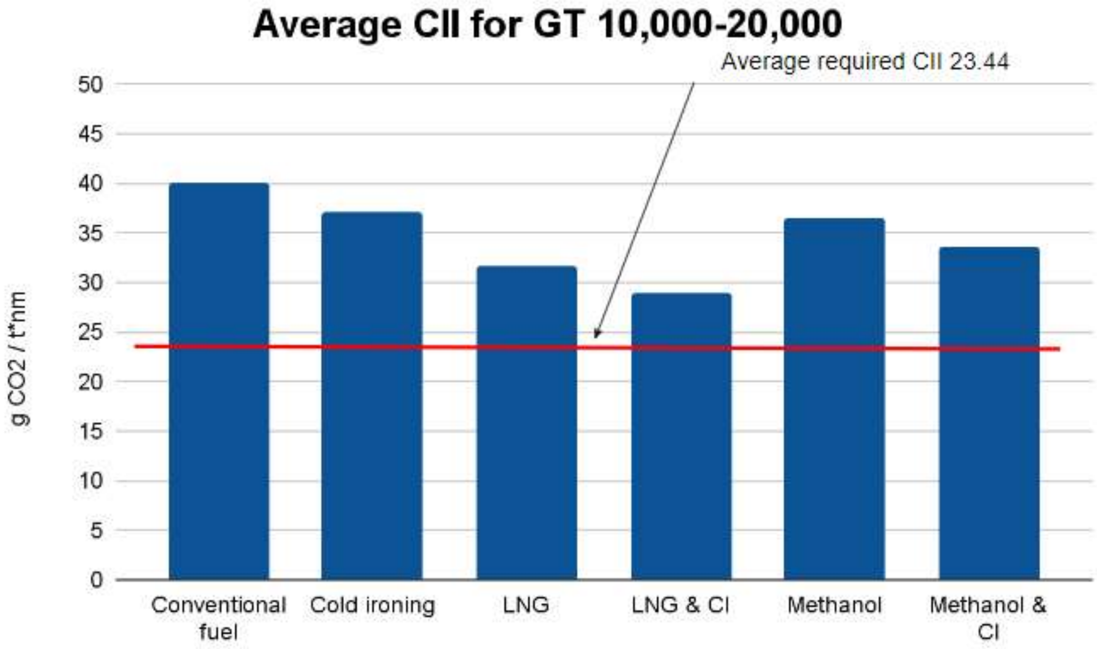


Figure 46: Average CII for GT 10,000-20,000

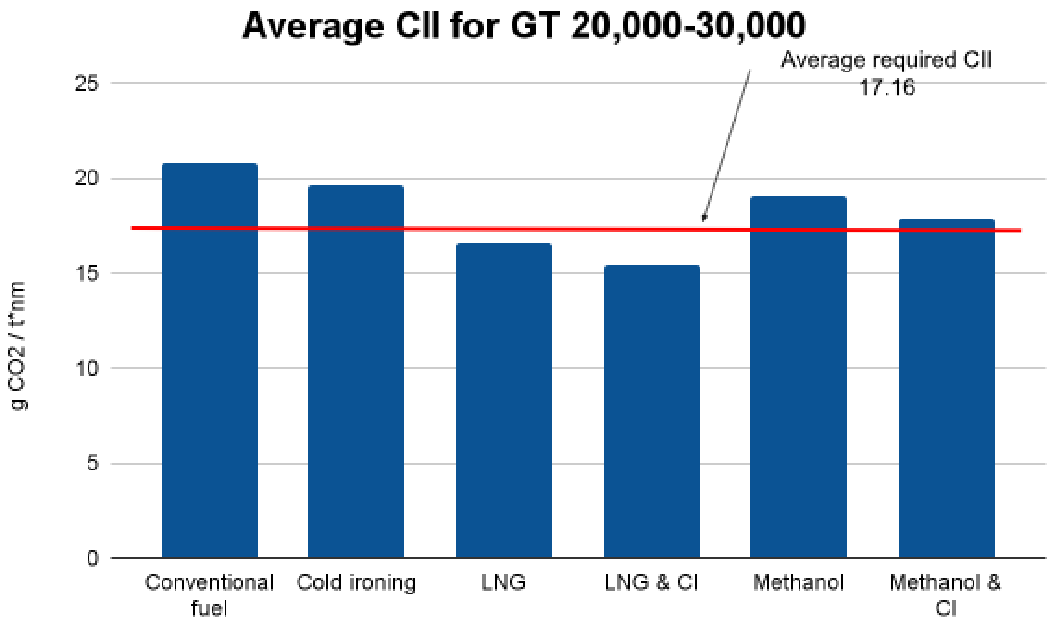


Figure 47: Average CII for GT 20,000-30,000

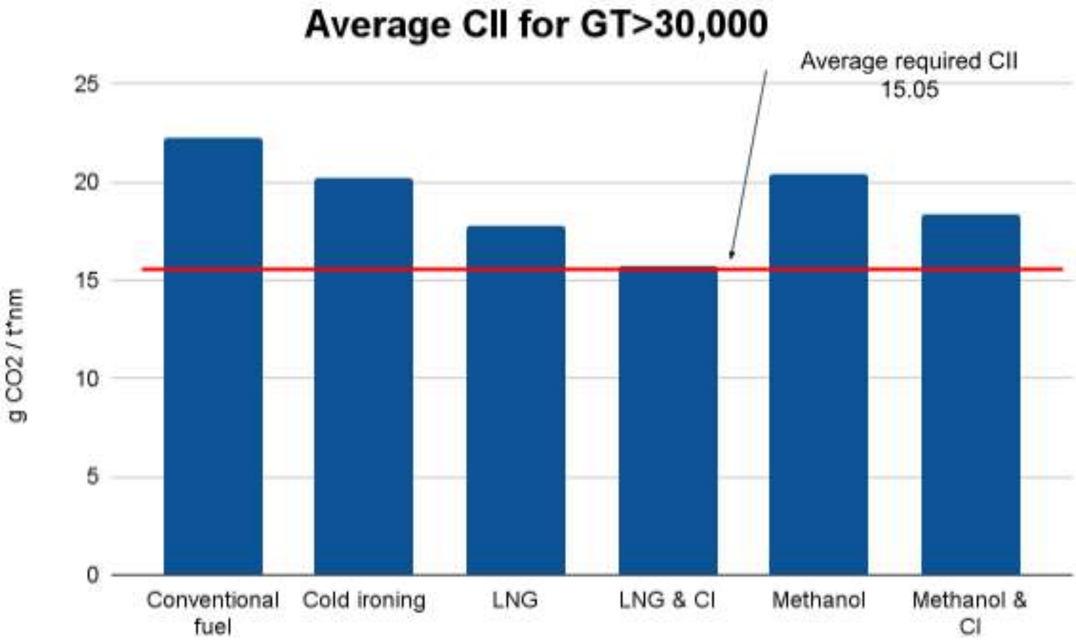


Figure 48: Average CII for GT>30,000

6.2 Fuel consumed

According to the diagrams below, a rational trend of fuel consumption on all the cases is displayed, showing that the bigger the size of the vessel, the bigger the consumption. The rapid increase from high speed crafts to ships with gross tonnage between 10,000 and 20,000 tonnes is due to less time spent at sea and less power needs when in port. The notable fact is that the increase of the average amount of fuel needed to cover the energy needs of a ship that runs on methanol is either 101.17%for high speed crafts or 80.48% for RoPax ships. These numbers in the case of methanol & cold ironing are slightly reduced to 93.92% and 73.81%

respectively. This huge increase to almost two times the initial fuel amount is due to the lower calorific value of methanol, as it equals almost half of the lower calorific value of HFO, meaning that double amount of fuel is needed in order to produce the same amount of energy produced with the conventional fuel. In the case of LNG, these numbers show a decrease by 9.53% for high speed crafts and 13.04% for RoPax ships. Thus, when cold ironing applies simultaneously with LNG as the main fuel, these numbers move to 16.79% and 19.71% decrease respectively.

