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Decarbonization Analysis of Shipping: Regulatory Challenges and the transition of Marine Diesel Engines.

Diploma Thesis

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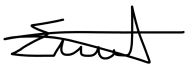
DECLARATION OF AUTHORSHIP

I hereby declare that I am the author of this diploma thesis and that, in the text I submit, I have explicitly and specifically cited or referenced all sources from which I have used data, ideas, or text, whether quoted verbatim (in the original or in translation) or paraphrased. I further declare that this work has been prepared personally by me, in the context of carrying out my diploma thesis.

THE DECLARANT



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Abstract

This thesis examines the decarbonization process of the maritime sector through a comprehensive analysis of global and regional legislative frameworks, particularly those established by the European Union, that promote the transition toward alternative fuels with lower environmental impact. The study outlines the main international and European policies shaping the path toward sustainable shipping, with particular emphasis on the regulatory mechanisms that encourage the reduction of greenhouse gas emissions and the adaptation of marine diesel engines to new fuel technologies. Furthermore, the thesis presents and analyses the emission calculation methodology and the FuelEU model, which assess compliance performance and determine the potential imposition of penalties based on emission levels and the types of fuels employed. In addition, selected case studies are examined to demonstrate the practical application of the FuelEU mechanism and to evaluate how different engine configurations and fuel choices influence emission outcomes and regulatory compliance within the framework of maritime decarbonization.

Περίληψη

Η παρούσα διπλωματική εργασία εξετάζει τη διαδικασία απανθρακοποίησης της ναυτιλίας μέσω μιας ολοκληρωμένης ανάλυσης του διεθνούς και ευρωπαϊκού νομοθετικού πλαισίου που προωθεί τη μετάβαση σε εναλλακτικά καύσιμα με μειωμένο περιβαλλοντικό αποτύπωμα. Παρουσιάζονται οι κυριότερες διεθνείς και ευρωπαϊκές πολιτικές και κανονισμοί που διαμορφώνουν την πορεία προς μια πιο βιώσιμη ναυτιλία, με ιδιαίτερη έμφαση στους μηχανισμούς που αποσκοπούν στη μείωση των εκπομπών αερίων του θερμοκηπίου και στην προσαρμογή των ναυτικών μηχανών εσωτερικής καύσης στις νέες τεχνολογίες καυσίμων.

Στο πλαίσιο αυτό, αναλύονται οι βασικές αρχές λειτουργίας των κινητήρων διπλού καυσίμου, καθώς και οι προκλήσεις και οι προοπτικές που συνδέονται με τη χρήση εναλλακτικών καυσίμων, όπως το υγροποιημένο φυσικό αέριο, η μεθανόλη και η αμμωνία. Παράλληλα, παρουσιάζεται η μεθοδολογία υπολογισμού των εκπομπών αερίων του θερμοκηπίου σύμφωνα με τις απαιτήσεις του κανονισμού FuelEU Maritime, καθώς και το μοντέλο αξιολόγησης συμμόρφωσης που χρησιμοποιείται για τον προσδιορισμό πιθανών κυρώσεων σε περίπτωση υπέρβασης των προβλεπόμενων ορίων εκπομπών.

Τέλος, εξετάζονται επιλεγμένες μελέτες περίπτωσης με στόχο την πρακτική εφαρμογή του μηχανισμού FuelEU Maritime και την αξιολόγηση της επίδρασης διαφορετικών τύπων καυσίμων και τεχνολογιών πρόωσης στις εκπομπές αερίων του θερμοκηπίου. Μέσω της ανάλυσης αυτής αναδεικνύεται ο ρόλος των κινητήρων διπλού καυσίμου ως μεταβατικής τεχνολογίας προς μια πιο βιώσιμη και περιβαλλοντικά φιλική ναυτιλία, καθώς και οι προκλήσεις που εξακολουθούν να υφίστανται όσον αφορά τη διαθεσιμότητα καυσίμων, τις υποδομές και την τεχνολογική ωριμότητα των νέων λύσεων.

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1.Introduction

The decarbonization of the maritime sector has emerged as one of the most complex yet crucial challenges in the global transition toward a climate-neutral economy. International shipping, which accounts for 2–3 % of global greenhouse gas emissions, represents the backbone of world trade, transporting around 90 % of goods by volume. Despite being one of the most energy-efficient modes of transport, the industry's heavy reliance on fossil fuels, mainly heavy fuel oil and marine diesel, makes it a emitter of carbon dioxide (CO_2), nitrogen oxides (NO_x), and sulfur oxides (SO_x). As global attention turns to meeting the goals of the Paris Agreement and achieving net-zero emissions by mid-century, shipping has come under growing regulatory, technological, and societal pressure to reduce its carbon footprint and align with broader climate objectives.

At the international level, the International Maritime Organization (IMO) has set the framework for maritime decarbonization through its Initial Green House Gas (GHG) Strategy adopted in 2018 and its Revised Strategy of 2023. These strategies outline the ambition to reduce total GHG emissions from international shipping by at least 20 % by 2030 and to reach net-zero by or around 2050. However, progress under the IMO framework has often been perceived as slower than required to meet global climate goals, prompting regional actors, most notably the European Union (EU), to take more decisive action. The EU has long been a frontrunner in climate policy, establishing a robust legal and regulatory framework to ensure the decarbonization of all transport sectors, including maritime. The introduction of the European Green Deal in 2019 marked a turning point, setting the overarching objective for the EU to achieve climate neutrality by 2050. To translate this ambition into legislative action, the Commission launched in July 2021 the Fit for 55 Package, a comprehensive set of policy measures aimed at reducing the EU's net GHG emissions by at least 55 % by 2030 compared with 1990 levels.

Within this package, shipping was, for the first time, brought squarely into the EU's climate architecture. The inclusion of maritime transport recognizes both its strategic role in European trade and its potential contribution to the Union's decarbonization pathway. The Fit for 55 Package comprises several interlinked legislative pillars that together reshape the operational, financial, and technological landscape of EU shipping. The EU Emissions Trading System (EU ETS), FuelEU Maritime Regulation, Renewable Energy Directive (RED III), Alternative Fuels Infrastructure Regulation (AFIR), and the revision of the Energy Taxation Directive (ETD) form the backbone of this integrated approach.

This thesis aims to unfold and clarify the complex network of environmental regulations and initiatives governing the maritime sector, in order to provide a comprehensive understanding of their content and to present a calculation methodology within the framework of decarbonization analysis. Through the detailed examination of each regulatory component and its specific objectives, a clearer understanding of the new regulatory framework and its functioning is achieved.

Furthermore, the inclusion of a calculation method offers deeper insight into how emissions are assessed under the new European regulation governing the maritime industry, namely FuelEU Maritime. After providing an overview of the wider efforts and initiatives toward the decarbonization of shipping, the thesis analyses in detail all the legislative "pillars" of the regulatory framework. Dual-fuel engines are increasingly regarded as a central pathway toward the maritime energy transition. By operating on alternative fuels, these propulsion systems have the potential to significantly reduce the environmental footprint of ships while also contributing to lower operating costs. This economic advantage arises not only from improved combustion efficiency, but also from the structure of emerging environmental regulations, which increasingly incentivize the use of low- and zero-carbon fuels through mechanisms such as carbon pricing and fuel-intensity limits.

The present analysis of dual-fuel engines is conducted from the perspective of a structured literature review. It provides a concise yet technically grounded overview of their operational capabilities and main design characteristics, with particular emphasis on the engine technologies most relevant to the near-term transformation of the shipping industry. Special attention is given to propulsion systems capable of utilizing liquefied natural gas (LNG), ammonia and methanol, as these fuels are widely regarded as the most prominent transitional or alternative solutions for reducing emissions in international maritime transport.

The literature review of the regulatory framework and innovative engine technologies is subsequently followed by a computational analysis of energy consumption, incorporating all potential reward factors where applicable, and concludes with findings concerning the imposition of penalties in cases of surplus or deficit.

Understanding these new regulations constitutes a fundamental step for the maritime sector, as it promotes the transition toward green growth, the use of clean and sustainable fuels, and the reduction of the industry's environmental footprint. Moreover, this thesis seeks to serve as a practical guide for maritime professionals by providing clear and direct answers to key questions related to the implementation of the new European legislative framework.

2.Literature Review of Regulatory Frameworks

2.1 Decarbonization of shipping

Maritime shipping is an essential pillar of global trade, transporting approximately 80–90 % of goods worldwide by volume. However, despite its efficiency in terms of tonne-kilometres per unit of energy, the sector remains a calculable source of GHG emissions, responsible for 2–3 % of global CO_2 emissions in recent years. In 2018, total international shipping emissions were estimated at around 1,076 Mt CO_2, representing an increase of nearly 10 % since 2012. Unlike most sectors, maritime transport emissions largely occur beyond national jurisdictions, making them difficult to allocate within traditional national carbon accounting systems under the United Nations Framework Convention on Climate Change (UNFCCC). Consequently, regulation of maritime emissions has been delegated primarily to the IMO, the United Nations' specialized agency responsible for maritime safety and environmental protection. In parallel, regional institutions such as the European Union have taken independent measures to accelerate maritime decarbonization, linking it to broader climate frameworks such as the European Green Deal and the ‘’Fit for 55” policy package [1].

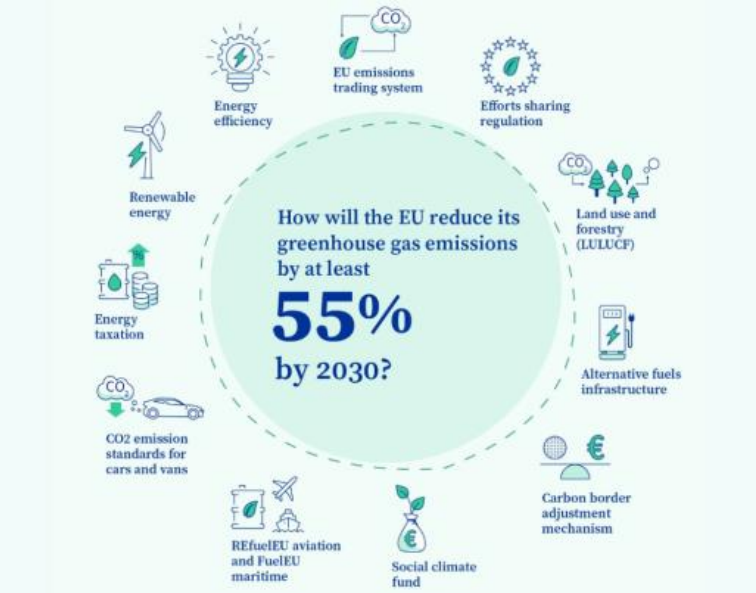

Figure 1: Fit for 55 targets

Retrieved from: https://build-up.ec.europa.eu/en/resources-and-tools/links/fit-55

Decarbonizing the maritime sector is essential if transport (and trade) is to align with the goals of the Paris Agreement and keep global warming well below 2 °C. However, the challenge is substantial: the sector must balance long asset lifetimes, fuel logistics, infrastructure constraints, safety considerations, and international coordination.

2.1.1 IMO initiatives

The IMO, established mid-20th century, initially focused on safety and pollution control (oil spills, sulfur oxides, nitrogen oxides) under conventions such as MARPOL (International Convention for the Marine Pollution from ships) and SOLAS (International Convention for the Safety of Life At Sea). Greenhouse gases (especially CO_2) were not a primary concern in earlier decades. From the early 2000s onward,

climate change pressures prompted the IMO to consider market-based mechanisms (MBMs) and emissions control, though consensus was elusive.

A pivotal shift occurred in 2011, when IMO adopted amendments to MARPOL Annex VI to introduce two complementary measures: the Energy Efficiency Design Index (EEDI) (mandatory for new ships) and the Ship Energy Efficiency Management Plan (SEEMP) (operational measures) for energy-efficiency improvements in existing vessels. These entered into force on 1 January 2013.

EEDI compels new ships above certain thresholds to meet a maximum CO_2 emission per transport work, varying by ship type and size, while SEEMP requires ships to implement energy-efficiency operational practices. Over time, revisions have strengthened these standards. Despite these advances, early IMO measures remained limited in ambition and scope, emphasizing intensity rather than absolute reductions or fuel switching. As climate urgency grew, the IMO began developing more robust GHG strategies and instruments.

In April 2018, the IMO's Marine Environment Protection Committee (MEPC) adopted the Initial Strategy on Reduction of GHG Emissions from Ships (MEPC.304(72))**,** anchoring 2008 as the baseline. The strategy set targets: reduce carbon intensity (CO_2 per transport work) by 40 % by 2030 and 70 % by 2050; additionally, it proposed to reduce total annual GHG emissions by at least 50 % by 2050 relative to 2008 levels. The 2018 strategy also recognized the need for technical, operational, and market instruments, capacity building, and cooperation (including for developing states). However, it lacked binding mechanisms and left much in the domain of further study and voluntary adoption.

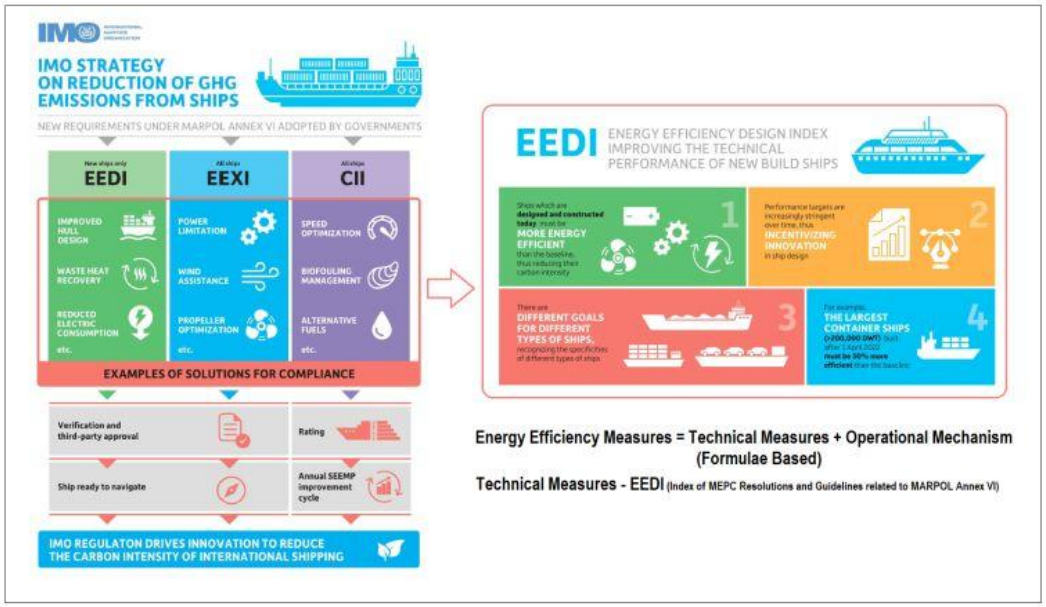

Figure 2: IMO strategy.

Retrieved from: https://www.imo.org/en/ourwork/environment/pages/improving%20the%20energy%20efficiency%20of%20ships.aspx

The successful implementation of any decarbonization strategy in maritime transport depends not only on ambitious regulatory frameworks but also on reliable, verifiable data. Without systematic monitoring of ships' fuel consumption and associated greenhouse gas emissions, the effectiveness of international and regional policies cannot be assessed or improved. Recognizing this need, IMO established the Data Collection System (DCS) for fuel oil consumption of ships through amendments to MARPOL Annex VI, adopted in October 2016 and entering into force on 1 March 2018 [2]. The DCS forms a cornerstone of the IMO's global monitoring architecture and provides the foundation for assessing progress toward the Organization's GHG reduction strategies (2018 and 2023). It also represents the global counterpart of the EU Monitoring, Reporting and Verification (MRV**)** mechanism, with which it shares common objectives but differs in scope and methodology.

The IMO DCS was established under Resolution MEPC.278(70), which amended Regulation 22A of MARPOL Annex VI.
Its primary objectives are:

- to collect consistent and reliable data on ships' annual fuel oil consumption;
- to enable the IMO to evaluate the carbon intensity of the world fleet and identify trends in energy efficiency;
- to support evidence-based policymaking for future GHG reduction measures; and
- to enhance transparency and comparability across the global shipping sector.

The system applies to all ships of 5 000 gross tonnage and above engaged in international voyages**,** regardless of flag, type, or fuel used. Ships operating solely on domestic voyages are exempt, as these fall under national jurisdiction.

Under the DCS, each ship must record specific parameters for every calendar year, including:

- Fuel oil consumption by fuel type (in metric tonnes);
- Distance travelled (in nautical miles);
- Hours underway; and
- Technical identifiers (ship type, gross tonnage, engine power, etc.).

Unlike the EU MRV system, which requires monitoring of CO_2 emissions**,** cargo carried, and transport work, the DCS focuses on fuel consumption data as the key input for calculating emissions using standardized conversion factors [3].

The data are aggregated at the ship level and reported annually to the vessel's flag State Administration or a Recognized Organization (RO) acting on its behalf. Once verified, these data are transmitted to the IMO, which maintains a global fuel oil consumption database**.** This database underpins the periodic IMO GHG Studies (e.g., the Fourth IMO GHG Study 2020 [4]).

In July 2023, the IMO adopted a revised 2023 IMO Strategy on Reduction of GHG Emissions from Ships**,** replacing the initial strategy with stronger ambition and clearer pathways. Key elements include:

- A reaffirmed vision that global shipping should achieve net-zero GHG emissions ''by or around 2050," with recognition of a just transition.
- A binding target to reduce carbon intensity across international shipping (CO_2 per transport work) by at least 40 % by 2030 (relative to 2008).
- A further aim that zero or near-zero GHG technologies/fuels should represent at least 5 % (striving for 10 %) of energy use by international shipping by 2030.
- Indicative checkpoints: reduce total annual GHG emissions by at least 20 % (striving for 30 %) by 2030, and by at least 70 % (striving for 80 %) by 2040 relative to 2008.
- A scheduled review of short-term efficiency measures by 1 January 2026, and an overarching strategy review by 2028.

The 2023 strategy also emphasizes supportive measures: capacity building, technical cooperation, governance frameworks, and avoiding emissions shifting to other sectors [5].

In 2025, the IMO advanced a Net-Zero Framework, combining a mandatory marine fuel standard with a global emissions pricing mechanism for large ships (over 5,000 gross tonnage). The framework was approved in draft form at MEPC 83 (April 2025), pending formal adoption and entry into force (likely 2027).

However, on October 2025, Member States have not reached full consensus on the final structure, implementation details, and revenue allocation mechanisms. Consequently, the framework remains subject to political negotiation and technical refinement.

Under the framework:

- Ships exceeding emission thresholds must pay fees (or purchase remedial units), while ships below thresholds may obtain credits.
- The revenues would be accumulated in an IMO Net-Zero Fund, intended to support decarbonization projects (especially in developing countries).
- These measures would be integrated into a new Chapter 5 of MARPOL Annex VI, making them legally binding for applicable ships.
- The framework is expected to capture approximately 85 % of international shipping CO_2 emissions by targeting large ocean-going vessels.
- This combined fuel standard and pricing approach represents the first globally binding carbon regulation for an entire industry sector [6].

2.1.2 European Union's framework

In the EU, maritime transport (intra-EU voyages and international shipping to/from EU ports) accounts for approximately 3–4 % of total EU CO_2 emissions (e.g. about 124 Mt CO_2 in 2021). Under the European Green Deal and the net-zero target by 2050, all sectors, including shipping, must reduce emissions. The "Fit for 55" package (2021) set the stage for ambitious climate policies toward 2030 (55 % GHG reduction from 1990 levels), including mechanisms targeting transport, energy, and emissions trading. Because international shipping largely lies outside national jurisdictions, the EU opted to regulate emissions via its control over ports, ship operations in its waters, and regulatory oversight [7], [8].

The EU MRV Regulation 2015/757 was a first step, entering into force in 2018. It requires ships above 5,000 gross tonnage calling at EU ports to monitor and report CO_2 emissions, fuel consumption, cargo, and distance. Member states verify the data. This regime enhanced transparency, data availability, and emissions accounting. From 2024 onward, MRV scope expands to include methane (CH_4) and nitrous oxide (N_2O), aligning with the broader GHG accounting approach.

A major shift occurred when the EU extended the EU ETS to maritime transport beginning in January 2024.

- Ships ≥ 5,000 gross tonnage must surrender allowances for CO_2 emissions on voyages between EU ports (100 % coverage) or between EU and non-EU ports (50 % coverage).
- From 2024, only CO_2 is covered; inclusion of CH_4 and N_2O is to be phased in from 2026.
- Operators must monitor emissions, surrender allowances, and comply with the declining cap on allowances.
- In the first year (2024), operators must surrender allowances equal to 40 % of emissions; the share increases over time (e.g., 70 % for 2025). By 2026, full surrender (100 %) is required.
- The inclusion pushes shipping operators calling in EU ports to internalize the cost of emissions and shift toward cleaner fuels or mitigation.

FuelEU Maritime (Regulation (EU) 2023/1805) is another cornerstone of EU maritime decarbonization. It applies from 1 January 2025 (with monitoring rules partly active from August 2024. Its principal features:

- It places well-to-wake lifecycle GHG intensity limits on the fuels used by ships in EU waters or calling at EU ports.
- The regulation defines a pathway of gradually tightening intensity limits (e.g. 2 % reduction in 2025, rising over time) with ambitious long-term reductions (up to 80 % by 2050 vs. 2020 levels).
- Ships that do not comply must pay a penalty or contribute equivalent compensation.
- FuelEU aims to stimulate adoption of renewable and low-carbon marine fuels and ensure consistent demand signals within the EU internal market [9], [10].

2.2 Fit For 55

The European Union has launched one of its most ambitious and innovative initiatives in recent years, aiming to significantly reduce greenhouse gas emissions and move towards a climate-neutral future. This commitment became legally binding with the enforcement of the European Climate Law in July 2021. The law forms a cornerstone of the European Green Deal, which is the Union's overarching growth and environmental strategy. Within this framework, the Fit for 55 package has been introduced as the central mechanism to ensure that the EU reduces its net GHG emissions by at least 55 percent by the year 2030, using 1990 as the reference baseline, and to achieve full climate neutrality by 2050. By adopting this legislation, the Member States of the EU have not only set ambitious national and regional goals but have also

signaled their determination to lead the global transition toward a sustainable future and to act decisively against climate change.

The Fit for 55 package is therefore much more than a single piece of legislation; it is a comprehensive framework that translates the aspirations of the European Green Deal into concrete actions. It represents the means through which the strategy for a greener and more sustainable Europe is put into practice. The package is composed of numerous legislative proposals that have been carefully discussed, negotiated, and agreed upon among EU institutions and Member States. Its central objectives are to secure a socially fair and equitable transition, to guarantee the long-term competitiveness of European industries in an increasingly decarbonized global economy, and to establish the EU as the world's leader in the transition toward climate neutrality. In order to realize these objectives, the package introduces a broad range of policies and mechanisms that collectively aim to accelerate the pace of emission reductions and ensure that environmental, social, and economic dimensions are addressed simultaneously [11].

To meet the climate objectives for 2030, the Fit for 55 package introduces reforms across virtually every sector of the economy. Among the most significant measures are the expansion and strengthening of the Emissions Trading System (ETS), which is extended to new sectors of activity, and the more ambitious promotion of renewable energy at a large scale across the continent. Furthermore, the package includes systemic improvements in energy efficiency that are intended to reduce energy consumption without compromising growth and prosperity. In parallel, it places particular emphasis on the decarbonization of the transport sector, which has historically been one of the most challenging areas for emission reduction. This involves supporting the adoption of low-emission transport technologies, promoting the development of sustainable fuels, and ensuring that adequate infrastructure is in place for their use. In addition, the package harmonizes energy taxation with the principles of the European Green Deal, introduces instruments to prevent carbon leakage, and reinforces mechanisms designed to conserve, restore, and enhance natural carbon sinks, which remain essential for offsetting unavoidable emissions [12].

Because transport is one of the largest contributors to emissions within the European Union, extending the Fit for 55 measures to this sector has major implications, particularly for maritime transport. The shipping industry alone accounts for around 13.5 percent of the EU's total transport-related emissions, which makes it a central target for new policy measures. The legislative framework seeks to minimize GHG emissions from maritime activities by promoting the gradual and systematic use of sustainable fuels. To this end, the EU Emissions Trading System has been extended to cover the shipping industry. The ETS is a market-based mechanism that operates under a cap-and-trade principle. A cap is placed on the total amount of CO_2 emissions that may be produced, and this cap is progressively lowered over time, creating increasing pressure for emission reductions. Companies are required to hold European Union Allowances (EUAs) equivalent to their verified emissions, and these allowances can be bought, sold, and traded on the carbon market, creating an economic incentive to reduce emissions. Alongside this, the Energy Taxation Directive (ETD) has been revised to ensure that fuels with higher carbon intensity are subject to higher taxation rates, while sustainable and renewable alternatives are incentivized through lower taxation. This dual approach combines market mechanisms with fiscal policy to guide the maritime industry towards decarbonization.

Perhaps the most significant and far-reaching proposal for the maritime sector within the Fit for 55 framework is FuelEU Maritime. This initiative directly addresses the fuel mix used by ships and obliges vessels above 5,000 gross tonnage that call at EU ports to progressively decrease their GHG intensity. The reduction targets increase gradually over time, leading up to an overall decrease of 80 percent by the year 2050. At the same time, FuelEU requires vessels to make use of onshore power supply while berthed, in order to minimize emissions during port stays. Importantly, the regulation also applies to voyages that either start or end in an EU port, even when the other end of the voyage is located in a third country. In such cases, 50 percent of the emissions are counted under the regulation. To ensure transparency and enforceability, companies must monitor, report, and verify the emissions of each ship individually. Non-compliance results in the imposition of financial penalties, which are designed to be significant enough to discourage avoidance and ensure that compliance is the economically rational choice [13], [14].

The successful implementation of FuelEU Maritime and the broader Fit for 55 framework requires the parallel development of supply chains and infrastructure that can support the uptake of sustainable fuels. This is where the Renewable Energy Directive (RED) and its revised version, RED III, come into play. These directives set binding targets for the share of renewable energy in the EU energy mix and establish clear definitions of which fuels qualify as renewable or low-carbon, together with strict sustainability and GHG reduction criteria. FuelEU Maritime creates the demand for cleaner fuels, but it does not itself specify which fuels are sustainable. This task is carried out by RED and RED III, which ensure consistency, legal certainty, and environmental integrity across the Union [15].

The transition to renewable and low-carbon fuels in the shipping sector also requires extensive infrastructure development, which is the central purpose of the Alternative Fuels Infrastructure Regulation (AFIR). AFIR establishes binding targets for the deployment of infrastructure that will enable the uptake of sustainable energy sources. For the maritime sector, this includes ensuring that onshore power supply facilities are available in all major EU ports by 2030, thereby supporting compliance with FuelEU requirements. In addition, AFIR encourages and facilitates the development of refueling and bunkering infrastructure for liquefied natural gas (LNG) and renewable fuels, ensuring that vessels have practical access to alternative energy sources across the European maritime network [16].