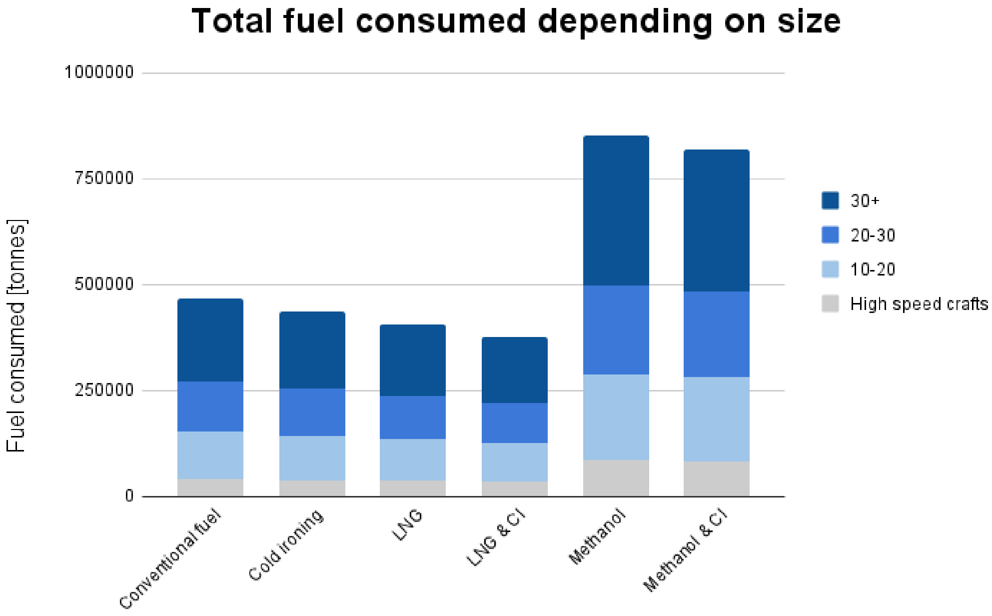


Figure 49: Total fuel consumed depending on size

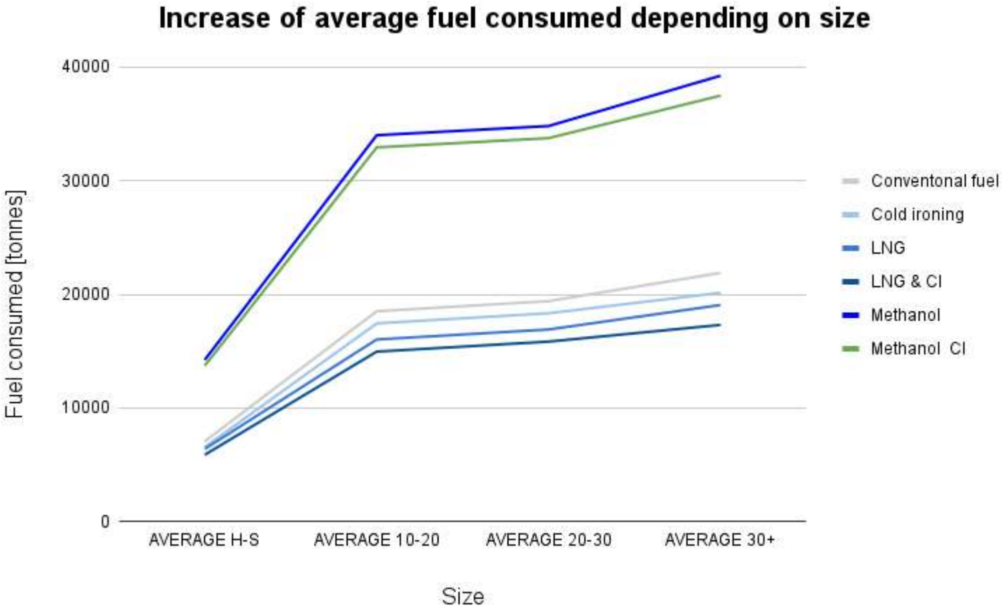


Figure 50: Increase of average fuel consumed depending on size

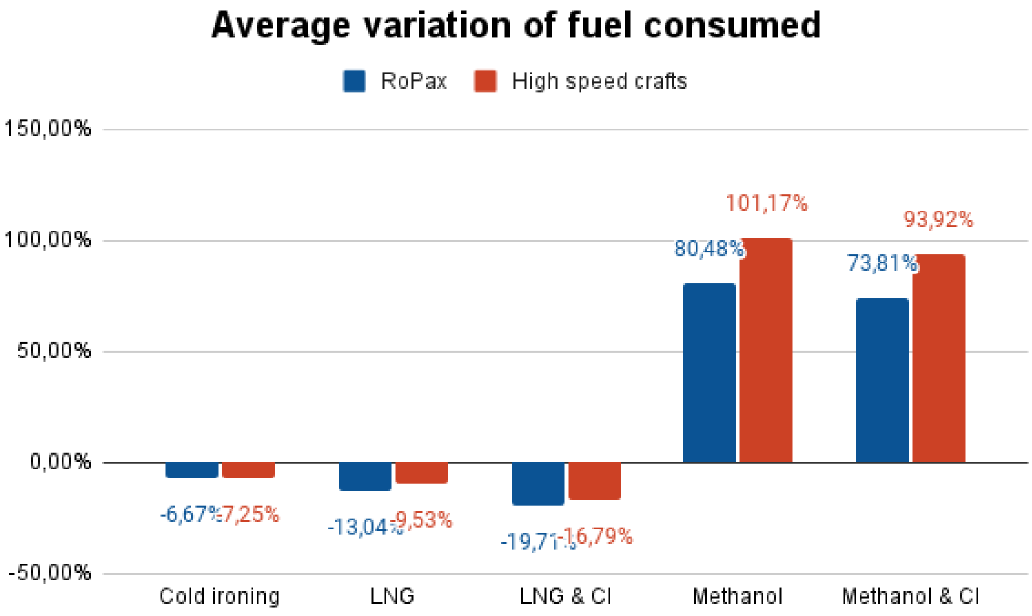


Figure 51: Average variation of fuel consumed

6.3 CO_2 emissions

As indicated by the diagrams below, the smallest share of the total CO_2 emissions goes to high speed crafts and the biggest goes to large RoPax ships with gross tonnage greater than 30,000 tonnes, with percentage numbers being approximately 9% and 41% respectively. In addition, the greatest reduction in the emissions emitted by the fleet comes from scenario iv, where LNG is used as the main fuel for the main engine, while simultaneously cold ironing is applied to avoid pollutants while ships are in port. In figure 54, a higher average reduction to the category of the high speed crafts is noticed, which is logical if anyone consider the much greater amount of fuel used for the auxiliary engines. If they combine the fuel used as pilot fuel in the alternative fuels' scenarios, then it make sense that the percentage of reduction of the CO2 emissions is higher for the high speed crafts, as much fewer MDO is consumed, compared to the other RoPax ships. That conclusion must not get misjudged and that percentage reduction must not be considered equal to the reduction of emissions in total numbers, as RoPax ships can save up to 6.4-8.8 times the amount high speed crafts can.

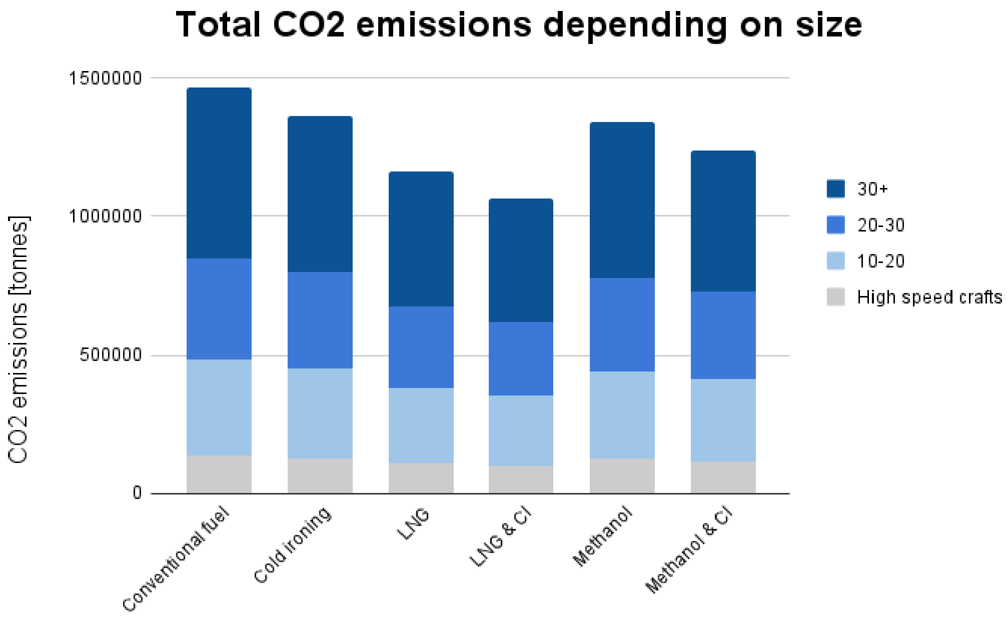


Figure 52: Total CO2 emissions emitted depending on size

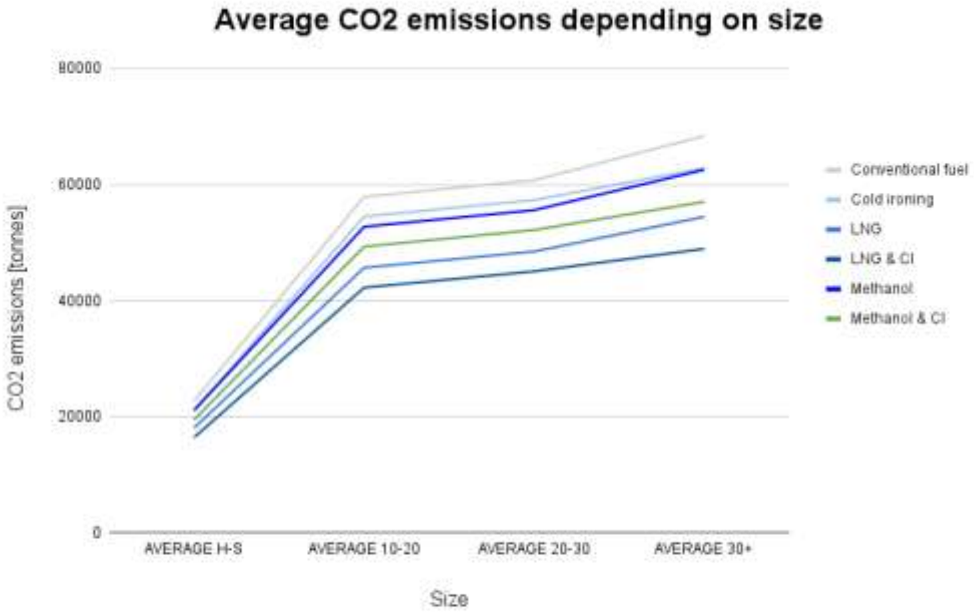


Figure 53: Average CO2 emissions depending on size

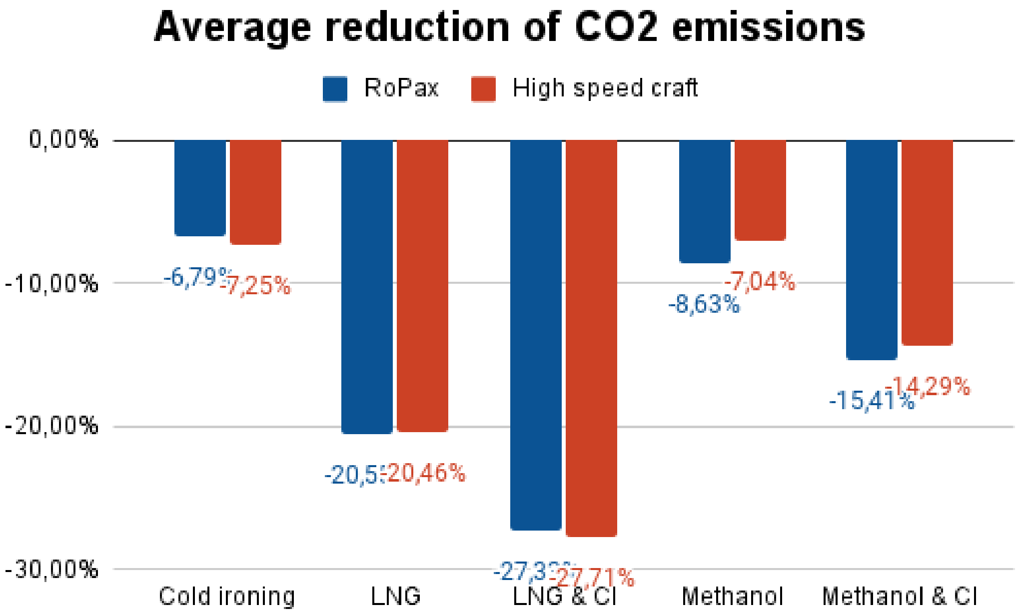


Figure 54: Average reduction of CO2 emissions

6.4 EU ETS

According to fit for 55, along with the entrance of shipping industry in the EU ETS, huge amounts of money must be paid so that the ship owning companies can acquire carbon permits. In the following diagrams, these amounts are calculated for the fleet this study is working on, referring either to the total penalty that has to be paid for three upcoming years, or the average penalty per scenario. In case no alternative fuels and innovative technologies are used, the amount of money that must be paid for the whole fleet is 187,389,998 €. Scenario iv clearly yields the best results when it comes to the reduction of this number, reaching up to 24.22%. Methanol, in conjunction with cold ironing can also bring some outstanding results, achieving a reduction of 11.43%, although this is less than half of the previous reduction. Cold ironing alone provides a considerable percentage of 6.59%. Although these percentages may not seem significant to someone who seeks huge cost savings, in total numbers they translate to 45,393,474 € for scenario iv, 21,410,834 € for scenario vi and 12,357,090 € for scenario ii.

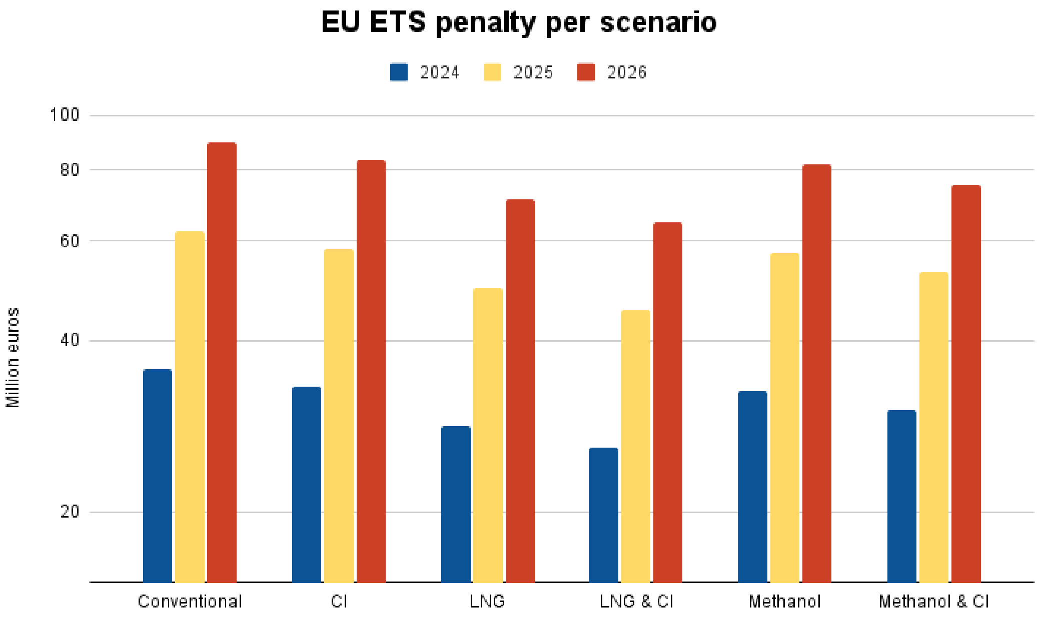


Figure 55: EU ETS penalty per scenario

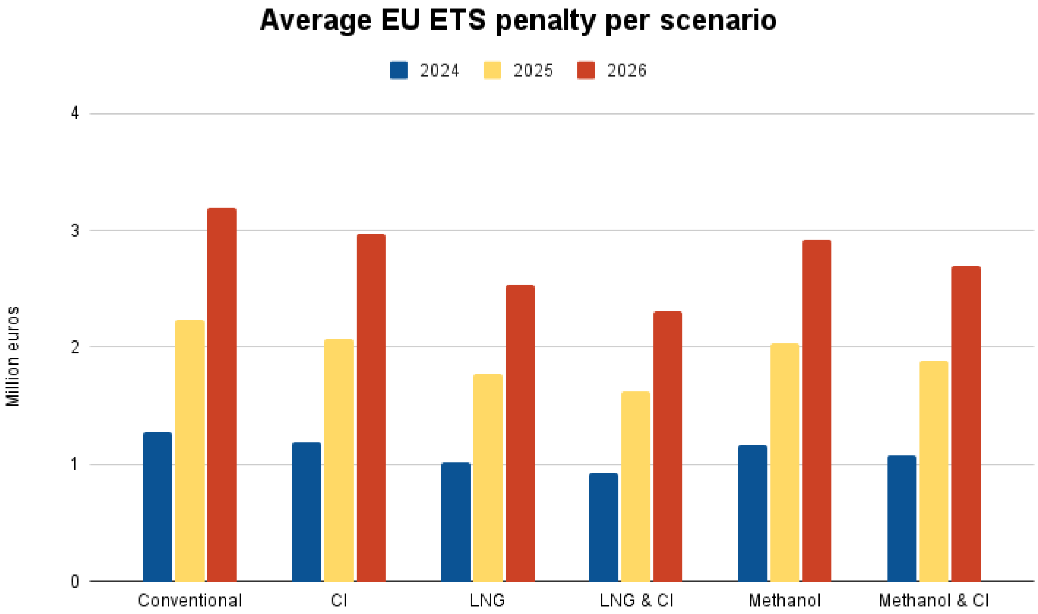


Figure 56: Average EU ETS penalty per scenario

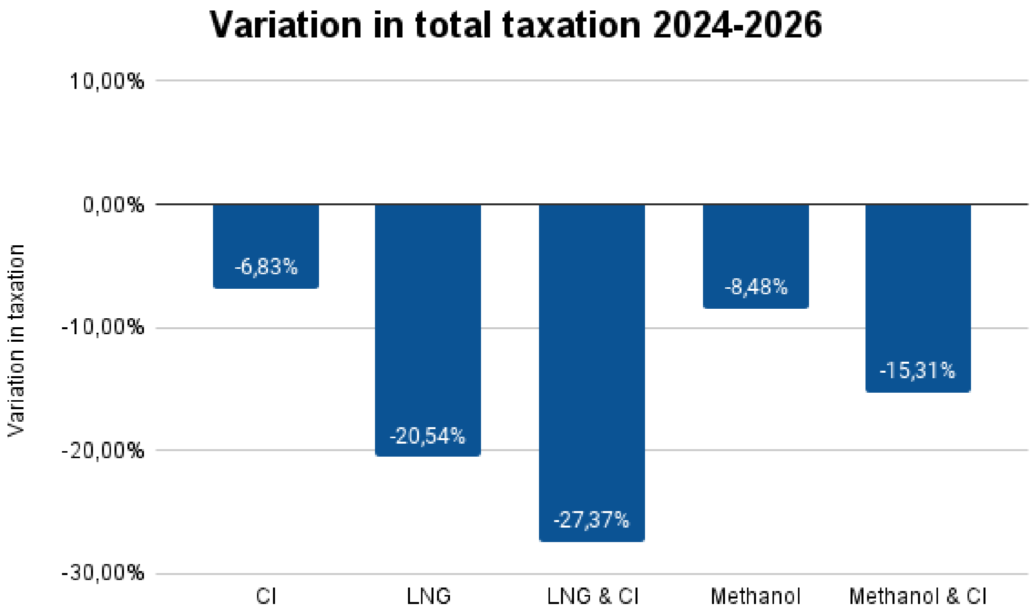


Figure 57: Variation in total taxation 2024-2026

6.5 Speed reduction

In the second phase of the study, changes to the operational profile of a portion of the fleet are applied to assess how the CII ratings react. The initial results regarding CII grades over the three-year period vary significantly depending on how the main engines operate. When all engines are in operation, speed reduction scenarios have a moderate impact on the CII ratings. The least effective scenario is the one with conventional fuels, where most vessels remain at an E grade, with only a few exceptions reaching up to a D grade. Conversely, scenario iv is the most effective, as most ships achieve a C grade with maximum speed reduction, and vessel 9 consistently scores a B grade for each of the three years. The following figures indicate the average CII while all four main engines operate, showing that if the LNG & CI scenario is applied, the fleet's average CII will achieve a C grade until 2029.

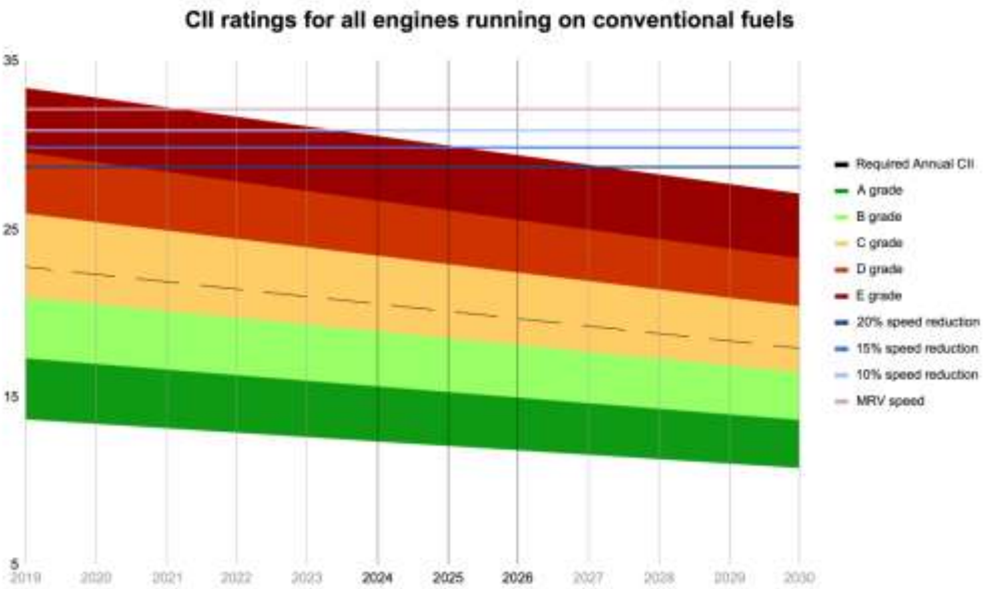


Figure 58: Average CII ratings of the fleet for scenario i while all main engines operate

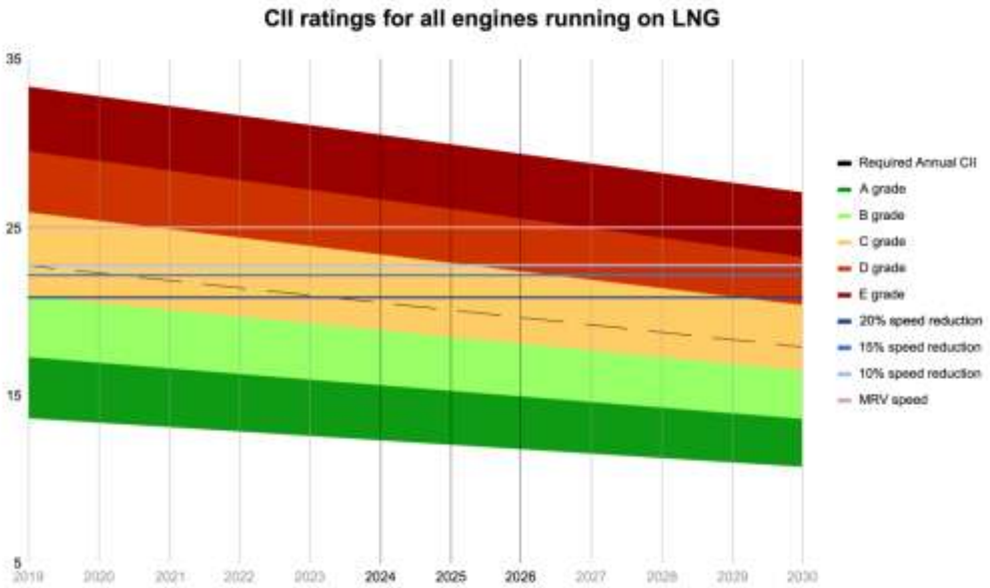


Figure 59: Average CII ratings for scenario iv while all main engines operate

Moreover, some vitally important statistics that has to be mentioned revolve around the fuel consumption and the CO_2 emissions, indicating that CII values, fuel consumed and CO_2 emissions are reduced when speed is reduced, as stated by the diagrams below:

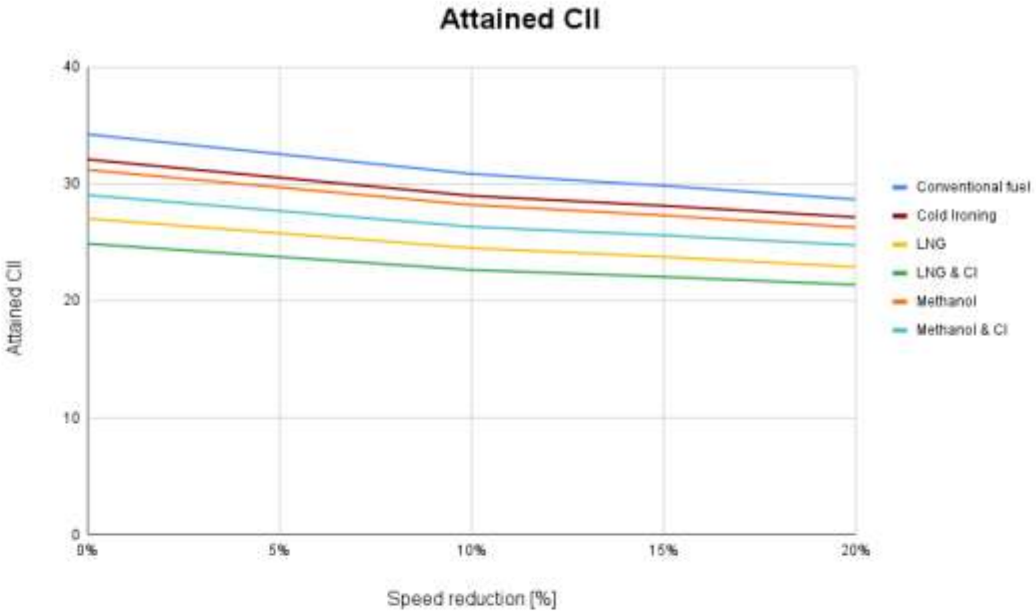


Figure 60: Attained CII for all scenarios while all main engines operate

When it comes to the amount of fuel consumed, it is reduced as speed is reduced. The best scenario for fuel savings is when methanol is used; for a 20% speed reduction, the fuel requirement decreases by 18.22%.