Taken together, the Fit for 55 package, FuelEU Maritime, ETS, RED III, and AFIR form a coherent set of interlinked policies that not only impose obligations on ship operators but also create the conditions necessary for the successful transition of the maritime industry toward decarbonization. By combining legislation on emissions reduction, fuel sustainability, taxation, and infrastructure, the European Union has established a comprehensive framework that addresses both the demand and supply sides of the energy transition in shipping.

2.3 European Trading System

The European Union Emissions Trading System, often described as the cornerstone of the Union’s climate policy, represents one of the most important and effective instruments for achieving gradual and sustained reductions in greenhouse gas emissions. It is structured as a cap-and-trade carbon market, under which industries that

fall within its scope are legally obliged to account for and financially compensate their emissions. In practice, this means that companies must pay for the amount of pollution they generate, thereby internalizing the environmental costs of their activities. The revenues generated through this system are subsequently reinvested to support a fair, sustainable, and socially inclusive green transition across the Member States.

The central principle of the ETS lies in the concept of the "cap." This cap sets a maximum limit on the total volume of GHG emissions permitted across the participating sectors, and the limit is progressively reduced on an annual basis to ensure alignment with the EU's climate targets—namely, a 55 percent reduction of emissions by 2030 (compared to 1990 levels) and net zero emissions by 2050. The cap is operationalized through the allocation of EUAs, each of which entitles its holder to emit one tonne of carbon dioxide equivalent (CO_2-eq). Companies regulated under the ETS must monitor, report, and verify their emissions annually. These emissions include not only CO_2 but also other powerful greenhouse gases such as N_2O and perfluorocarbons (PFCs), which can be measured with a high degree of accuracy. To remain compliant, companies must surrender an equivalent number of EUAs to match their verified emissions. Failure to do so results in substantial financial penalties, thereby creating a strong deterrent against non-compliance.

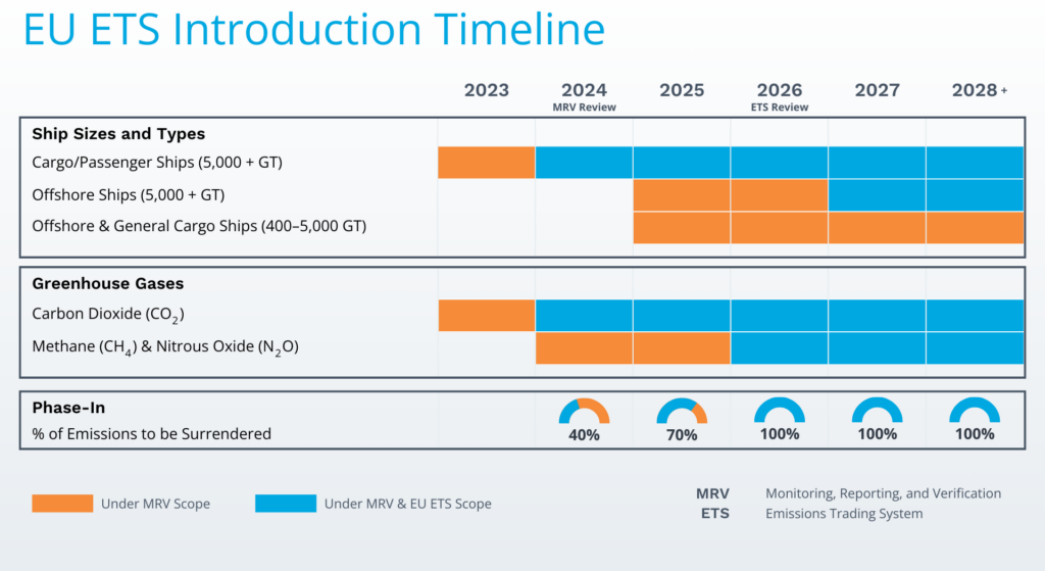

Figure 3: EU ETS mechanism.

Retrieved from: https://www.imo.org/en/ourwork/environment/pages/improving%20the%20energy%20efficiency%20of%20ships.aspx

Because the annual cap on emissions is continually reduced, the number of allowances available on the market also decreases over time. This deliberate scarcity exerts increasing pressure on industries with high emissions to adopt cleaner and more efficient technologies. At the same time, firms that successfully implement low-carbon innovations and reduce their emissions below their allocated threshold may accumulate surplus allowances. Such companies can either sell their excess EUAs on the carbon market, thereby generating additional revenue, or hold them in reserve for future compliance periods. The price of allowances is determined by supply and demand in

the EU carbon market, which operates under strict oversight rules to guarantee transparency, fairness, and equitable participation. Importantly, the revenues from the EU ETS are redistributed back to the Member States, where they are used to finance renewable energy initiatives, improve energy efficiency, and accelerate the development of low-carbon technologies [17].

In 2023, the ETS was revised and significantly strengthened in order to accelerate the pace of emission reductions. Under the revised framework, the overall ambition has been raised to a 65 percent reduction of emissions by 2030, compared with 2005 levels. A central element of this reform was the extension of the ETS to the maritime transport sector, which came into effect in 2024. This extension reflects the EU's commitment to ensuring that all major polluting industries, including those previously exempt, contribute to the achievement of the Union's climate neutrality goals.

The inclusion of shipping within the ETS applies to all vessels of 5,000 gross tonnage (GT) and above that call at EU ports, regardless of their flag of registration. The emissions covered by the ETS include 100 percent of those generated on voyages between two EU ports, as well as 50 percent of those produced on voyages where either the departure or arrival port is within the EU and the other port is located in a third country. In order to facilitate a smoother transition and to allow companies time to adapt, the obligations for shipping companies have been phased in gradually. Specifically, shipping companies are required to surrender allowances corresponding to 40 percent of their verified emissions for 2024 (to be reported in 2025), 70 percent for emissions generated in 2025, and the full 100 percent from 2027 onwards.

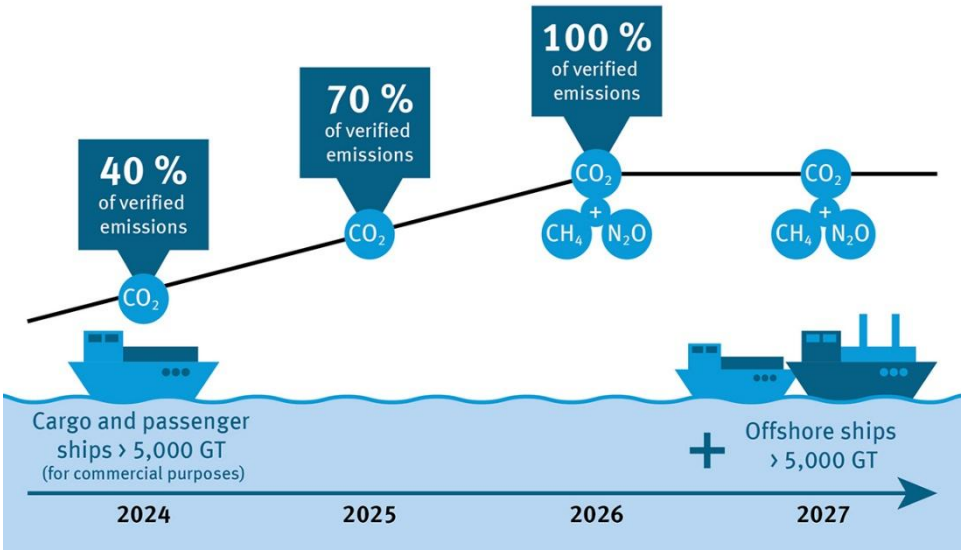

Figure 4: Gradual Implementation of EU ETS.

Retrieved from: https://www.dehst.de/EN/Topics/EU-ETS-1/Maritime-Transport/EU-ETS-1-Maritime-Transport/eu-ets-1-maritime-transport_artikel.html

This phased approach reflects the EU's recognition of the challenges facing the maritime sector, while still ensuring that progress towards decarbonization is maintained. By creating a direct financial cost for carbon emissions, the framework provides a clear economic incentive for shipping companies to invest in more efficient

operations, adopt alternative fuels such as biofuels, LNG, methanol, or hydrogen-based solutions, and deploy advanced energy-saving technologies. Furthermore, because EUAs can be traded, the system promotes cost-effective emissions reductions across the sector by allowing companies with lower abatement costs to sell allowances to those facing higher costs. In this way, the ETS supports innovation while ensuring overall environmental effectiveness.

The extension of the EU ETS to maritime transport is therefore regarded as a significant milestone. It represents the first time that the shipping industry, which is often described as one of the last major sectors not subject to carbon pricing, has been comprehensively integrated into the EU's climate policy framework. Beyond its immediate impact on emissions, this move is also intended to set an international precedent by demonstrating how carbon markets can be successfully applied to maritime transport. Ultimately, it aligns the shipping sector with the broader decarbonization pathways of the European Union and reinforces its commitment to achieving long-term climate neutrality [18].

2.4 Renewable Energy Directive

The Renewable Energy Directive designed to increase the contribution of renewable energy sources within the overall energy mix of Member States and thereby reduce GHG emissions in line with the Union's climate commitments. Since its initial adoption, the directive has been revised several times in order to raise its level of ambition and ensure consistency with the EU's evolving climate and energy objectives. The first version of the directive, adopted in 2009, established a binding target requiring that by 2020 at least 20 percent of the EU's gross final energy consumption originate from renewable sources, alongside a specific sub-target of 10 percent renewable energy use in the transport sector. These obligations marked a historic turning point, as they were the first binding EU-wide targets designed to push Member States toward the adoption of renewables on a large scale.

The adoption of RED in 2009 was widely regarded as a pioneering step in Europe's transition to a more sustainable energy system. For the first time, Member States were compelled to restructure their energy markets, integrate renewable sources such as wind, solar, and bioenergy into their electricity grids, and actively promote the use of renewables in heating, cooling, and transport. In this sense, RED 2009 created the foundation for the Union's long-term decarbonization trajectory, while also contributing to energy security and the reduction of dependence on imported fossil fuels.

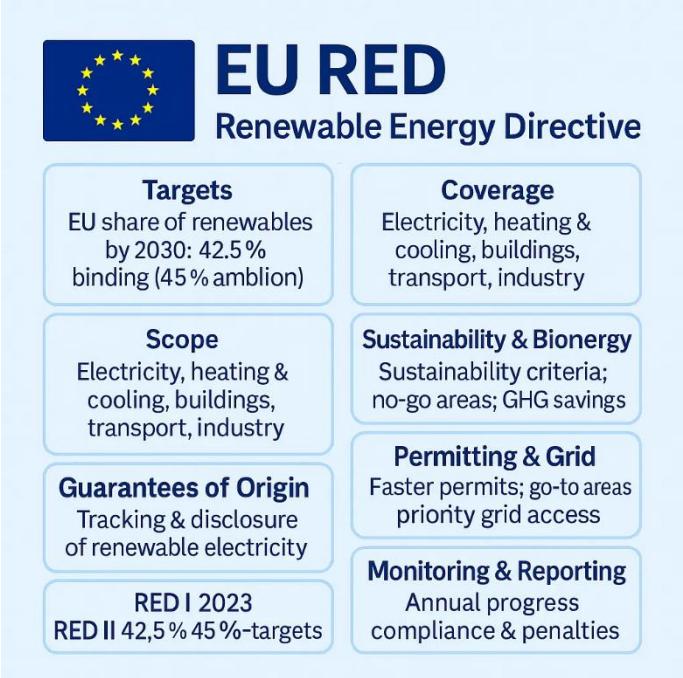

Figure 5: Scope of RED and its goals.

Retrieved from: https://zeroemissionshub.com/red-renewable-energy-directive/

The first major revision of the directive, commonly known as RED II, was adopted in 2018 as part of the broader Clean Energy for All Europeans package. RED II significantly raised the Union's climate ambition by setting a binding EU-wide target of at least 32 percent renewable energy in final energy consumption by 2030, with a sub-target of 14 percent specifically for the transport sector. Importantly, RED II introduced stricter sustainability criteria for biofuels, bioliquids, and biomass fuels, as well as measures to mitigate indirect land-use change (ILUC) effects associated with bioenergy production. These provisions sought to ensure that the expansion of renewable energy would not inadvertently lead to environmental or social harms, such as deforestation or food security issues. RED II also established a certification scheme to verify sustainability and greenhouse gas savings, thereby increasing transparency and accountability across the renewable energy supply chain. Moreover, it recognized the central role of renewables in decarbonizing road and rail transport, while simultaneously promoting research, innovation, and deployment of advanced biofuels derived from non-food feedstocks.

With the announcement of the Fit for 55 package, the European Union raised its climate ambition even further, which necessitated an update of the directive. The most recent revision, RED III, was adopted in 2023 and introduced substantially higher binding targets for 2030. Under RED III, the overall share of renewable energy in the EU's energy mix must reach at least 42.5 percent, with a legally non-binding aspirational target of 45 percent. In transport, the target was increased to 29 percent renewable energy use by 2030, more than doubling the ambition compared to RED II. This revision clearly reflects the Union's recognition of the urgency of decarbonizing hard-to-abate sectors such as aviation and shipping, which have historically lagged behind road and rail in renewable energy uptake.

RED III introduced not only higher numerical targets but also new qualitative requirements. It tightened the sustainability and greenhouse gas reduction criteria applied to biofuels, introduced mandatory traceability provisions through mass-balance systems, and established robust certification mechanisms to ensure credibility of renewable energy claims. Particular emphasis was placed on renewable fuels of non-biological origin (RFNBOs), such as green hydrogen and synthetic fuels, which are expected to play a crucial role in the EU's transition to a climate-neutral economy. By explicitly prioritizing these fuels, RED III positions them at the center of Europe's strategy to decarbonize sectors where direct electrification is either technologically or economically infeasible.