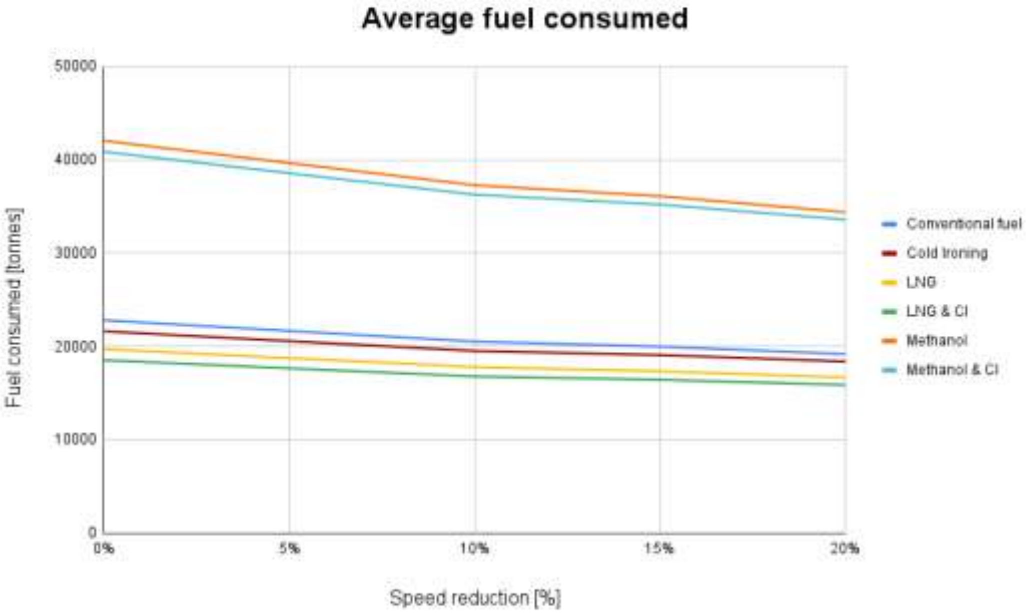


Figure 61: Average fuel consumed for all scenarios while all main engines operate

Similar are the results regarding CO_2 emissions, with the best case scenario in total numbers being scenario iv; for a 20% speed reduction, CO_2 emissions are decreased by 38.74% in comparison with the MRV records. Along with this emissions reduction comes the EU ETS penalty reduction, with 38.74% reduction being the maximum value for 20% speed reduction, the amount of money that can be saved exceeds 33,300,000 Euros.

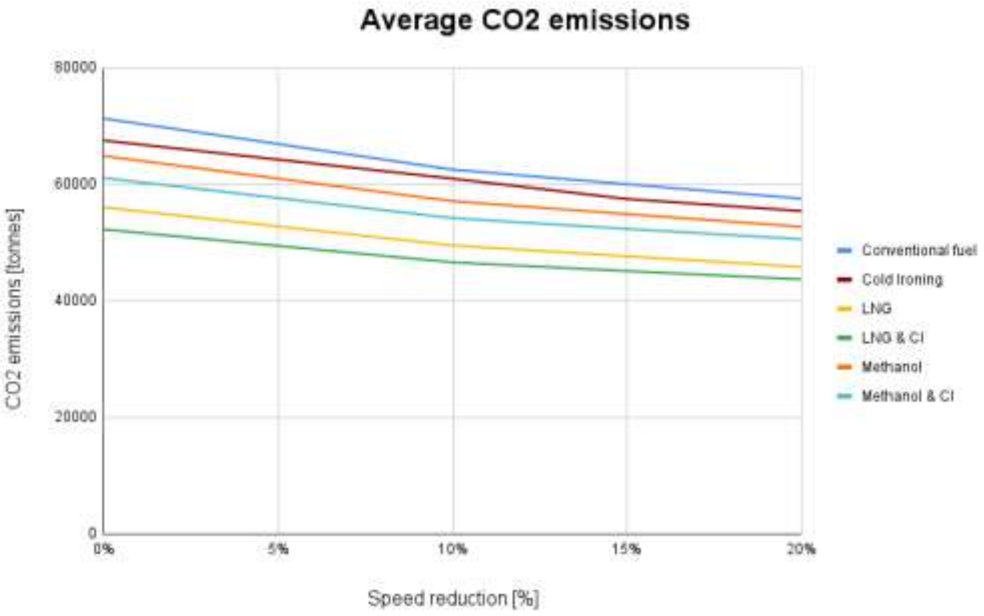


Figure 62: Average CO2 emissions for all scenarios while all main engines operate

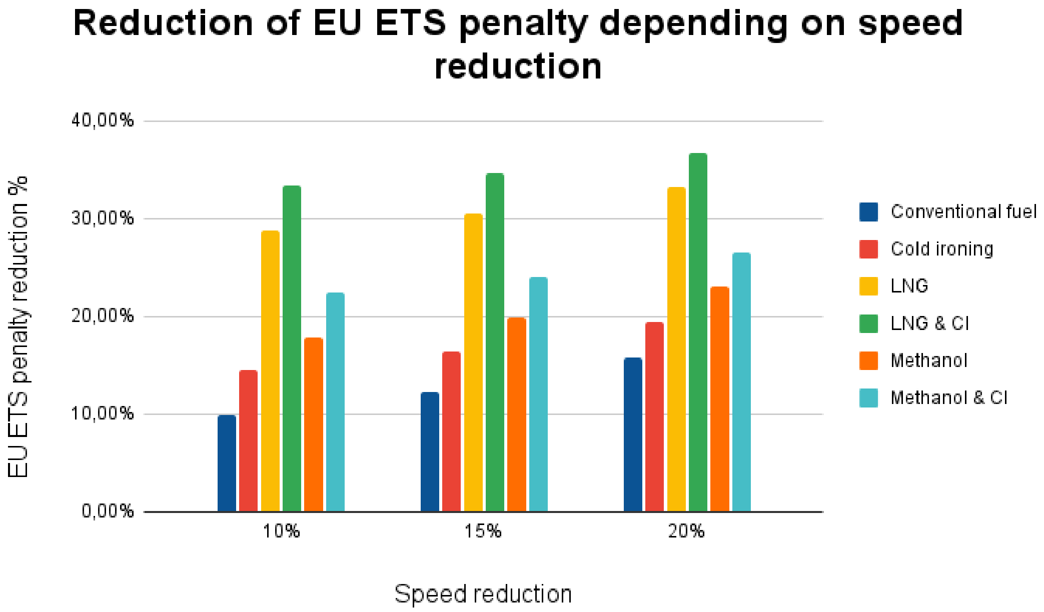


Figure 63: EU ETS penalty reduction for all scenarios while all main engines operate

On the contrary, when only half of the main engines operate, the results are quite encouraging. Although speed reduction is a costless action compared to the retrofits needed for the other scenarios, all ships perform significantly better in scenario i, moving from an E grade for three consecutive years to one or two grades higher (half achieving C and the rest D). Notably, the worst ratings at maximum speed reduction belong to Vessels 11 and 21, scoring D, D, and E for 2024, 2025, and 2026 respectively. Additionally, these are the only vessels in the fleet that score an E grade for at least one year until 2026. This proves that this method can immediately reduce the carbon footprint of any ship without the need for a significant investment. Nonetheless, when this method is combined with alternative fuels, the results are utterly outstanding. The following diagrams show the average attained CII values of these ships for each speed reduction scenario, highlighting the best and worst case scenarios, which are scenario i and scenario iv when half of the engines are used. The most noteworthy result is that, on average, in scenario iv, the CII grade will be B until 2026 and then fall to C until 2030.

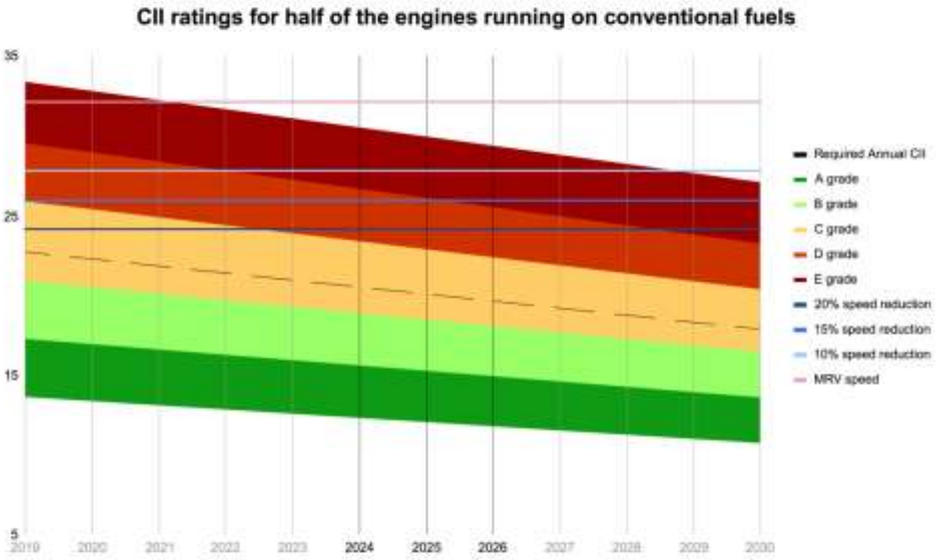


Figure 64: Average CII ratings of the fleet for scenario i while half of the engines operate

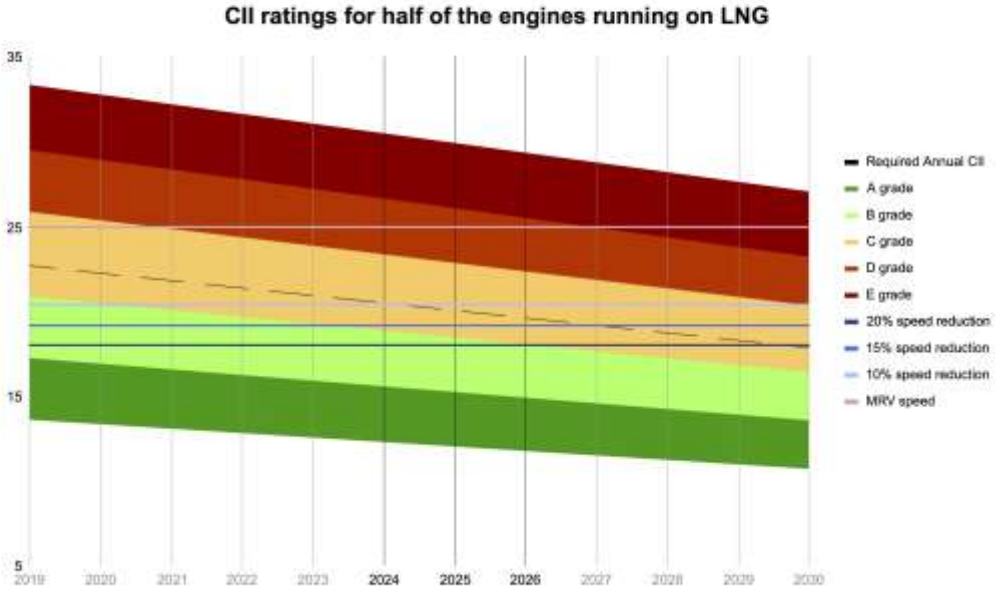


Figure 65: Average CII rating for scenario iv while half of the main engines operate