The maritime sector, traditionally considered one of the most challenging industries to decarbonize due to technological, economic, and logistical constraints, has been directly integrated into the RED III framework. A notable provision of RED III obliges Member States to guarantee the availability of renewable and low-carbon fuels at maritime ports. This requirement creates the supply-side conditions necessary for ships to access alternative fuels such as advanced biofuels, LNG, green ammonia, and hydrogen-based fuels. This is a critical step in ensuring that shipping companies can comply with other regulatory initiatives, particularly the FuelEU Maritime Regulation, which imposes demand-side obligations by setting progressive limits on the greenhouse gas intensity of fuels used on board vessels. In this way, RED III and FuelEU Maritime operate as complementary instruments: the former ensures that sufficient volumes of certified renewable fuels are produced and supplied, while the latter guarantees that the shipping industry uses them.

Another important innovation under RED III is the legal requirement for full traceability of renewable fuels. By implementing digital certification systems and mass balance accounting methods, the directive ensures that sustainability claims are verifiable at each stage of the supply chain, from production to end use. This transparency is particularly significant for the maritime sector, where accountability for fuel use has historically been limited and where international voyages complicate regulatory oversight. By mandating such traceability, RED III increases confidence in the integrity of the renewable fuels market and reduces the risk of greenwashing.

Overall, the Renewable Energy Directive and its revisions—RED, RED II, and RED III—reflect the European Union's progressively increasing ambition to transform its energy systems in line with climate neutrality objectives. RED III, in particular, represents a decisive evolution of the framework by embedding stringent renewable energy and GHG reduction targets that explicitly extend to maritime transport. Through the promotion of sustainable marine fuels, the provision of supportive infrastructure at ports, and the introduction of robust certification mechanisms, RED III plays a crucial role in facilitating the decarbonization of one of the most difficult sectors to regulate. When combined with complementary legislation such as the FuelEU Maritime Regulation and the Alternative Fuels Infrastructure Regulation (AFIR), RED III forms part of an integrated and interdependent regulatory landscape that compels the shipping industry to innovate, invest, and adapt. In this way, the directive not only advances the EU's climate policy objectives but also reshapes the

strategic priorities of maritime stakeholders, making sustainability and accountability essential pillars of the sector's future development [19], [20].

2.5 Alternative Fuels Infrastructure

The Alternative Fuels Infrastructure Regulation constitutes a fundamental element of the European Union's regulatory framework for decarbonizing the transport sector, including maritime transport. Adopted as part of the wider Fit for 55 package, AFIR replaces earlier directive-based approaches with a regulation that sets binding and directly applicable rules across all EU Member States. This shift from directives to regulation eliminates variations in national transposition and guarantees a uniform level of ambition throughout the Union. AFIR's primary objective is to ensure that transport systems across Europe are equipped with the necessary infrastructure to transition away from fossil fuels and adopt alternative, low- and zero-carbon energy sources. This is essential not only for the achievement of the EU's climate targets but also for fulfilling international obligations under agreements such as the Paris Agreement [21].

AFIR addresses the transport sector in a comprehensive and integrated manner. It covers road, rail, aviation, and maritime transport, setting minimum requirements for the availability of charging points, refueling stations, and shore-side electricity supply. By making these requirements legally binding in all Member States, AFIR promotes harmonization and creates a level playing field for investment in alternative fuels infrastructure. This approach contrasts sharply with earlier directives, which allowed national discretion in implementation and thus often led to fragmented progress across the Union.

With respect to maritime transport, AFIR introduces transformative obligations. All major EU seaports, and particularly those forming part of the Trans-European Transport Network (TEN-T), must ensure the deployment of Onshore Power Supply (OPS) facilities for seagoing container and passenger vessels above 5,000 gross tonnage by 2030. The regulation stipulates that at least 90 percent of port calls by the specified vessel categories must have access to OPS by this deadline. This measure is specifically designed to reduce emissions of both greenhouse gases and local air pollutants produced by ships while berthed. Traditionally, vessels at port rely on auxiliary engines powered by fossil fuels, which emit not only CO_2 but also nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter that contribute to air quality degradation in coastal and urban areas. By mandating OPS availability, AFIR directly addresses this issue, enabling vessels to switch to clean grid electricity while at berth and significantly reducing their environmental footprint.

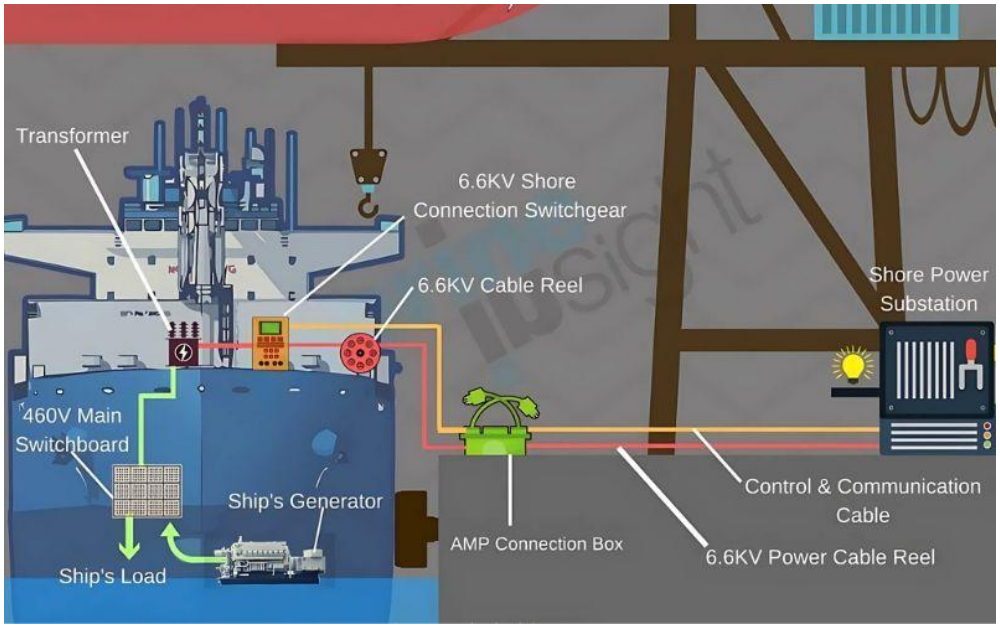

Figure 6: Onshore Power supply.

Retrieved from: https://www.marineinsight.com/understanding-onshore-power-supply/

Beyond OPS, AFIR also establishes requirements for the deployment of bunkering infrastructure for a wide range of alternative marine fuels. These include LNG, green hydrogen, ammonia, and methanol, all of which are considered promising options for the decarbonization of shipping. By obliging Member States to prepare national plans for the roll-out of such infrastructure, AFIR ensures that vessels adopting alternative propulsion technologies will have the logistical support and refueling capacity needed to operate at scale across European waters. In doing so, the regulation seeks to eliminate one of the main barriers to the adoption of alternative fuels in shipping: where shipowners are reluctant to invest in vessels using new fuels without guaranteed supply infrastructure, while fuel suppliers are unwilling to invest in infrastructure without sufficient demand from ships.

AFIR therefore represents a comprehensive and forward-looking strategy to "future-proof" European ports. Its design acknowledges that decarbonization will not rely on a single technological pathway but rather a combination of solutions, including electrification at berth and the uptake of diverse alternative fuels. This dual focus on electricity and renewable liquid or gaseous fuels provides flexibility for shipowners, port authorities, and fuel suppliers, while ensuring that the Union remains on track to meet its ambitious climate objectives.

Furthermore, AFIR is closely interconnected with other elements of the Fit for 55 package, particularly the FuelEU Maritime Regulation. While FuelEU Maritime creates market demand for clean fuels and requires the use of OPS by ships during port stays, AFIR guarantees the availability of the corresponding supply infrastructure. In this way, the two instruments operate in tandem: FuelEU imposes obligations on shipowners and operators on the demand side, while AFIR addresses the supply side by mandating infrastructure deployment at ports. Together, these measures create a coherent

regulatory environment that reduces uncertainty for investors and accelerates the maritime sector's transition towards low- and zero-carbon fuels [22].

2.6 Energy Taxation Directive

The Energy Taxation Directive, originally established as Directive 2003/96/EC, provides the European Union's legislative framework for the taxation of energy products and electricity. At the time of its adoption, the ETD was primarily intended to harmonize national energy taxation rules, prevent distortions in the internal market, and ensure fair competition among Member States. Over time, however, the directive has assumed a broader role, becoming an important regulatory tool for influencing patterns of energy consumption, promoting the uptake of cleaner fuels, and supporting the Union's overarching climate and energy transition objectives. In particular, the ETD has acquired renewed significance in the context of the European Green Deal and the Fit for 55 package, both of which set ambitious targets for reducing GHG emissions and achieving climate neutrality.

Nevertheless, since its adoption in 2003, the policy landscape within the EU has changed radically. The Union's climate ambition has become more stringent, while its energy system has undergone profound structural transformations. As a result, the original ETD is no longer aligned with the EU's current decarbonization strategy, nor is it sufficiently effective in ensuring the proper functioning of the internal market. One of the main criticisms of the existing framework is that it continues to favor fossil fuels through exemptions or reduced rates, thereby undermining the EU's climate goals. Moreover, the directive's reliance on volume-based taxation has often created inconsistencies, as it fails to reflect the energy content or environmental impact of different fuels.

In recognition of these shortcomings, the European Commission tabled a proposal in 2021 for a comprehensive revision of the ETD. The revision aims to fully align the directive with the objectives of the European Green Deal, thereby contributing to the Union's 2030 climate targets and the ultimate goal of climate neutrality by 2050. The proposal rests on three main pillars: first, aligning the taxation of energy products and electricity with EU energy, climate, and environmental policies; second, modernizing the scope and rate structure in order to safeguard and enhance the functioning of the internal market; and third, ensuring that the directive preserves its capacity to generate stable revenues for Member States' budgets.

To achieve these objectives, the revised ETD introduces a number of fundamental changes. Most importantly, it shifts the basis of taxation from volume to energy content, thereby ensuring that fuels are taxed more proportionately to the actual energy they provide and their environmental performance. This change corrects the distortion of the earlier system, under which fossil fuels could be taxed at rates that did not correspond to their true energy efficiency or climate impact. The revision also introduces a ranking system for energy products, categorizing them according to their environmental performance in line with other Fit for 55 proposals. Under this new system, conventional fossil fuels such as petrol and gas oil will be taxed at the highest rate, reflecting their significant contribution to greenhouse gas emissions.

The next tier of taxation applies to fossil-based fuels that are somewhat less harmful and may still contribute to decarbonization in the short and medium term. Examples include natural gas, liquefied petroleum gas (LPG), and fossil-based hydrogen. These fuels are to be taxed at two-thirds of the reference rate for a transitional period of ten years, after which their taxation will rise to the full reference rate. A further category is created for sustainable but not advanced biofuels, which are taxed at half of the reference rate in recognition of their partial contribution to reducing emissions. Finally, the lowest rate is reserved for electricity, regardless of end use, as well as for advanced biofuels, bioliquids, biogases, and hydrogen of renewable origin. This preferential treatment reflects their critical role in driving the EU's transition to a clean energy system and their potential to enable deep decarbonization across multiple sectors.

In addition, by phasing out subsidies and exemptions for fossil fuels, including those historically granted to the aviation and maritime sectors, the directive seeks to ensure that all industries contribute fairly to the Union's climate efforts. For maritime transport in particular, this represents a paradigm shift. Traditionally exempt from energy taxation, the sector will now face gradually increasing costs for fossil-based marine fuels such as heavy fuel oil (HFO) and marine gas oil (MGO), while benefiting from lower rates for renewable alternatives such as green ammonia, methanol, and hydrogen.

Through these reforms, the revised ETD complements other instruments within the Fit for 55 package, such as the EU ETS and the FuelEU Maritime Regulation. While the ETS introduces a carbon price through a cap-and-trade mechanism, and FuelEU sets progressive limits on the greenhouse gas intensity of fuels, the ETD reshapes the fiscal landscape by adjusting the relative costs of energy products in accordance with their climate impact. Together, these instruments form a coherent policy mix, ensuring that decarbonization is driven simultaneously by market signals, regulatory obligations, and fiscal incentives [23].

2.7 FuelEU Maritime

2.7.1 The FuelEU Maritime Regulation (EU 2023/1805)

The decarbonization of the maritime sector has emerged as one of the European Union's most pressing environmental priorities. As the shipping industry accounts for around 3% of global GHG emissions [24], achieving carbon neutrality by 2050 requires a major policy and technological transformation. The European Union, through its European Green Deal and the Fit for 55 legislative package, has positioned maritime transport at the centre of its broader decarbonization strategy.

The FuelEU Maritime Regulation (EU 2023/1805) was adopted in September 2023 as a key component of the Fit for 55 framework. Its purpose is to reduce the GHG intensity of the energy used on board ships by promoting the uptake of renewable and low-carbon fuels, incentivizing technological innovation, and ensuring a level playing field for all vessels calling at EU ports. The regulation complements other legislative pillars such as the EU ETS, the RED III, the AFIR, and the revised ETD.

FuelEU Maritime establishes rules to ensure that the GHG intensity of energy used on board ships gradually decreases over time. The regulation applies to all ships above 5,000 gross tonnage (GT) that call at EU ports, regardless of flag [25]. It covers:

- 100% of emissions from voyages between two EU ports (intra-EU voyages).
- 50% of emissions from voyages between an EU port and a non-EU port.
- Emissions occurring during a ship's stay at an EU port.

The reduction targets are set relative to a 2020 baseline as follows:

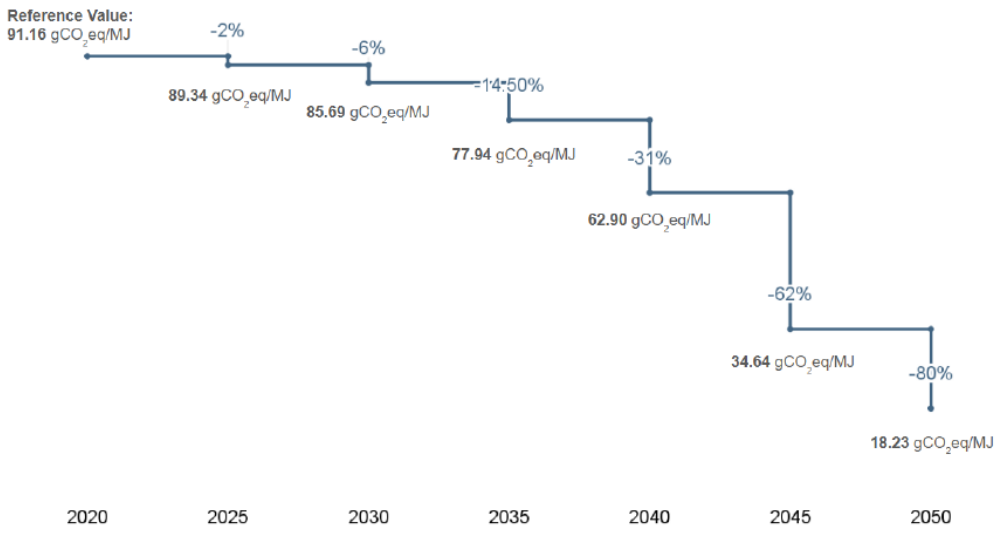

Figure 7: GHG Emission Intensity Limit of Energy Consumed on Board.

Retrieved from : European Sustainable Shipping Forum (ESSF)-Report on calculation of methodologies under Regulation (EU) 2023/1805 (FuelEU)

These reductions are measured according to the well-to-wake GHG intensity of the energy used. In practice, this means that both the upstream emissions (production and transport of fuel) and downstream emissions (combustion) are considered [26].

Ships must hold a valid FuelEU Document of Compliance (DoC), issued annually after verification by an accredited body. Non-compliance results in financial penalties, which are proportional to the amount of GHG intensity deviation (measured in gCO_{2eq}/MJ). The regulation also allows the transfer of compliance surpluses between ships within the same company (a "pooling mechanism"), providing flexibility for operators with diverse fleets [27].

2.7.2 Interaction with ETS, RED III, and AFIR

The FuelEU Maritime Regulation does not exist in isolation. It forms part of a policy ecosystem in which different legislative acts operate synergistically.

The EU ETS now includes shipping emissions from 2024 onwards, gradually phasing in coverage (40% in 2024, 70% in 2025, and 100% from 2026). While the ETS creates a carbon price signal for emissions, FuelEU sets the performance standard for fuels. This dual approach—price and regulation—ensures that operators face both economic and operational incentives to decarbonize [28].

The RED III, revised in 2023, complements FuelEU by setting binding national targets for renewable energy use, including in transport. It defines sustainability criteria for biofuels and RFNBOs. FuelEU relies on RED III's certification schemes (e.g., ISCC and RSB) to verify fuel sustainability [29].

The AFIR, also adopted under Fit for 55, ensures that ports and refueling stations can support the transition to new energy carriers such as LNG, methanol, hydrogen, and electricity. AFIR mandates the provision of on-shore power supply (OPS) for container and passenger ships at major EU ports by 2030, which directly supports compliance with FuelEU requirements on zero-emission operations at berth [30].

The ETD, which is still under revision, aims to remove the long-standing tax exemptions on marine fuels, aligning fiscal incentives with environmental goals. Together, these four instruments, ETS, RED III, AFIR, and ETD, form the legislative backbone of EU maritime decarbonization [31].

2.7.3 Alternative Fuels and Propulsion Technologies

Achieving the decarbonisation objectives of the FuelEU Maritime Regulation depends fundamentally on the development and commercial deployment of fuels with substantially lower greenhouse-gas intensity than conventional heavy fuel oil. The Regulation deliberately follows a technology-neutral philosophy, establishing GHG-intensity targets without prescribing which fuel or energy system must be used. This approach enables shipowners to pursue the most appropriate pathway according to vessel type, operational profile, and regional fuel availability.

- **Liquefied Natural Gas (LNG) and Bio-LNG**; currently represents the most mature transition fuel in the market. It can achieve around a 20 per cent reduction in CO_2 emissions relative to heavy fuel oil and contributes to lower sulphur-oxide and particulate-matter emissions. However, its overall climate performance is constrained by methane slip, unburned methane that escapes during engine operation or along the supply chain. Methane has a global-warming potential roughly 28 times higher than CO_2, meaning that even small leakages can offset combustion-stage benefits. To mitigate this risk, engine manufacturers are developing low-pressure dual-fuel engines and catalytic oxidation systems, while bio-LNG, produced from organic waste, offers a renewable variant that can meet stricter future intensity thresholds if properly certified under RED III sustainability criteria [32].
- **Methanol and E-Methanol**; Methanol has emerged as a strong contender for short- and medium-term compliance. It is liquid at ambient temperature, easy to handle, and requires limited modification of existing bunkering infrastructure When derived from renewable hydrogen and captured CO_2, so-called e-methanol, its well-to-wake emissions can be nearly carbon-neutral. Engine technology is rapidly progressing; several large shipyards have announced

methanol-ready designs across container, tanker, and bulk segments. Challenges remain regarding global supply chains, toxicity handling measures, and the high electricity demand associated with e-methanol synthesis, but the technology's operational maturity positions it as one of the earliest large-scale alternatives [28].

- **Ammonia (NH_3)**; Ammonia offers a carbon-free energy carrier that can be produced from green hydrogen via the Haber-Bosch process. Its combustion releases no CO_2, yet it introduces distinct safety concerns owing to its toxicity and corrosiveness. Additionally, ammonia combustion can generate nitrogen-oxide emissions, which must be controlled through selective catalytic reduction. Despite these issues, numerous joint-industry projects are testing ammonia-fueled engines and safety protocols, while DNV anticipates initial commercial deployments before 2030 in the deep-sea segment where high energy density is crucial [27], [32].
- **Hydrogen (H_2)**; Hydrogen represents the ultimate zero-carbon option at the point of use, with water as its only combustion by-product. It can power fuel-cell systems or modified internal-combustion engines. Nevertheless, its storage at either cryogenic temperatures (−253 °C) or very high pressure poses design and cost challenges. Liquefied hydrogen requires about four times the storage volume of conventional fuel, significantly influencing ship architecture. The European Commission views hydrogen primarily as a long-term solution, particularly for short-sea and passenger vessels operating between ports equipped with dedicated refueling infrastructure [33].
- **Biofuels and Renewable Diesel;** Advanced biofuels, derived from residues, waste oils, or lignocellulosic biomass, offer a near-drop-in alternative compatible with existing engines and logistics systems. Their sustainability depends on robust certification through schemes such as ISCC or RSB. Although limited by feedstock availability and competition with other sectors, biofuels can provide a critical bridge toward full decarbonisation in the 2020s and 2030s. Hydrotreated Vegetable Oil (HVO) and Fatty Acid Methyl Ester (FAME) are already accepted under the RED III framework and can be blended to meet incremental GHG-intensity targets [31].
- **E-fuels (RFNBOs);** E-fuels, renewable fuels of non-biological origin (RFNBOs), are synthesized by combining green hydrogen with captured carbon dioxide. Although they hold the greatest potential for deep decarbonization, current production costs remain high and depend heavily on renewable-electricity prices and electrolyser efficiency. According to DNV, large-scale deployment of RFNBOs in shipping will likely occur after 2035, once industrial clusters for e-fuel production reach maturity [26], [32].
- **Hybrid and Zero-Emission Technologies;** Beyond alternative fuels, the regulation recognises the contribution of propulsion innovations such as battery-hybrid systems, wind-assisted propulsion, and OPS. These technologies reduce fuel demand during port operations and improve overall energy efficiency. The AFIR ensures the progressive availability of OPS infrastructure across European ports by 2030, facilitating zero-emission operations while berthed [26].

2.7.4 Key Parameters and Definitions

A clear understanding of the core variables and definitions used in the FuelEU Maritime Regulation is essential for the accurate calculation of compliance and GHG intensity indicators. The following parameters are drawn from the Regulation itself and associated EU guidance documents.

Compliance Balance
The compliance balance quantifies whether a vessel surpasses or falls short of the annual GHG-intensity limit established for the energy consumed onboard. It reflects the vessel's degree of over- or under-performance relative to the average yearly target. The value is determined according to Part A of Annex IV *and* Article 3(35) of the FuelEU Maritime Regulation. This metric effectively measures how the ship's operational profile aligns with the prescribed emission-intensity boundaries and serves as the basis for potential penalties or credits.

E Value (Emission Value)
The E value denotes the verified GHG emission factor stated in the Proof of Sustainability (PoS), a document issued by an accredited fuel supplier under an EU-recognised certification scheme. It expresses the total well-to-wake (WtW) emissions in grams of CO_2 equivalent per megajoule (gCO_2eq/MJ), encompassing the emissions from both the supply and use of the fuel. Within FuelEU, this value functions as the reference emission factor for non-fossil and renewable fuels, facilitating the calculation of GHG-intensity compliance according to the sustainability criteria of the RED III.

Intra-EEA Voyages
For voyages entirely within the European Economic Area (EEA), the Regulation applies to all energy used throughout the voyage. This includes energy consumed between ports under EEA jurisdiction, energy used while the ship is at berth, and energy expended during port manoeuvres or repositioning between two voyages. By accounting for the complete operational cycle within EEA waters, the Regulation ensures consistent monitoring and reporting of all fuel-related emissions within Member State boundaries.

Extra-EEA Voyages
For voyages connecting an EEA Member State port with a third-country port (and vice versa), the FuelEU Maritime Regulation applies to 50% of the total energy used. This proportional treatment acknowledges the jurisdictional limits of EU law while maintaining fair representation of international voyages in the ship's compliance assessment. It prevents regulatory double-counting and ensures that only the share of activity linked to EU waters is included in GHG-intensity calculations.

GHG Intensity (Well-to-Wake Approach)
The GHG intensity represents the WtW greenhouse gas emissions generated per unit of energy used onboard, measured in grams of CO_2 equivalent per megajoule (gCO_2eq/MJ). It integrates all emissions produced along the entire lifecycle of the fuel, from raw material extraction through production and delivery to its final combustion within the vessel's engines.
This metric accounts for the primary greenhouse gases, CO_2, CH_4, and N_2O, each expressed in CO_2-equivalent terms using their 100-year global-warming-potential (GWP) factors. The *WtW* intensity is derived from two key components:

- Well-to-Tank (WtT) emissions**:** emissions from fuel extraction, production, and transport until it is onboard.
- Tank-to-Wake (TtW) emissions: emissions resulting from combustion or onboard usage, including methane slip and other fugitive discharges.

Together, these components provide a holistic measure of the climate impact of the fuel used and constitute the core of the FuelEU compliance calculation.

Lower Calorific Value (LCV)
The Lower Calorific Value expresses the usable energy content released during the complete combustion of a fuel, typically measured in megajoules per gram (MJ/g). It reflects the net amount of energy available for propulsion or onboard consumption, excluding the latent heat of water vapour formed during combustion. The LCV is an essential parameter in calculating the energy base used for GHG-intensity assessments and compliance balance evaluations.

Proof of Sustainability (PoS)
The Proof of Sustainability is an official declaration issued under an EU-approved voluntary certification scheme. It demonstrates that a fuel complies with the Renewable Energy Directive (RED II/III) sustainability requirements. The PoS includes verified data on the fuel's well-to-wake GHG emissions—expressed as an E value in gCO_2eq/MJ—and serves as the primary evidence used in FuelEU compliance verification for non-fossil fuels.

Proof of Compliance (PoC)
The Proof of Compliance is an alternative documentation method referenced in EU ETS and MRV guidance (document no. 18, SAPS WS2). It is used when the original PoS cannot be presented, often because it has been surrendered to fulfil national renewable-energy targets. The PoC provides equivalent sustainability and GHG-intensity information to substantiate compliance claims under the FuelEU Maritime Regulation.

Slip (Fugitive Emissions)
The term slip refers to uncombusted fuel escaping into the atmosphere during the combustion process or from leaks within the engine and fuel system. This phenomenon is particularly relevant to gaseous fuels such as LNG, where methane slip can significantly affect overall well-to-wake GHG performance. Effective engine design, regular maintenance, and the adoption of oxidation catalysts are therefore critical mitigation measures for reducing slip-related emissions [34].

3.Dual Fuel Engines

The continuous tightening of environmental regulations—particularly those that now directly influence vessel operations through the introduction of the EU ETS and FuelEU Maritime—has significantly altered fuel consumption economics and compliance strategies within the shipping sector. As a result, engine manufacturers and ship operators have increasingly turned toward the testing and gradual adoption of dual-fuel propulsion systems. These technologies are viewed as a transitional solution capable of enhancing regulatory compliance while maintaining operational flexibility.

As previously discussed, maritime transport remains a notable source of atmospheric pollutants, including SOx, NOx, and particulate matter (PM). Recent studies examining emission concentrations both in port areas and on a global scale indicate that approximately 50% of the NOx measured in regions adjacent to major ports can be attributed to marine engines. Furthermore, ocean-going vessels collectively account for an estimated 20 million tonnes of NOx, 10 million tonnes of SOx, and roughly one million tonnes of particulate matter annually.

With regard to greenhouse gases, maritime propulsion systems have been reported to contribute approximately 15% of global NOx emissions, 7% of SOx emissions, and about 3% of worldwide CO_2 emissions. These figures underscore the strategic environmental footprint of the shipping industry. Despite its substantial emission profile, the sector performs a disproportionately high volume of transport work relative to the pollutants generated, distinguishing it from many other industrial activities within the broader global economy [35], [36].