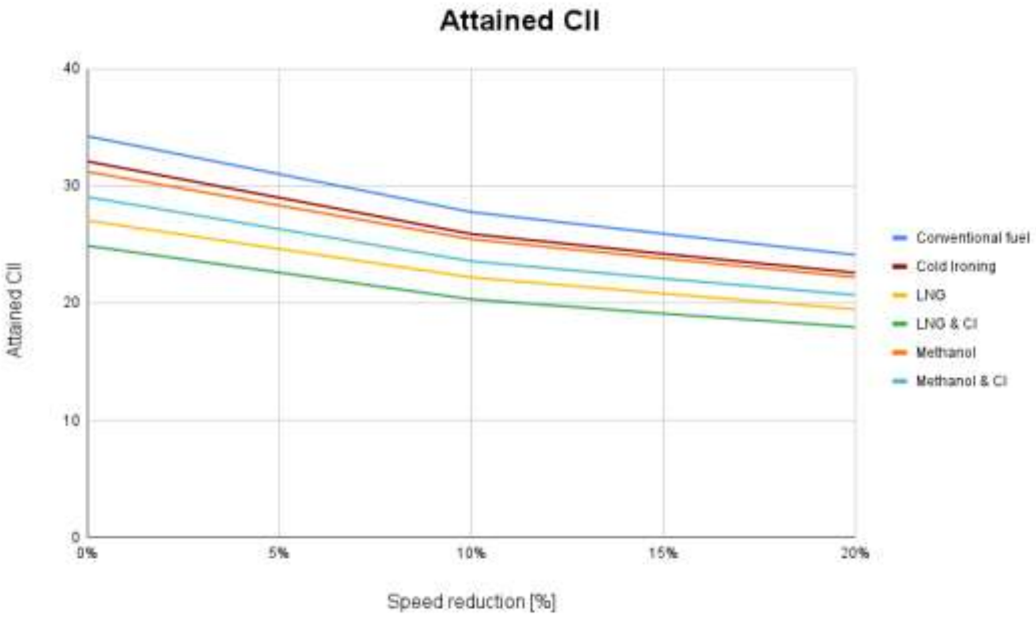


Figure 66: Attained CII for all scenarios while half of the main engines operate

When it comes to the fuel consumed, dramatic changes are observed. Especially when speed is reduced by 20%, the average fuel reduction is more than 30%, with the highest value spotted for the methanol scenarios at 33.37%.

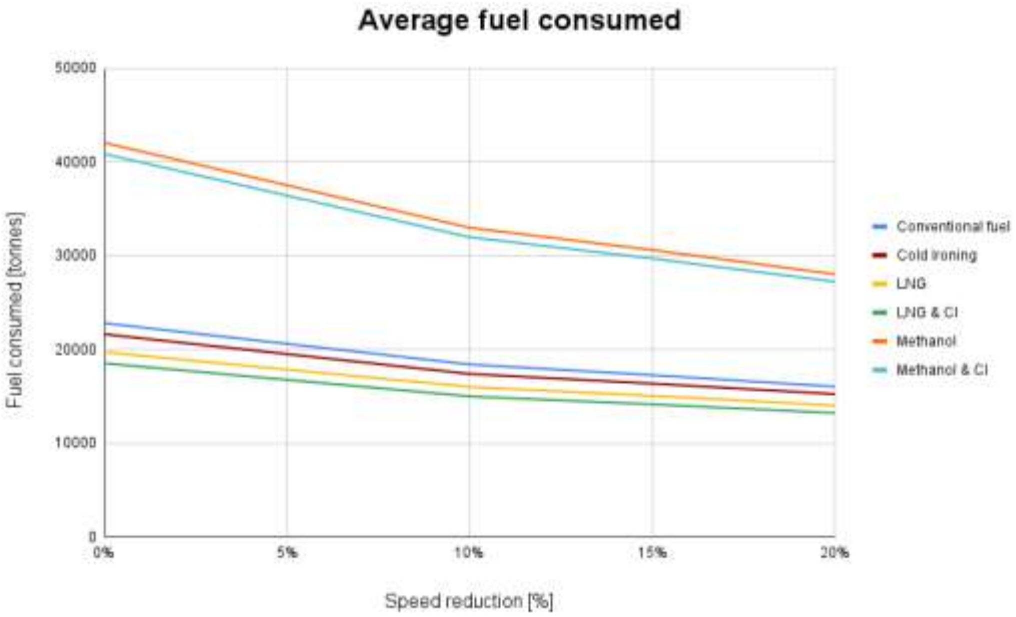


Figure 67: Average fuel consumed for all scenarios while half of the main engines operate

Similar results can be seen to the CO_2 emissions, as the reduction also reaches up to almost 30% for 20% speed reduction.

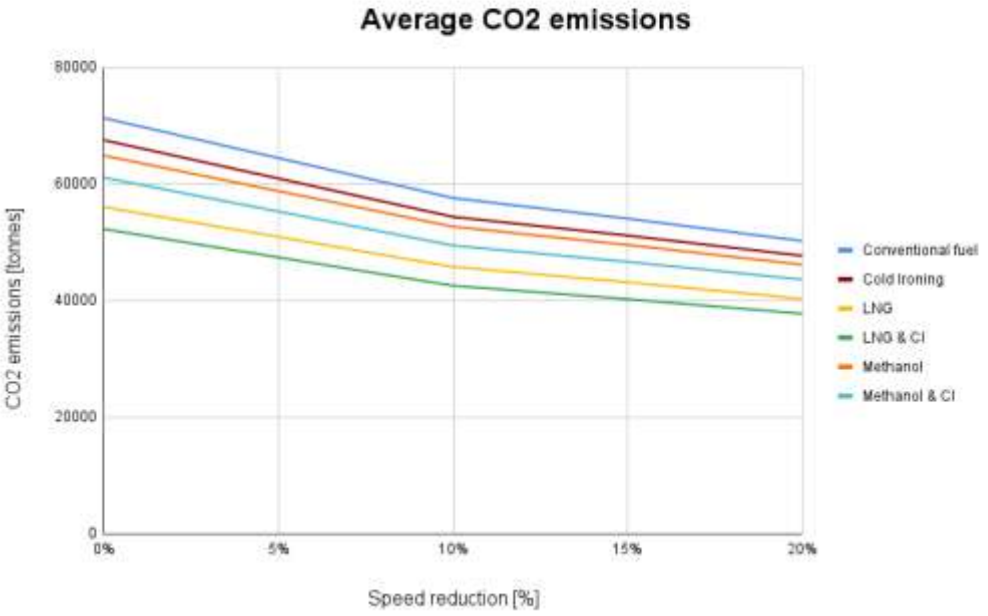


Figure 68: Average CO2 emissions for all scenarios while half of the main engines operate

In terms of both CO2 emissions and fuel consumption, the prospect of LNG, in conjunction with cold ironing, is still holding first place in the race for efficiency. When LNG and cold ironing are compared to other scenarios, the smallest amount of CO2 is emitted into the atmosphere and the least amount of fuel is burned. Additionally, it is evident that when speed is reduced by 10%, there is an approximately 19% reduction in fuel consumption and emissions. However, as speed is reduced further, the rate of reduction in fuel consumption and emissions deteriorates. The main reason for this is the increase in SFOC (Specific Fuel Oil Consumption). The greater the speed reduction, the greater the power reduction, which pushes the new load percentage of the engine closer to the edge of 40% load. When the load percentage gets that low, SFOC rises rapidly, resulting in a slower rate of fuel reduction. Last but not least, quite exceptional results can be observed when it comes to the EU ETS. The maximum reduction in emission trading system penalties is 47.08% and it is noted with a 20% speed reduction in scenario iv, where the amount of money that can be saved exceeds 46,900,000 Euros.

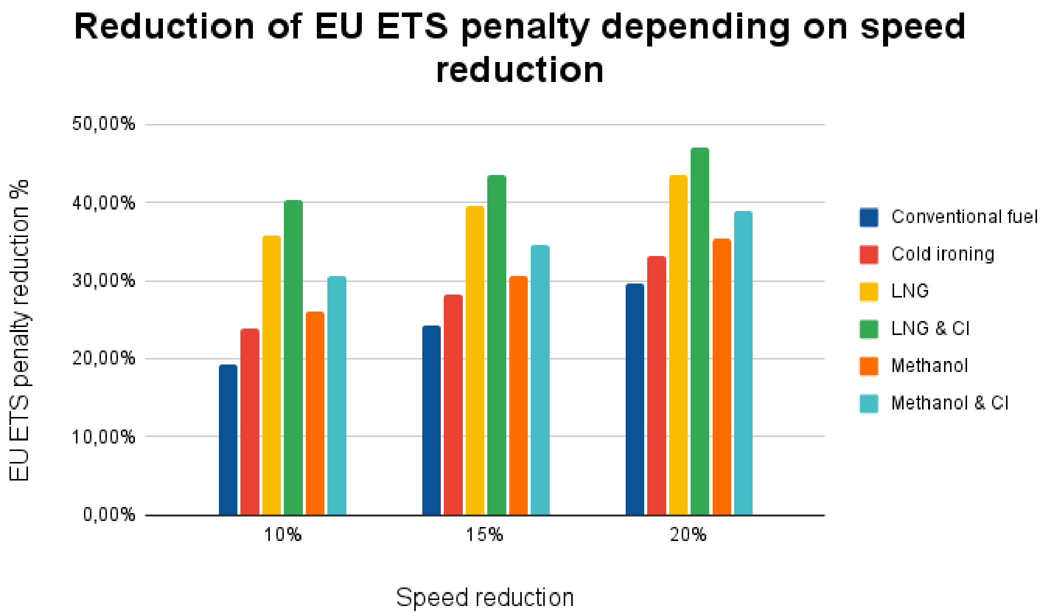


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Figure 69: ETS penalty reduction for all scenarios while half of the main engines operate

6.6 Future work

The present study focuses on tank-to-wake emissions and leaves well-to-tank emissions out of the spotlight. The FUEL EU regulation will come into effect on January 1st, 2025, and will definitely induce a change of scene. With that regulation in play, a more comprehensive study would be extremely important and interesting, incorporating a lifecycle assessment of marine fuels and examining the environmental and human health impacts of their production. Moreover, LNG and methanol should not be the only alternative fuels considered for reducing the fleet’s carbon footprint. Different types of propulsion, such as hybrid electric with batteries -which are very popular for RoPax ships- or propulsion derived from carbon-free fuels like hydrogen and ammonia, are options whose effects on CII should definitely be examined. Given the long timetable for the adoption of alternative fuels in the shipping sector, solutions like CCS and PTO/PTI may be key players in mitigating CO2 emissions from shipping. Both solutions have some drawbacks; for instance, CCS is not widely applicable at the moment, and the implementation of shaft generators may be an expensive and unprofitable investment for relatively older ships. Either way, examining the impact of both scenarios on the fleet's carbon footprint is vitally important. Last but not least, the assessment of the impact of ESDs, such as pre-swirl fins, twisted rudder and wake equalising duct, in conjunction with the scenarios of this study, would be interesting in future work. The only restriction on the validity of this study’s results is the constant variability of the data.