Taking into account both the environmental footprint of maritime transport and the particular sensitivity of certain coastal regions, the IMO, in cooperation with governments worldwide, introduced specific regulatory measures under Annex VI of MARPOL. These measures establish mandatory limits on nitrogen oxide NOx emissions from marine diesel engines through a tiered regulatory framework known as Tier I, Tier II and Tier III standards.

The Tier system defines progressively stricter NOx emission ceilings applicable to marine diesel engines with a power output exceeding 130 kW. As indicated on Fig. 8 engine classification depends primarily on the date of installation (or construction) and the engine's rated speed (rpm), which determines the corresponding emission limit curve. In this way, each engine is assigned to one of the three regulatory categories.

Tier I and Tier II standards apply on a global basis, forming the baseline NOx compliance framework for international shipping. In contrast, Tier III requirements are considerably more stringent and apply only when vessels operate within designated Nitrogen Oxides Emission Control Areas (ECAs). This geographically targeted approach reflects the need to provide enhanced environmental protection in regions where air quality and ecosystem vulnerability demand stricter controls.

Tier	Ship construction date on or after	Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm)		
		n < 130	n = 130 - 1999	n ≥ 2000
I	1 January 2000	17.0	$45.n^{-0.2}$ e.g., 720 rpm – 12.1	9.8
II	1 January 2011	14.4	$44.n^{-0.23}$ e.g., 720 rpm – 9.7	7.7
III	1 January 2016*	3.4	$9.n^{-0.2}$ e.g., 720 rpm – 2.4	2.0

Figure 8:Categories of Tier Emissions Standards.

Retrieved from : https://deckofficer.ru/news/item/meet-marpol

In addition to the global regulatory framework, certain maritime regions around the world have been designated as ECAs, where substantially stricter limits apply to both NOx and SOx. These areas have been established in response to heightened environmental sensitivity and air quality concerns, particularly in densely populated coastal zones.

Within ECAs, the maximum permissible sulphur content of marine fuel has been limited to 0.10% m/m since 1 January 2020. This requirement has effectively compelled vessels operating in these regions to switch to very low-sulphur distillate fuels, such as MGO, or to adopt equivalent compliance solutions. The stricter sulphur threshold aims to significantly reduce SOx emissions and associated particulate matter, thereby mitigating adverse impacts on human health and marine ecosystems.

At the global level, a sulphur cap of 0.50% m/m has been in force since 2020 under Annex VI of MARPOL. Compliance with this global limit typically involves the use of Very Low Sulphur Fuel Oil (VLSFO) or, alternatively, the installation of exhaust gas cleaning systems (scrubbers), which enable ships to continue operating on high-sulphur fuel oil while ensuring that emissions remain within regulatory limits.

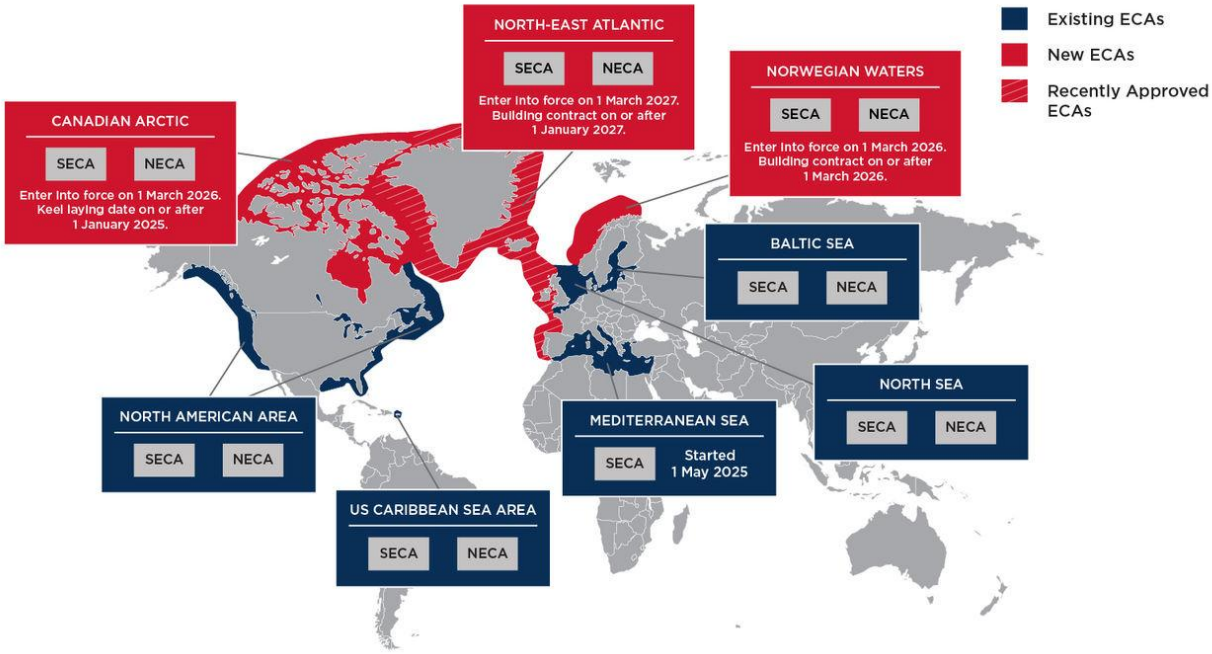

Figure 9:ECAs and SECAs areas.

Retrieved from: https://ww2.eagle.org/en/rules-and-resources/regulatory-updates/emission-control-areas.html

Certain maritime regions have been formally designated as SECAs, including the Baltic Sea, the North Sea, the Mediterranean Sea and the English Channel. Within these zones, significantly stricter sulphur limits apply in comparison with the global cap, reflecting the environmental sensitivity and high population density of the surrounding coastal areas.

In parallel with regional sulphur controls, the IMO introduced mandatory energy-efficiency instruments aimed at reducing CO_2 emissions from ships. For newbuild vessels, the EEDI was established as a design-based metric that quantifies a ship's CO_2 emissions per tonne-mile, taking into account its technical characteristics and propulsion efficiency. The EEDI therefore links environmental performance directly to the vessel's design stage.

For ships in operation, the SEEMP was introduced as a structured operational framework to enhance energy performance. SEEMP is divided into three parts. Part I focuses on practical measures to improve operational efficiency and reduce fuel consumption, such as weather routing, trim optimization, slow steaming and hull and propeller cleaning. Part II relates to the collection and reporting of fuel consumption data to the IMO under the DCS. Part III incorporates the Carbon Intensity Indicator (CII), a performance-based mechanism that rates vessels annually according to their CO_2 emissions intensity. Ships are assigned a rating from A to E, with lower-performing vessels required to implement corrective action plans in order to improve their environmental performance [37].

Considering the increasingly stringent regulatory framework, the decarbonization targets set by the IMO, and the mounting pressure for immediate emission reductions,

the development of propulsion systems capable of utilizing alternative fuels has become an operational and strategic necessity. Among the most mature and near-term solutions are dual-fuel engines designed to operate on LNG, methanol or ammonia. These technologies offer improved combustion efficiency and the potential for substantial emission reductions, positioning them as transitional pathways toward lower- or even zero-carbon maritime transport.

3.1 Two stroke and Four stroke engine cycle classification

With regard to the main propulsion engines used in ocean-going vessels, they are generally classified into two broad categories: the widely used two-stroke low-speed marine diesel engines and, increasingly, four-stroke marine engines operating on dual-fuel technology. Two-stroke marine engines require only two strokes of the piston to complete a full operating cycle, corresponding to one revolution of the crankshaft, while their rotational speed typically remains relatively low, often around 100 rpm. These engines have traditionally dominated the propulsion systems of large merchant vessels due to their high efficiency, reliability and capability to operate on heavy fuels.

In recent years, however, two major engine manufacturers, MAN Energy Solutions and WinGD, have introduced different technological approaches that enable the use of dual-fuel two-stroke engines in commercial shipping. In the case of MAN's concept, natural gas is injected near the top dead centre of the piston, where the combustion pressure exceeds approximately 150 bar. Under these conditions, the gas is injected at very high pressure, typically around 300 bar. In order to facilitate stable combustion and enhance the temperature and turbulence within the cylinder, a small quantity of diesel fuel is injected through a micro-pilot injector. The ignition of this pilot fuel initiates the combustion process through diffusion, resulting in efficient energy release and comparatively low emissions of carbon monoxide and carbon dioxide.

A different combustion strategy is adopted in the engine design developed by WinGD. In this configuration, gas is introduced into the cylinder earlier in the compression process, when the pressure is significantly lower, typically around 16 bar. As the piston approaches the top dead centre, a small amount of pilot fuel is injected in order to ignite the air–fuel mixture already present in the cylinder. A distinctive feature of this approach is that the pilot fuel is initially injected into a pre-chamber, which increases both pressure and temperature before ignition occurs, thereby facilitating a more controlled combustion process.

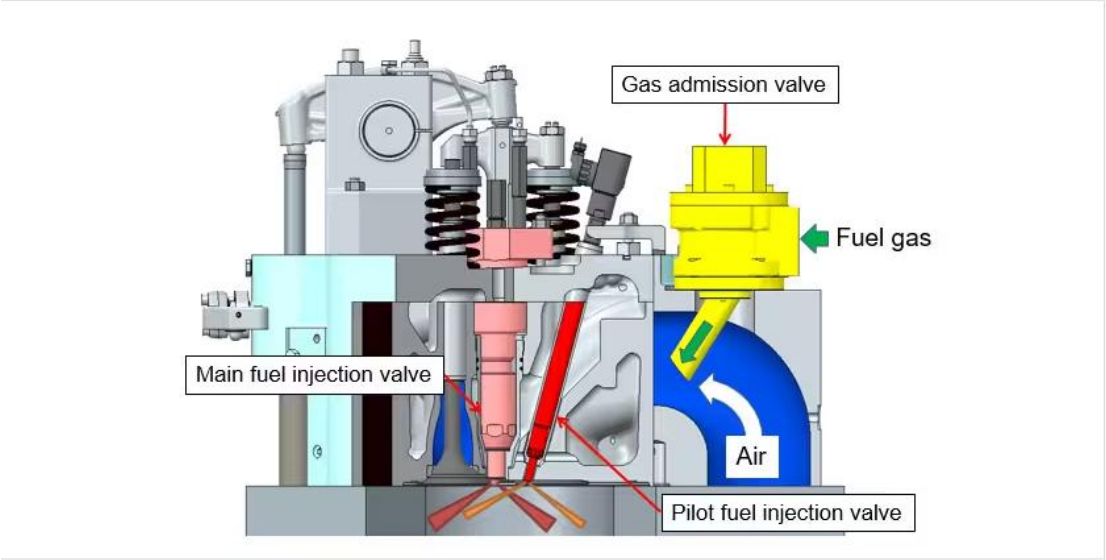

Figure 10: Cross-section of cylinder head.

Retrieved from: https://www.yanmar.com/global/about/technology/technical_review/2019/0403_4.html

In four-stroke marine engines, a complete operating cycle requires four piston strokes**,** corresponding to two full revolutions of the crankshaft. In general, these engines operate at higher rotational speeds and are typically smaller in size compared with the large low-speed two-stroke engines used for main propulsion in large ocean-going vessels. In dual-fuel four-stroke engines, the primary gaseous fuel is usually introduced through the intake manifold, where it mixes with the incoming air before entering the combustion chamber. This creates a homogeneous air–fuel mixture inside the cylinder. As the piston approaches top dead centre, a small quantity of pilot fuel, typically diesel, is injected directly into the combustion chamber in order to initiate ignition of the gas–air mixture. Following the combustion process, the exhaust valves open, allowing the combustion products to exit the cylinder and preparing the chamber for the next cycle. This sequence, intake, compression, combustion and exhaust, constitutes the complete thermodynamic cycle of a four-stroke marine engine.

Compared with two-stroke engines, four-stroke engines offer several operational advantages, including greater flexibility in fuel selection, smoother load response and simpler integration with gas fuel systems**.** For this reason, they are widely used not only for propulsion in smaller vessels but also for auxiliary power generation on large ships, particularly in configurations designed to operate with alternative fuels such as LNG, methanol or other emerging low-carbon fuels[38]**.**

3.2 Diesel and Otto cycle

Starting with the Diesel cycle, which is widely encountered in marine engines, it describes the thermodynamic operation of internal combustion engines operating according to the compression ignition principle. The operation of these engines can be illustrated through the theoretical pressure–volume (P–V) diagram, as presented in Fig.11.

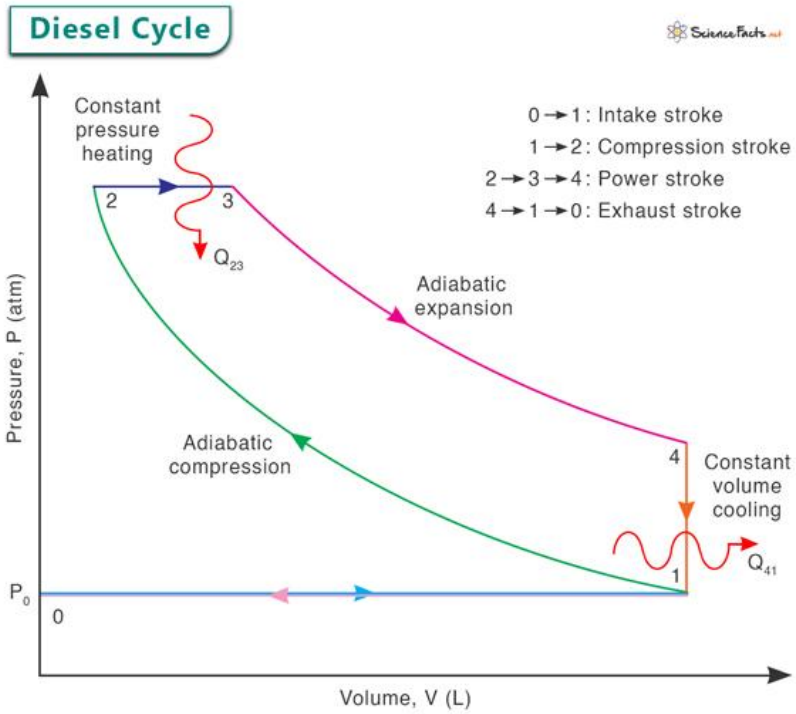

Figure 11:Diesel cycle diagram.

Retrieved from: https://www.sciencefacts.net/diesel-cycle.html

Process 1–2 represents the isentropic compression of air inside the cylinder. During process 2–3, heat is added under conditions approximating constant pressure, corresponding to the combustion phase. Process 3–4 describes the isentropic expansion of the combustion gases, during which the useful mechanical work of the engine is produced. Finally, process 4–1 corresponds to heat rejection at approximately constant volume, preparing the system for the next operating cycle.

The internal combustion engine operating according to the Diesel principle differs from the Otto cycle mainly due to the use of a significantly higher compression ratio. This high compression enables the fuel to auto-ignite without the need for an external ignition source such as a spark. In the ideal Diesel cycle, air is compressed adiabatically with a compression ratio typically ranging between 15 and 20, which leads to a substantial increase in air temperature inside the cylinder. When fuel is injected into the hot compressed air, a combustible mixture is formed and the temperature is sufficiently high to initiate auto-ignition.

The Otto cycle refers to engines operating at relatively lower pressures, in which fuel and air are mixed prior to the combustion process. According to the thermodynamic diagram presented in Fig. 12, the Otto cycle consists of the following processes. Process 1–2 corresponds to isentropic compression, process 2–3 represents heat addition at constant volume, process 3–4 is the isentropic expansion of the working gases, and process 4–1 corresponds to heat rejection at constant volume.

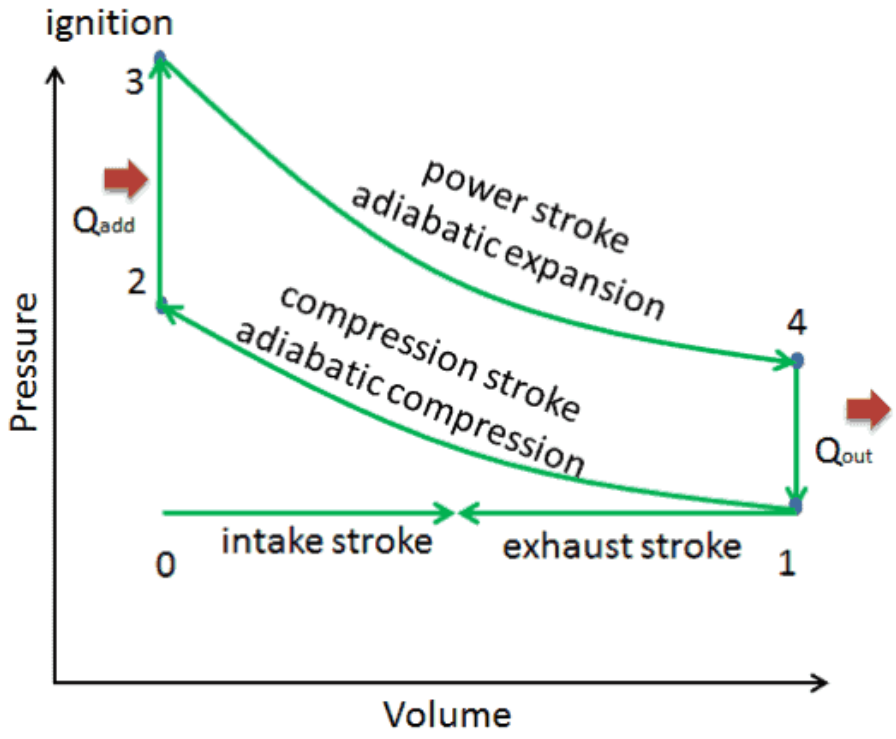

Figure 12: Otto cycle diagram.

Retrieved from: https://www.thermal-engineering.org/what-is-otto-cycle-otto-engine-definition/

Describing the process in more detail, during process 0–1 a mass of air is drawn into the cylinder at approximately atmospheric pressure through the intake valve in order to initiate the cycle, while at the same time the exhaust valve remains closed. The intake valve closes at point 1.

During process 1–2, the piston moves from the bottom dead centre (BDC), where the cylinder volume is maximum, to the top dead centre (TDC), where the volume is minimum, resulting in compression of the air.

During process 2–3, ignition occurs as the air–fuel mixture is present in a highly compressed state within a small volume. Heat is transferred to the working fluid as a result of the combustion of the injected fuel. Under the assumption of constant volume, the pressure in the cylinder increases significantly.

Due to the combustion process and the resulting high pressure, a force is exerted on the piston, driving it towards the bottom dead centre. During this stage the gases undergo an adiabatic expansion, while the cylinder volume increases.

Finally, during process 4–1 heat is rejected from the system, while the piston momentarily remains at the bottom dead centre. Subsequently, during process 1–0 the exhaust valve opens, allowing the combustion gases to be discharged from the cylinder [39].

3.3 LNG-Fueled Dual Fuel Marine Engines

Before describing the operating principles of dual-fuel engines using LNG, it is useful to outline some key characteristics of natural gas as a fuel. Understanding these properties is important in order to evaluate both the technical feasibility and the operational implications of its use in marine propulsion systems.

Natural gas belongs to the category of fossil fuels, which means that it is generally considered a transitional or alternative fuel rather than a fully green energy source. It is typically extracted from geological formations similar to those where crude oil is found. Its chemical composition consists primarily of methane (CH_4), while smaller fractions of other hydrocarbons such as ethane, propane, butane and pentane may also be present. During the processing stage prior to its final use as fuel, various inert or undesirable components, including nitrogen, carbon dioxide and water vapour, are removed in order to improve its calorific value and combustion characteristics.

Several physical properties of natural gas are particularly important for its safe handling and operational use. The fuel is colorless, odourless and non-corrosive. The absence of odour may pose a safety challenge, since potential leaks cannot be easily detected through smell. For this reason, in many land-based distribution systems odorizing substances are added in order to make gas leaks detectable. In marine applications, however, leak detection is typically ensured through dedicated gas detection sensors and monitoring systems that continuously measure methane concentrations in enclosed spaces.

Another important property is the relative density of natural gas, defined as the ratio between the density of the gas and the density of atmospheric air under the same temperature and pressure conditions. This value usually ranges between 0.57 and 0.64, meaning that natural gas is lighter than air. This characteristic has significant safety implications, since in the event of a release the gas tends to rise and disperse into higher atmospheric layers rather than accumulate at lower levels, thereby reducing the probability of ignition.

An additional important characteristic is that natural gas liquefies at atmospheric pressure at approximately −161 °C. This property makes it possible to transport and store the fuel in liquid form aboard LNG carriers, significantly increasing its volumetric energy density compared with its gaseous state.

Regarding its chemical behavior, natural gas is characterized by a high octane number, typically around 130. This property contributes to the avoidance of knocking phenomena and facilitates its use in engines operating at relatively high compression ratios. The auto-ignition temperature of natural gas is approximately 600 °C, while diesel fuel ignites at lower temperatures, typically between 330 and 350 °C. As a result, in dual-fuel engines operating on both fuels, the diesel pilot fuel ignites first and subsequently initiates the combustion of the natural gas–air mixture inside the cylinder.

The use of natural gas as an alternative marine fuel has therefore gained increasing attention in recent years. As its application in maritime propulsion continues to expand,

both the advantages and the operational challenges associated with its use are becoming increasingly evident through practical experience and technological development.

Advantages:

• Natural gas is essentially free of sulphur due to the processing and liquefaction stages it undergoes before use. As a result, its combustion does not produce SOx, allowing vessels operating on natural gas to comply with sulphur emission regulations without the need for additional exhaust gas treatment systems.

• During the premixed combustion phase, lower combustion temperatures generally prevail. This leads to a significant reduction in the formation of NOx, since the formation of these compounds is strongly dependent on high combustion temperatures.

• The production of soot-related products, such as particulate matter, is significantly reduced or even nearly eliminated. This is mainly attributed to methane, the principal component of natural gas, which does not undergo pyrolysis under typical combustion conditions. Consequently, the formation of carbon deposits inside the combustion chamber is minimized. This contributes to improved engine performance and helps reduce operational issues such as cylinder liner scuffing and piston ring failures.

• A substantial reduction in carbon dioxide emissions can also be achieved. In comparison with conventional marine fuels, the use of natural gas can lead to CO_2 reductions of approximately 20–30%. This characteristic makes natural gas an attractive transitional solution in the context of increasingly strict environmental regulations governing maritime transport.

Disadvantages:

• When the air–fuel mixture becomes excessively lean, considerable quantities of unburned methane and carbon monoxide may be released. This phenomenon is commonly referred to as methane slip. Methane emissions are particularly harmful from an environmental perspective, since methane has a global warming potential approximately 20 to 25 times greater than that of carbon dioxide over a comparable time horizon.

• Marine engines operating with premixed combustion systems typically function within a relatively narrow air–fuel ratio range as shown in Fig.13, usually close to the lean mixture region. If the mixture becomes too lean, ignition instability or misfiring may occur, whereas excessively rich mixtures can lead to knocking phenomena. Consequently, maintaining an optimal air–fuel mixture is essential for ensuring stable combustion and reliable engine operation.

• As previously mentioned, natural gas must be maintained at approximately −161 °C in order to remain in its liquefied state. Consequently, its storage and handling require specialized cryogenic systems, including advanced insulation and dedicated storage tanks. The installation and integration of such tanks onboard vessels present significant design and shipbuilding challenges, as they require additional space, specialized materials, and careful consideration of safety and structural constraints.

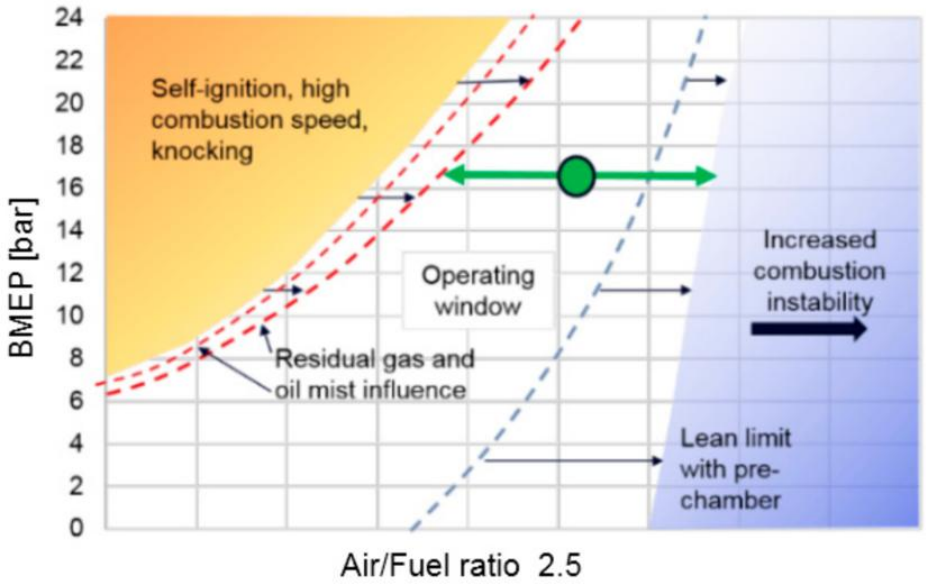

Figure 13:DF-Combustion limits.

Retrieved from: https://www.researchgate.net/figure/Lean-burn-DF-engine-Otto-combustion-limits_fig5_337459240

As shown in Fig. 14 below, liquefied natural gas storage tanks are typically cylindrical in shape for reasons related to mechanical strength. This geometry allows stresses to be distributed more uniformly across the structure of the tank, while the cylindrical form also provides improved resistance to internal pressure compared with other shapes. For this reason, cylindrical or spherical tank designs are commonly used in LNG storage systems.

At this point it is also important to mention the phenomenon known as boil-off gas. Liquefied natural gas has a natural tendency to evaporate due to the very low boiling temperature of methane and the presence of other components such as nitrogen. Even with advanced insulation systems, a small portion of the stored LNG gradually vaporizes during storage and transport. This process can lead to changes in the composition and density of the remaining liquid fuel inside the tank. In addition, the presence of lighter components such as nitrogen may increase evaporation rates due to variations in the surface-area-to-volume ratio, which can further intensify the vaporization process.

In certain circumstances, the preferential evaporation of nitrogen can lead to rapid and sudden LNG evaporation, potentially affecting both engine operation and fuel management. Such variations in fuel composition may also have commercial implications, sometimes leading to disputes or claims between shipowners and charterers regarding the delivered fuel quantity or quality.

On LNG carriers, however, this vaporized gas is not wasted. The generated boil-off gas is typically captured and utilized as fuel for the vessel's propulsion system or auxiliary engines, thereby improving overall energy efficiency and reducing fuel losses during transport [41].

Figure 14:DF Crude oil tanker.

Retrieved from:
https://www.shipspotting.com/photos/3628295?navList=moreOfThisShip&perPage=8&page=1&search_uid=97244&page_limit=96&viewtype=4b&viewType=normal&sortBy=newest&imo=9953470&lid=3594067

Operating Principle

The fundamental operating principle of these dual-fuel engines is based on the presence and combustion of two different fuels: a primary fuel and an alternative one. The secondary fuel is introduced into the engine through a different pathway than the conventional fuel normally used for combustion. Depending on the engine design, the alternative fuel may either be injected directly into the combustion chamber or supplied through the intake manifold during the intake phase of the cycle.