Appendix

Table 12: Fleet's composition in terms of type, route and GT

VESSEL	SHIP TYPE	ROUTES	GROSS TONNAGE
Vessel 1	High speed craft	Aegean Sea	5005
Vessel 2	High speed craft	Aegean Sea	5007
Vessel 3	High speed craft	Aegean Sea	5335
Vessel 4	High speed craft	Aegean Sea	5819
Vessel 5	High speed craft	Aegean Sea	6330
Vessel 6	High speed craft	Aegean Sea	6402
Vessel 7	RoPax	Ionian Sea	9024
Vessel 8	RoPax	Aegean Sea	10438
Vessel 9	RoPax	Aegean Sea	10438
Vessel 10	RoPax	Aegean Sea	13955
Vessel 11	RoPax	N. Aegean Sea	14157
Vessel 12	RoPax	Aegean Sea	18663
Vessel 13	RoPax	Aegean Sea	18664
Vessel 14	RoPax	Ionian Sea	25612
Vessel 15	RoPax	Ionian Sea	25843
Vessel 16	RoPax	Ionian Sea	26302
Vessel 17	RoPax	Ionian Sea	26302
Vessel 18	RoPax	Aegean Sea	29858
Vessel 19	RoPax	Aegean Sea	29858
Vessel 20	RoPax	Ionian Sea	30882
Vessel 21	RoPax	Ionian Sea	31090
Vessel 22	RoPax	Ionian Sea	32694
Vessel 23	RoPax	Ionian Sea	32694
Vessel 24	RoPax	Aegean Sea	33635
Vessel 25	RoPax	Ionian Sea	33958
Vessel 26	RoPax	Aegean Sea	36894
Vessel 27	RoPax	Aegean Sea	36900
Vessel 28	RoPax	Ionian Sea	37550

Table 13: Typical generator sets

GENSET	MANUFACTURER	POWER OUTPUT	MODELS FOR 60Hz	MODELS FOR 50Hz
L16/24	MAN	450-990	4/5/6/7	4/5
L23/30	MAN	625-1200	1/3	2
L21/31	MAN	1000-1980	8/9/10/11	12/13
L27/38	MAN	2040-3285	14/15/18	16/17

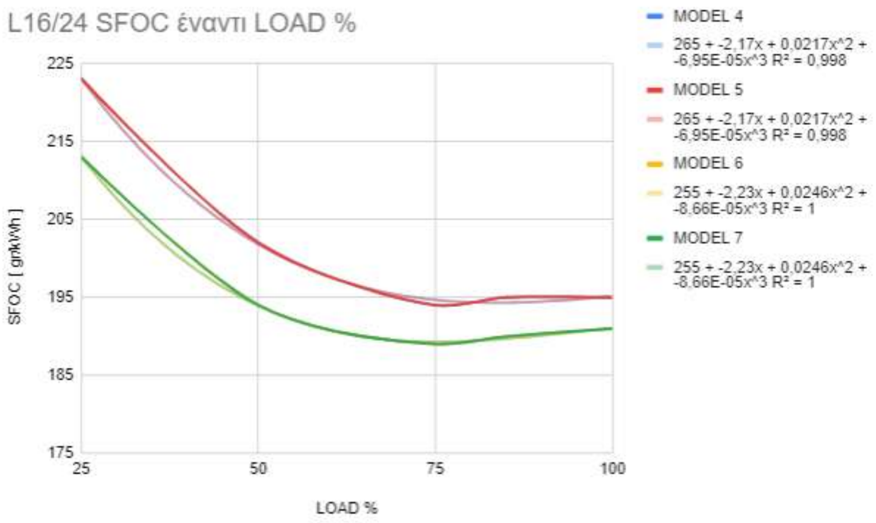

Figure 70: MAN L16/24

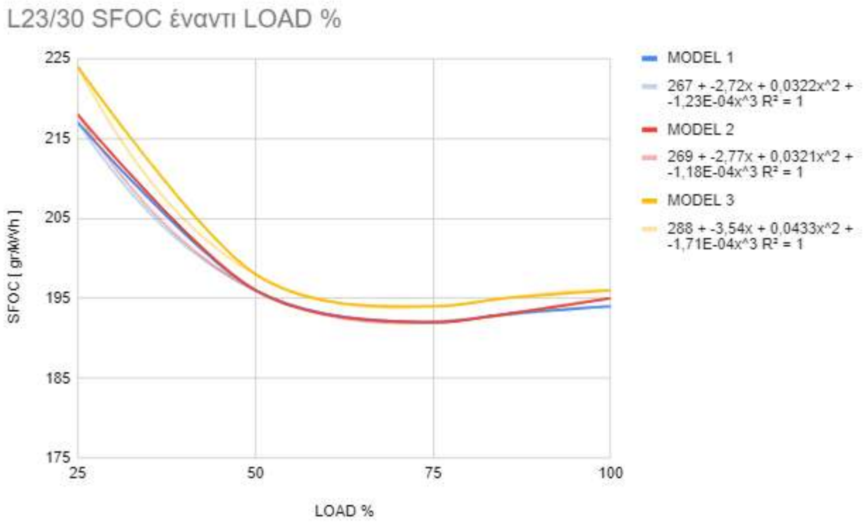

Figure 71: MAN L23/30

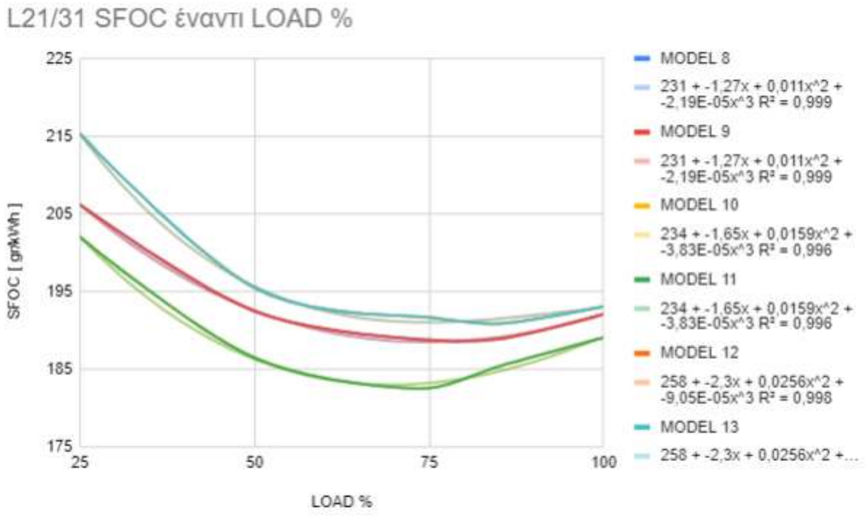

Figure 72: MAN L21/31

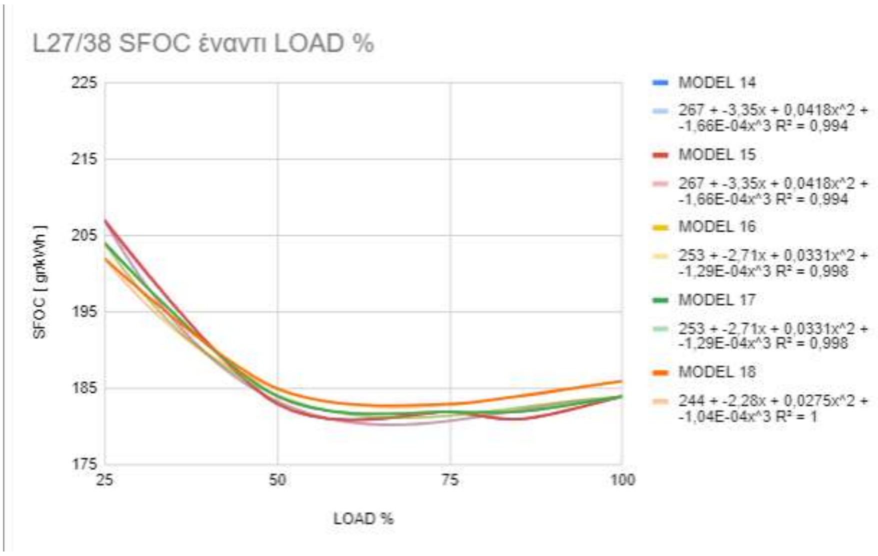

Figure 73: MAN L27/38

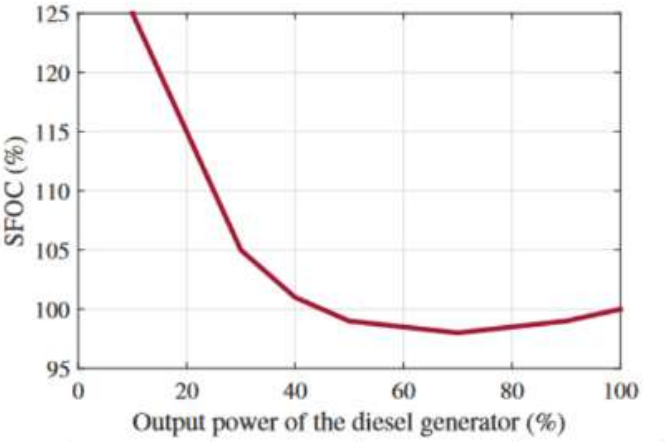

Figure 74: SFOC curve of a diesel generator [85]

Table 14: Main engines, generator power and frequency of the fleet [88]

VESSEL	MAIN ENGINE		GENERATOR POWER	Hz
	Number	Model		
Vessel 1	4	20RK270	240	60
Vessel 2	4	20RK270	240	60
Vessel 3	4	20V1163TB73	269	60
Vessel 4	4	3618TA	240	50
Vessel 5	4	3618TA	280	50
Vessel 6	2	LM2500	370	60
Vessel 7	2	16V28/32A	500	60
Vessel 8	4	6L38B	1020	50
Vessel 9	4	6L38B	1020	50
Vessel 10	4	12V38	1020	50
Vessel 11	4	12V38	1020	50
Vessel 12	4	16V32/40	1320	50
Vessel 13	4	16V32/40	1320	50
Vessel 14	2	12V46	1600	60
Vessel 15	2	12V46	1600	60
Vessel 16	2	9l 48/60b	1600	60
Vessel 17	2	9l 48/60b	1600	60
Vessel 18	4	8L58/64	1240	60
Vessel 19	4	8L58/64	1240	60
Vessel 20	2	14PC4-2V-570	1240	60
Vessel 21	4	12V46C	2000	60
Vessel 22	4	12V46C	1485	50
Vessel 23	4	12V46C	1485	50
Vessel 24	2	12PC4-2V-570	1260	60
Vessel 25	4	8ZAL40S	1260	60
Vessel 26	4	16V46	2400	60
Vessel 27	4	16V46	2400	60
Vessel 28	4	16V46	2260	60

Table 15: ELA of SUPERFAST II [84]

SUPERFAST II - BILANCIO ELETTRICO						
DESCRIZIONE/ SERVIZIO		CONDIZIONI DI FUNZINAMENTO NAVE				
		EMERGENZA	PORTO	MANOVRA	NAVIGAZIONE INVERNALE	NAVIGAZIONE ESTIVA
		POTENZA [kW]	POTENZA [kW]	POTENZA [kW]	POTENZA [kW]	POTENZA [kW]
A	COPERTA E SERVIZI SCAFO	84.8	119.4	2288.1	119.4	119.4
B	NAVIGAZIONE AUTOMAZIONE	9.8	9.7	37.5	27.3	14.8
C	APARATO MOTORE	121.0	556.4	585.6	635.6	635.6
D	SICUREZZA	116.4	7.5	7.0	7.0	7.0
E	CARICO-SCARICO	0.0	610.9	474.2	864.2	864.2
F	CONDIZIONAMENTO E VENTILAZIONE	5.3	346.9	453.2	284.4	511.8
G	SANITARI-CAMERA	15.0	45.9	28.0	43.1	43.1
H	CAMBUSA-CELLE FRIFO	0.0	51.5	45.8	48.5	68.7
I	RISTORO-CUCINA	0.0	198.3	1.4	297.6	297.6
L	ILLUMINAZIONE E PICCOLA FORZA	36.9	146.1	139.5	147.8	152.6
M	OFFICINA	0.0	36.2	0.0	24.7	24.7
POTENZA RICHIESTA	[kW]	389.1	2128.8	4060.2	2499.6	2739.5
POTENZA DISPONIBILE	[kW]	550.0	3200.0	4800.0	3200.0	3200.0
FATTORE DI CARICO DEI GENERATORI	[%]	70.8	66.5	84.5	78.1	85.6

Table 16: Variation of calculated-reported emissions

VESSEL	EMISSIONS		VARIATION %
	CALCULATED	REPORTED	
Vessel 1	28747.30	28747.30	0.00%
Vessel 2	15383.54	15383.54	0.00%
Vessel 3	22042.69	22042.69	0.00%
Vessel 4	17815.80	17815.81	0.00%
Vessel 5	20959.12	20959.13	0.00%
Vessel 6	31212.97	31212.97	0.00%
Vessel 7	10608.24	10807.60	1.84%
Vessel 8	41006.68	40781.19	0.55%
Vessel 9	29969.42	29771.92	0.66%
Vessel 10	47319.75	47107.95	0.45%
Vessel 11	67886.58	67668.51	0.32%
Vessel 12	79365.51	79093.74	0.34%
Vessel 13	81931.66	81645.16	0.35%
Vessel 14	60894.65	60625.28	0.44%
Vessel 15	54325.87	54045.87	0.52%
Vessel 16	68416.35	68149.05	0.39%
Vessel 17	56013.80	55786.33	0.41%
Vessel 18	54285.66	54034.65	0.46%
Vessel 19	70652.96	70436.41	0.31%
Vessel 20	69490.94	69332.83	0.23%
Vessel 21	104271.31	103875.62	0.38%
Vessel 22	98423.55	98108.00	0.32%
Vessel 23	92038.28	91726.38	0.34%
Vessel 24	54029.64	53827.47	0.38%
Vessel 25	41502.80	41434.98	0.16%
Vessel 26	56849.96	57013.25	0.29%
Vessel 27	52639.83	52804.64	0.31%
Vessel 28	46309.85	46430.53	0.26%

Table 17: Four Active main engines and load % of each one

VESSEL	Speed reduction					
	10%		15%		20%	
	Main Engines					
	Active	Load%	Active	Load%	Active	Load%
Vessel 8	4/4	34,8	4/4	29,3	4/4	24,5
Vessel 9	4/4	41,4	4/4	34,8	4/4	29,0
Vessel 10	4/4	35,6	4/4	30,0	4/4	25,0
Vessel 11	4/4	41,8	4/4	35,2	4/4	29,3
Vessel 12	4/4	45,9	4/4	38,7	4/4	32,2
Vessel 13	4/4	40,1	4/4	33,7	4/4	28,1
Vessel 19	4/4	38,1	4/4	32,1	4/4	26,8
Vessel 21	4/4	41,8	4/4	35,2	4/4	29,4
Vessel 22	4/4	33,0	4/4	27,8	4/4	23,2
Vessel 23	4/4	38,2	4/4	32,1	4/4	26,8

Table 18: Two Active main engines and load % of each one

VESSEL	Speed reduction					
	10%		15%		20%	
	Main Engines					
	Active	Load%	Active	Load%	Active	Load%
Vessel 8	2/4	69,6	2/4	58,7	2/4	48,9
Vessel 9	2/4	82,7	2/4	69,7	2/4	58,1
Vessel 10	2/4	71,2	2/4	60,0	2/4	50,0
Vessel 11	2/4	83,6	2/4	70,4	2/4	58,7
Vessel 12	2/4	91,8	2/4	77,3	2/4	64,5
Vessel 13	2/4	80,1	2/4	67,5	2/4	56,3
Vessel 19	2/4	76,2	2/4	64,2	2/4	53,5
Vessel 21	2/4	83,6	2/4	70,4	2/4	58,7
Vessel 22	2/4	66,0	2/4	55,6	2/4	46,3
Vessel 23	2/4	76,3	2/4	64,3	2/4	53,6

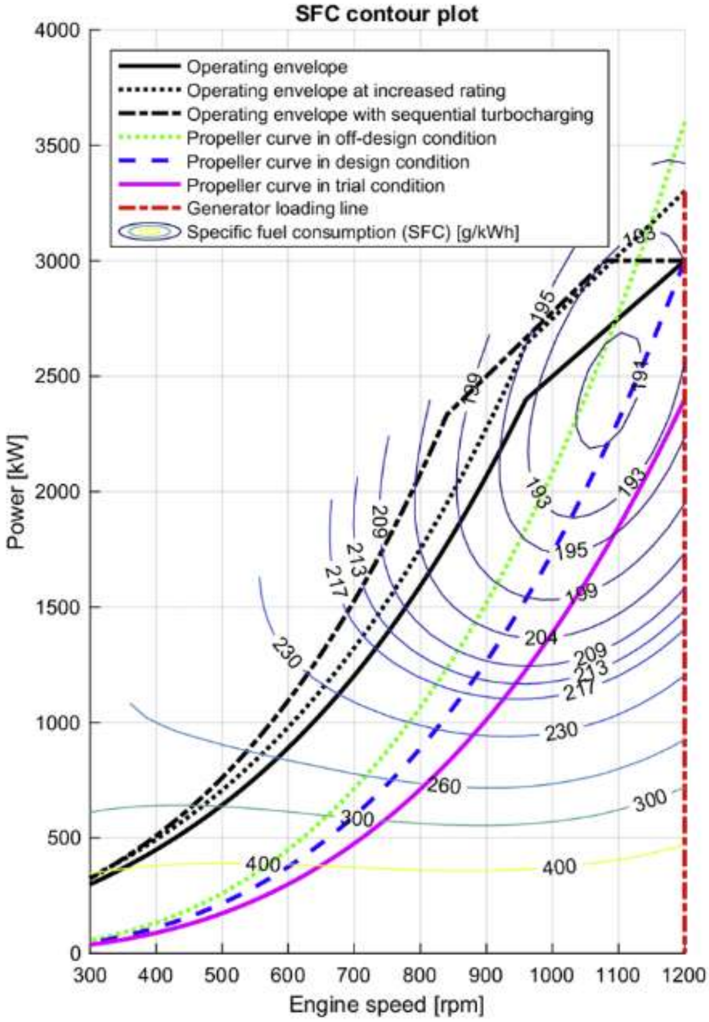

Figure 75: SFC contour plot

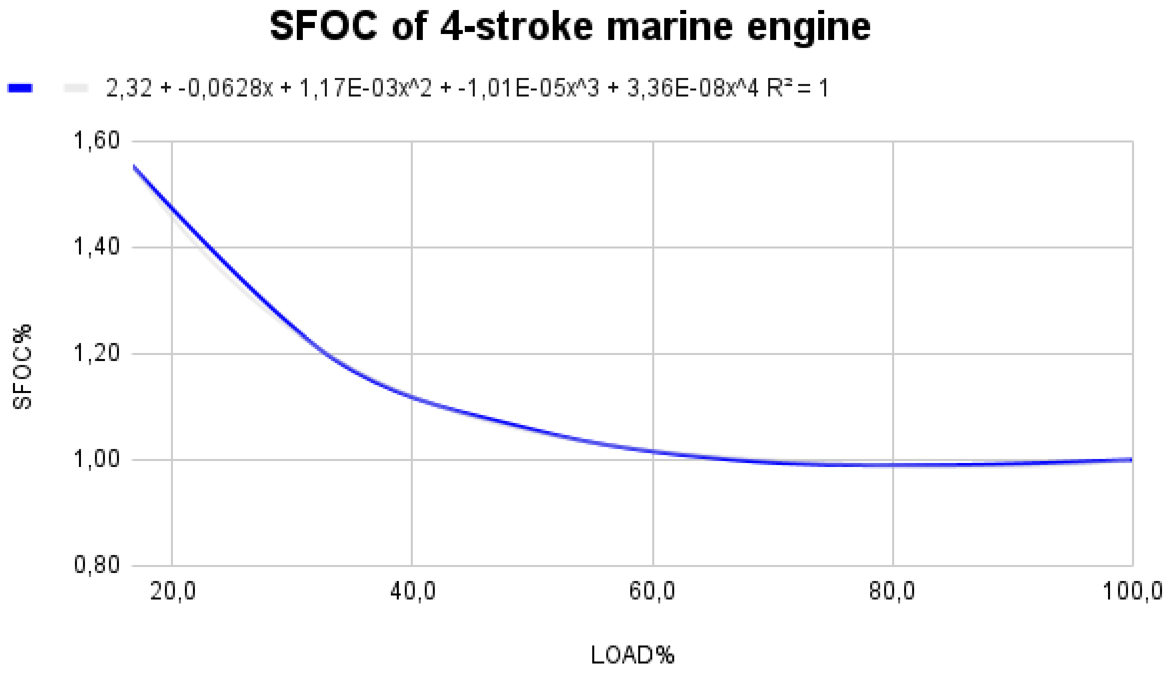

Figure 76: SFOC of 4-stroke marine engine

References/Citations

[1] M. Stopford, Maritime Economics, 2009.

[2] D. Kemp and P. Kemp, The Oxford Companion to Ships and the Sea, Oxford University Press, 2006.

[3] Maritime Cyprus, "Maritime Cyprus," 12 March 2020. [Online]. Available: https://maritimecyprus.com/2020/03/12/infographic-the-evolution-of-ship-propulsion/.

[4] Britannica, "Shipping," 29 October 2023. [Online]. Available: https://www.britannica.com/technology/shipping-water-transportation.

[5] IMO, "Brief History of IMO," [Online]. Available: https://www.imo.org/en/About/HistoryOfIMO/Pages/Default.aspx.

[6] IMO, "MARPOL," 02 November 2023. [Online]. Available: https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx.

[7] National Geographic, "Pollution," National Geographic, 19 October 2023. [Online]. Available: https://education.nationalgeographic.org/resource/pollution/.

[8] P. Rosado and H. Ritchie, "Fossil Fuels," 02 October 2022. [Online]. Available: https://ourworldindata.org/fossil-fuels.

[9] M. E. Mann, "Britannica/science/GHG," 15 November 2023. [Online]. Available: https://www.britannica.com/science/greenhouse-gas.

[10] H. Ritchie and M. Roser, "OurWorldInData," April 2022. [Online]. Available: https://ourworldindata.org/co2-and-greenhouse-gas-emissions.

[11] EDGAR, "GHG emissions of all world countries," 2023. [Online]. Available: https://edgar.jrc.ec.europa.eu/report_2023.

[12] EPA, "EPA/Overview of GHG," 2021. [Online]. Available: https://www.epa.gov/ghgemissions/overview-greenhouse-gases.

[13] UNCTAD, "Review of Maritime Transport," 2023.

[14] IMO, "4th GHG Study," 2020.

[15] EEA, 17 December 2019. [Online]. Available: https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-air-pollutants-8/transport-emissions-of-air-pollutants-8.

[16] United Nations, "Goals," [Online]. Available: https://sdgs.un.org/goals/goal13.

[17] UNFCCC, "Kyoto Protocol," [Online]. Available: https://unfccc.int/kyoto_protocol.

[18] EPA, "Paris Agreement," [Online]. Available: https://www.epa.ie/environment-and-you/climate-change/what-is-europe-and-the-world-doing/paris-agreement/.

[19] IMO, "Clean air in shipping," [Online]. Available: https://www.imo.org/en/OurWork/Environment/Pages/Clean%20air%20in%20shipping.aspx.

[20] Sustainable Ships, "ECAs," [Online]. Available: https://www.sustainable-ships.org/rules-regulations/eca.

[21] M. Vaferi, K. Pazouki and A. Van Klink, "Declines in EROI of Main Fuels and the Implications on Developing LNG as Marine Fuel," 2020.

[22] UN, "Mediterranean becomes ECA," [Online]. Available: https://www.unep.org/unepmap/news/press-release/mediterranean-historic-milestone-MedSOxECA.

[23] IMO, "Cutting sulphur emissions," 2020. [Online]. Available: https://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx.

[24] MARPOL VI, "EEDI-SEEMP," [Online]. Available: https://www.marpol-annex-vi.com/eedi-seemp/.

[25] DNV, "MRV," [Online]. Available: https://www.dnv.com/maritime/insights/topics/mrv/index.html.

[26] IMO, "DCS," [Online]. Available: https://www.imo.org/en/ourwork/environment/pages/data-collection-system.aspx.

[27] IMO, "Initial GHG Strategy," 2018. [Online]. Available: https://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx.

[28] Transport & environment, 2017. [Online]. Available: https://www.transportenvironment.org/wp-content/uploads/2021/07/Statistical%20analysis%20of%20the%20energy%20efficiency%20performance%20(EEDI)%20of%20new%20ships.pdf.

[29] Bureau Veritas, "Updated IMO Amendments," [Online]. Available: https://marine-offshore.bureauveritas.com/updated-imo-amendments-bring-sustainability-forefront.

[30] IMO, "EEXI," [Online]. Available: https://www.imo.org/en/MediaCentre/HotTopics/Pages/EEXI-CII-FAQ.aspx.

[31] Marine Insight, "EEXI," [Online]. Available: https://www.marineinsight.com/maritime-law/energy-efficiency-design-index/.

[32] ClassNK, "EEXI," [Online]. Available: https://www.classnk.or.jp/hp/pdf/activities/statutory/eexi/eexi_rev3e.pdf.

[33] DNV, "CII," [Online]. Available: https://www.dnv.com/maritime/insights/topics/CII-carbon-intensity-indicator/.

[34] EU council, "Fit for 55," [Online]. Available: https://www.consilium.europa.eu/el/policies/green-deal/fit-for-55/#0.

[35] European Commission, "EU ETS," [Online]. Available: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en.

[36] DNV, "EU ETS," 23 January 2023. [Online]. Available: https://www.dnv.com/news/eu-ets-preliminary-agreement-to-include-shipping-in-the-eu-s-emission-trading-system-from-2024-238068.

[37] Bureau Veritas, "Well to Wake," [Online]. Available: https://marine-offshore.bureauveritas.com/insight/business-insights/what-well-wake-decarbonization-means-shipowners.

[38] Council of the EU, “FuelEU Maritime Initiative,” 25 July 2023. [Online]. Available: https://www.consilium.europa.eu/en/press/press-releases/2023/07/25/fueleu-maritime-initiative-council-adopts-new-law-to-decarbonise-the-maritime-sector/.

[39] DNV, “FuelEU Maritime,” [Online]. Available: https://www.dnv.com/maritime/insights/topics/fuel-eu-maritime/index.html.

[40] DNV, “Fuels,” [Online]. Available: https://www.dnv.com/maritime/hub/decarbonize-shipping/fuels/index.html.

[41] DNV, “AFI,” [Online].

[42] MAN energy solutions, “Energy transition,” [Online].

[43] ABS, “Marine Fuel Oil Advisory,” March 2023.

[44] T. Wlodek, “Analysis of boil-off rate problem in Liquefied Natural Gas(LNG) receiving terminals,” 2019.

[45] International Gas Union, “World LNG Report,” 2023.

[46] International Institute of Refrigeration, “Liquefied Natural Gas: production process and cold energy recovery,” [Online]. Available: https://iifiir.org/en/encyclopedia-of-refrigeration/liquefied-natural-gas-production-process-and-cold-energy-recovery-br-nbsp.

[47] H. Al-Yafei, “Energy Strategy Reviews,” November 2021. [Online]. Available: https://doi.org/10.1016/j.esr.2021.100768.

[48] MAN Energy Solutions, “Methane slip,” 2023. [Online]. Available: https://www.man-es.com/discover/decarbonization-glossary---man-energy-solutions/methane-slip.

[49] Riviera, “LPG,” 19 June 2023. [Online]. Available: https://www.rivieramm.com/news-content-hub/news-content-hub/well-to-wake-lpg-as-a-marine-fuel-is-hard-to-beat-76539.

[50] Shivgas, “LPG as a marine fuel,” 17 February 2024. [Online]. Available: https://shivgas.com/lpg-marine-fuel-exploring-role-commercial-application/.

[51] MAN, “Energy Solutions: Methanol in shipping”.

[52] Sustainable ships, “The state of methanol as marine fuel 2023,” 2023. [Online]. Available: https://www.sustainable-ships.org/stories/2023/methanol-marine-fuel.

[53] Stena Line, “World's first Ropax running on methanol,” 31 March 2021. [Online]. Available: https://stenaline.com/media/stories/the-worlds-first-methanol-ferry/.

[54] MAN Energy Solutions, “Biofuels,” [Online]. Available: https://www.man-es.com/marine/strategic-expertise/future-fuels/biofuel.

[55] MAN Energy Solutions, “SNG - Biogas,” [Online]. Available: https://www.man-es.com/marine/strategic-expertise/future-fuels/sng-biogas.

[56] DNV, “Challenging road ahead for retrofitting to dual fuel engines,” 16 May 2023. [Online]. Available: https://www.dnv.com/expert-story/maritime-impact/challenging-road-ahead-for-retrofitting-to-dual-fuel-engine/.

[57] Bureau Veritas, “Ammonia,” [Online]. Available: https://marine-offshore.bureauveritas.com/shipping-decarbonization/future-fuels/ammonia.

[58] MAN Energy Solutions, “Ammonia,” [Online]. Available: https://www.man-es.com/marine/strategic-expertise/future-fuels/ammonia?e2763a79-6db1-453a-b7fc-eb3a9a541fb5%5B%5D=0.

[59] MAN Energy Solutions, “Hydrogen,” [Online]. Available: https://www.man-es.com/marine/strategic-expertise/future-fuels/hydrogen.

[60] Y. H. Teoh, T. D. Le, D. L. Loo, T. Rashid and S. Farooq, “A review on production and implementation of hydrogen as a green fuel in internal combustion engines,” [Online]. Available: https://doi.org/10.1016/j.fuel.2022.126525.

[61] Energy Education, “Types of hydrogen fuel,” [Online]. Available: https://energyeducation.ca/encyclopedia/Types_of_hydrogen_fuel.

[62] MAN Energy Solutions, “Energy transition with hydrogen,” [Online].

[63] DNV, “Hydrogen forecast 2022 to 2050,” [Online].

[64] Ballard, 9 October 2023. [Online]. Available: https://blog.ballard.com/marine/worlds-first-liquid-powered-hydrogen-ship-mf-hydra-is-powered-by-ballards-fuel-cells.

[65] Wartsila, “Full electric vessels,” [Online]. Available: https://www.wartsila.com/marine/products/ship-electrification-solutions/full-electric-vessels.

[66] Buraeu Veritas, “Electric ferries,” [Online]. Available: https://marine-offshore.bureauveritas.com/magazine/coming-wave-electric-ferries.

[67] CNN, “Yara Birkeland,” [Online]. Available: https://edition.cnn.com/2021/08/25/world/yara-birkeland-norway-crewless-container-ship-spc-intl/index.html.

[68] Sustainable ships, “world's first electric cargo ship,” [Online]. Available: https://www.sustainable-ships.org/stories/2021/worlds-first-electric-cargo.

[69] Safety4sea, “Cold Ironing: The role of ports in reducing shipping emissions,” 19 March 2019. [Online]. Available: https://safety4sea.com/cm-cold-ironing-the-role-of-ports-in-reducing-shipping-emissions/.

[70] I. Prousalidis, 2020. [Online]. Available: https://www.electrologos.gr/wp-content/uploads/2021/03/%CE%A4%CE%95%CE%A7%CE%9D%CE%99%CE%9A%CE%9F-%CE%91%CE%A1%CE%98%CE%A1%CE%9F-%CE%A0%CE%A1%CE%9F%CE%A5%CE%A3%CE%91%CE%9B%CE%99%CE%94%CE%97%CE%A3.pdf.

[71] T. Spengler and B. Tovar, “Potential of cold-ironing for the reduction of externalities from in-port shipping emissions: The state-owned Spanish port system case,” 2021. [Online]. Available: https://doi.org/10.1016/j.jenvman.2020.111807.

[72] Maritime Executive, “European and North American Ports Preparing for Cold Ironing,” 2020. [Online]. Available: https://maritime-executive.com/article/european-and-north-american-ports-preparing-for-cold-ironing.

[73] L. Styhre, "Greenhouse gas emissions from ships in ports – Case studies in four continents," July 2017. [Online]. Available: https://doi.org/10.1016/j.trd.2017.04.033.

[74] Safety4Sea, "Greek port to inaugurate first shore power supply in East Mediterranean," 2018. [Online]. Available: https://safety4sea.com/greek-port-to-inaugurate-first-shore-power-supply-in-east-mediterranean/.

[75] J. A. Smits, "Holland Marine Equipment," 4 September 2008. [Online]. Available: https://sustainableworldports.org/wp-content/uploads/Holland-Marine-Equipment-Shore-Connected-Power-for-the-ferry-Ro-Ro-vessels-in-the-port-of-Rotterdam.pdf.

[76] Global CCS Institute, "Global status of CCS report," 2023.

[77] Global CCS Institute, "Global status of CCS report," 2021. [Online]. Available: https://www.globalccsinstitute.com/wp-content/uploads/2021/10/2021-Global-Status-of-CCS-Report_Global_CCS_Institute.pdf.

[78] MAN Energy Solutions, "CO2 reduction toolbox".

[79] DNV, "CCS presentation," [Online]. Available: https://conference18.newsfront.gr/images/presentations/Chara_Georgopoulou.pdf.

[80] UNCTAD, "Handbook of Statistics," 2023.

[81] Equasis Report, "World Fleet Report," 2022.

[82] Marine Insight, "Why 2-stroke Engines are Used More commonly than 4-stroke on Ships?," 21 April 2021. [Online]. Available: https://www.marineinsight.com/main-engine/why-2-stroke-engines-are-used-more-commonly-than-4-stroke-on-ships/.

[83] N. N. A. Bakar, "Electrification of onshore power systems in maritime transportation towards decarbonization of ports: A review of the cold ironing technology," May 2023. [Online]. Available: https://doi.org/10.1016/j.rser.2023.113243.

[84] C. P. Pantazis, "Τεχνοοικονομική μελέτη αγοράς και εγκατάστασης εξοπλισμού ακτοπλοϊκών πλοίων με σκοπό την ηλεκτροδότηση από το λιμάνι," 7 July 2023. [Online]. Available: http://dx.doi.org/10.26240/heal.ntua.25889.

[85] M. Banaei, "Energy Management of Hybrd Diesel/Battery Ships in Multidisciplinary Policy Areas," 12 August 2020. [Online]. Available: https://doi.org/10.3390/en13164179.

[86] J. Antunes and J. Correia, "The retrofit of existing ships to," October 2014. [Online]. Available: https://www.tecnoveritas.net/wp-content/uploads/2019/05/The-retrofit-of-existing-ships-to-natural-gas-operation.pdf.

[87] Lloyd's Register, "Engine retrofit report 2023: Applying alternative fuels to existing ships," 2023.

[88] P. Kampylis, "An Environmental, Technical and Economical Approach for the Use of Shore-Power in Piraeus Port," 9 June 2016. [Online]. Available: http://dx.doi.org/10.26240/heal.ntua.12756.

[89] Britannica, "The steamboat," [Online]. Available: https://www.britannica.com/technology/ship/The-steamboat.

[90] C. Nunez, "National Geographic," 13 May 2019. [Online]. Available:

https://www.nationalgeographic.com/environment/article/greenhouse-gases.

[91] Clear Seas, 2022. [Online]. Available: https://clearseas.org/en/air-pollution/.

[92] K. Yiğit, “Evaluation of energy efficiency potentials from generator operations on vessels,” 15 October 2022. [Online]. Available: https://doi.org/10.1016/j.energy.2022.124687.