Depending on the role of natural gas in the combustion process, whether it is used as a supplementary fuel or as the main fuel, dual-fuel engines can be classified into two main categories. The first category includes engines where diesel fuel remains the primary energy source and natural gas is supplied in smaller quantities as a supplementary fuel. The second category includes engines in which natural gas acts as the principal fuel, while diesel is used only in small quantities as pilot fuel in order to initiate combustion.

In the first category, natural gas functions as an additional source of energy that partially substitutes the energy normally provided by diesel fuel. In this way, part of the energy required for engine operation is supplied by the combustion of natural gas, resulting in reduced consumption of conventional marine diesel fuel. However, in this configuration diesel fuel still plays the dominant role in controlling the engine load and maintaining stable operation.

In the second category, natural gas is used as the main fuel for the combustion process, while diesel fuel plays a much more limited role. In this case, diesel is injected in very small quantities primarily to initiate ignition of the gas–air mixture inside the cylinder. This combustion concept resembles the operating principles of the Otto cycle, where the gaseous fuel–air mixture is ignited after compression. Consequently, the contribution of diesel fuel to the total useful power produced by the engine is minimal, since its primary function is only to trigger the combustion of the gaseous fuel.

A further classification of engines operating with natural gas combustion concerns the injection pressure of the gaseous fuel, distinguishing between high-pressure and low-pressure gas engines.

In high-pressure gas engines as depicted in Fig.15, natural gas is injected directly into the combustion chamber near top dead centre at pressures that may reach approximately 300 bar through specially designed gas injectors. The gas is typically supplied at temperatures close to 40–45 °C. Ignition is initiated through the injection of a small quantity of diesel pilot fuel, which auto-ignites due to the high temperature and pressure conditions within the cylinder. Once ignition occurs, the combustion process continues with the burning of the injected natural gas. One of the main advantages of this engine type is the relatively low methane slip compared with low-pressure gas engines, while it also achieves higher thermal efficiency due to its combustion process, which resembles that of conventional diesel engines. However, a disadvantage of this configuration is that it generally cannot meet Tier III NOx emission limits without the use of additional exhaust gas treatment systems, such as exhaust gas recirculation (EGR) or selective catalytic reduction (SCR).

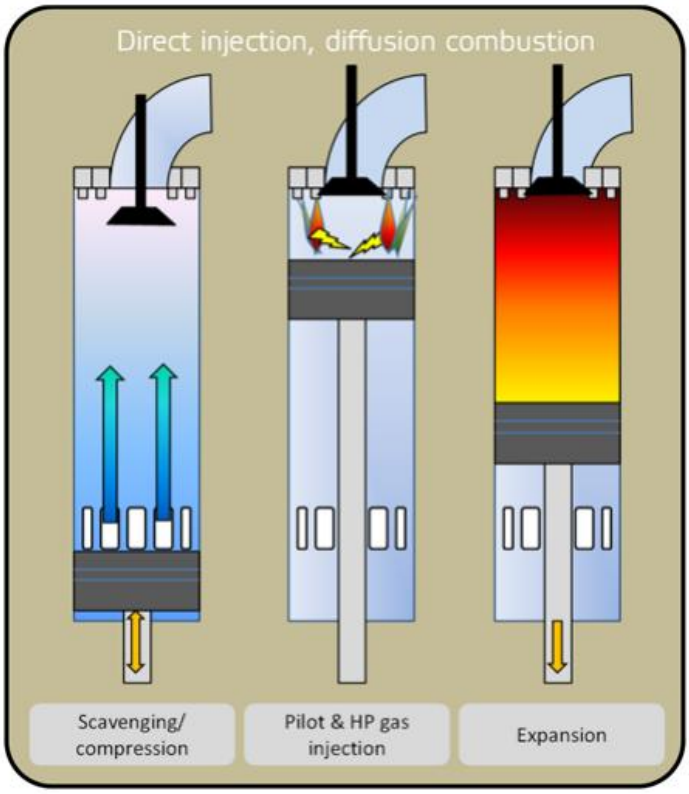

Figure 15:High-pressure gas injection with Diesel cycle combustion process.

Retrieved form: https://wingd.com/

Low-pressure gas engines, on the other hand, operate according to a different combustion concept. In these engines, natural gas is introduced into the cylinder during the compression phase at relatively low pressures, typically around 10 bar as shown in Fig. 16. The gas mixes with the incoming air, forming a premixed air–fuel mixture inside the combustion chamber. As the piston moves upward towards top dead centre, this mixture becomes compressed. At this point, a small quantity of diesel pilot fuel is injected in order to initiate combustion. In some engine designs, this pilot fuel is first injected into a small pre-chamber, where ignition occurs before the flame propagates into the main combustion chamber and ignites the premixed gas–air mixture.

One of the main advantages of low-pressure gas engines is that they can comply with Tier III NOx emission limits without requiring additional after-treatment systems such as catalytic converters or exhaust gas recirculation systems. On the other hand, these engines tend to exhibit lower thermal efficiency compared with high-pressure gas engines. They may also produce higher methane slip and increased emissions of carbon monoxide. Furthermore, depending on the air–fuel ratio, phenomena such as misfiring or knocking combustion may occur, which must be carefully controlled through engine management systems [42].

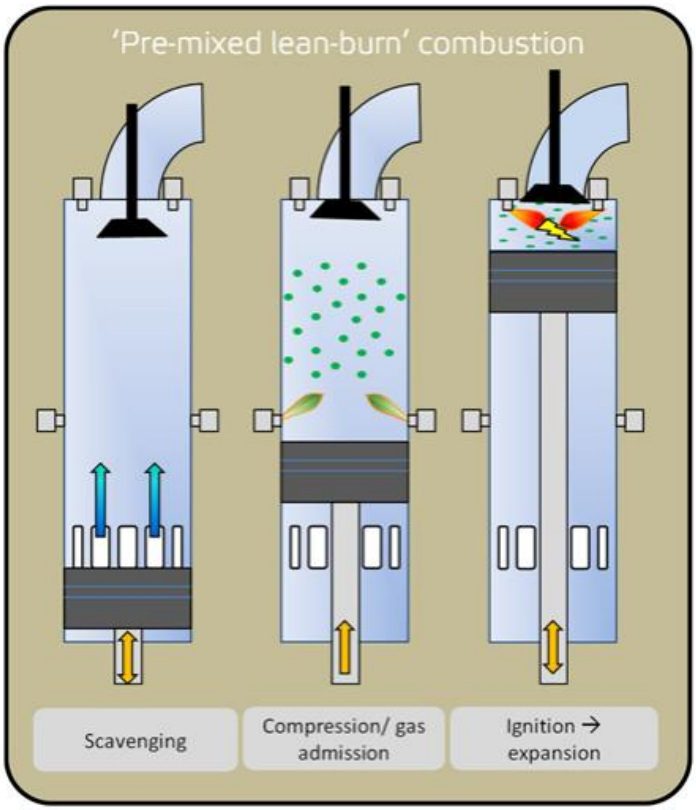

Figure 16:Low-pressure gas injection with lean-burn Otto cycle combustion process as implemented with WinGD low speed X-DF dual-fuel engines.

Retrieved from: https://wingd.com/

3.4 Methanol-Fueled Dual Fuel Marine Engines

Methanol is considered one of the most promising alternative fuels for the maritime sector, as it is a fundamental chemical compound already widely used in the production of everyday products such as adhesives, paints and pharmaceutical products. Consequently, both its production processes and the associated infrastructure are well established, which facilitates its potential adoption as a marine fuel compared with other emerging alternatives. Methanol can be produced from a variety of feedstocks, including coal, natural gas and biomass, as well as from any source capable of generating hydrogen together with carbon monoxide or carbon dioxide during its decomposition. In modern industrial practice, methanol is primarily produced through the generation of synthesis gas (syngas), consisting mainly of hydrogen, carbon monoxide and carbon dioxide. This gas mixture is subsequently converted into methanol through catalytic synthesis and is finally purified through distillation processes.

The molecular formula of methanol is CH_3OH and its density at 20 °C is approximately 791.3 kg/m³. As indicated by its molecular structure, methanol contains only one carbon atom and therefore does not form carbon–carbon bonds. This structural characteristic contributes to significantly reduced particulate matter emissions during combustion in internal combustion engines. Methanol is also characterized by a relatively high hydrogen-to-carbon ratio and lower combustion temperatures compared with conventional marine fuels [43].

Several properties of methanol influence engine operation. Methanol exhibits relatively low fuel reactivity due to its low cetane number, which can make ignition more challenging in compression ignition engines. At the same time, its high oxygen content promotes more complete combustion, contributing to lower emissions of nitrogen oxides and smoke. Another important characteristic is its high latent heat of vaporization, which is approximately three to four times greater than that of diesel fuel. This property leads to a cooling effect on the intake charge as the fuel evaporates, reducing the temperature of the air–fuel mixture entering the cylinder and influencing the combustion process.

The combustion of methanol can lead to lower carbon dioxide emissions compared with conventional hydrocarbon fuels. Methanol is an oxygenated fuel, with oxygen accounting for approximately half of its molecular mass, whereas conventional fuels such as diesel do not contain oxygen in their molecular structure. This characteristic promotes more complete combustion and contributes to the reduction of particulate matter emissions. At the same time, nitrogen oxide emissions can be effectively controlled through the use of exhaust after-treatment technologies, such as catalytic converters.

In addition, methanol may produce approximately 7% lower specific CO_2 emissions compared with gasoline-type fuels. This reduction is mainly related to the chemical structure of methanol and its lower carbon-to-hydrogen ratio compared with conventional fuels. As indicated by the stoichiometric combustion relationship, the carbon-to-hydrogen ratio of diesel fuel is significantly higher than that of methanol, which results in lower carbon dioxide formation when methanol is used as the primary

fuel. Furthermore, due to its oxygen content, methanol requires a relatively lower stoichiometric air–fuel ratio while maintaining a relatively high fuel fraction within the air–fuel mixture.

Another significant advantage of methanol is that it remains in liquid form under standard temperature and pressure conditions. This property simplifies its transportation, storage and handling compared with fuels such as liquefied natural gas, which require cryogenic conditions. As a liquid fuel, methanol can be stored and handled using systems similar to those employed for conventional marine fuels. Furthermore, methanol is biodegradable and dissolves rapidly in water, which reduces the environmental risk in the event of accidental spills. However, the high heat of vaporization that characterizes methanol may also create operational challenges. The strong cooling effect during fuel evaporation can make cold engine starting more difficult, particularly under low ambient temperature conditions [44].

Figure 17:Maersk's methanol powered container ship.

Retrieved from: https://www.dailybreeze.com/2024/08/27/going-green-at-maersk-new-ship-is-christened-with-a-new-name-at-port-of-la/

Operating Principle

When examining the properties of methanol, it is important to highlight certain characteristics that may pose challenges for its wider adoption in maritime applications. In compression ignition engines, the auto-ignition process is closely related to the cetane number of the fuel. A higher cetane number generally leads to a shorter ignition delay, resulting in more efficient and stable combustion. In the case of dual-fuel engines operating with methanol, it should be noted that methanol has a significantly lower cetane number compared with conventional diesel fuels.

However, it is also important to emphasize that the cetane number alone is not always a fully representative parameter for describing the auto-ignition characteristics of

methanol. These characteristics are strongly influenced by the thermodynamic conditions that develop inside the cylinder, such as temperature and pressure during the compression process. Due to the relatively poor auto-ignition properties of methanol, additional ignition assistance is often required in certain engine configurations, such as the use of glow plugs or pilot fuel injection in order to initiate combustion.

Another important consideration is related to the energy content of methanol. Methanol has a lower heating value compared with diesel fuel, which means that a larger quantity of fuel must be injected in order to produce the same engine power output. In practical terms, approximately twice the mass of methanol may be required to deliver an equivalent amount of energy compared with diesel.

Methanol also exhibits a latent heat of vaporization that is roughly four times higher than that of diesel fuel. This characteristic produces both positive and negative effects on engine operation. On the positive side, the strong cooling effect that occurs during fuel evaporation reduces the peak combustion temperatures inside the cylinder, which contributes to lower NOx emissions. Additionally, the cooling effect may help reduce the thermal stress experienced by certain engine components. On the other hand, the same evaporation-induced cooling effect can make ignition more difficult, particularly because the reduced temperatures inside the combustion chamber may further delay or hinder the auto-ignition process of methanol [45].

A significant challenge for the adoption of this technology lies in the fact that methanol is generally more suitable for spark-ignition engines than for compression-ignition engines, which are the most widely used propulsion systems in the maritime sector. Various approaches have been proposed to address this limitation. One option involves blending methanol with diesel fuel; however, this solution faces an important constraint, since methanol can mix effectively with diesel only at relatively low fractions. Another approach concerns the use of ignition-improving additives in methanol in order to enhance its combustion characteristics. Nevertheless, this method is still under investigation, partly due to concerns regarding potential toxic by-products that may be formed during combustion.

Taking these limitations into account, the solution that is currently applied and continues to be further developed is the use of dual-fuel engine technology. In this configuration, a combination of two fuels is utilized: one with a high cetane number, such as diesel, which facilitates ignition, and another with a high octane number, namely methanol, which is subsequently ignited by the combustion of the pilot diesel fuel. This concept allows methanol to be used in engines that would otherwise rely exclusively on compression ignition.

In practical applications, the technologies adopted by engine manufacturers today are primarily based on the direct injection of methanol into the cylinder. This approach has been implemented by major manufacturers such as MAN Energy Solutions and Wärtsilä. Another technological concept involves multi-point injection of methanol in the intake port, where the fuel forms a mixture with the incoming air before entering the cylinder during the intake process. This premixed air–fuel mixture is then drawn into the engine and ignited through the assistance of pilot fuel or other ignition mechanisms.

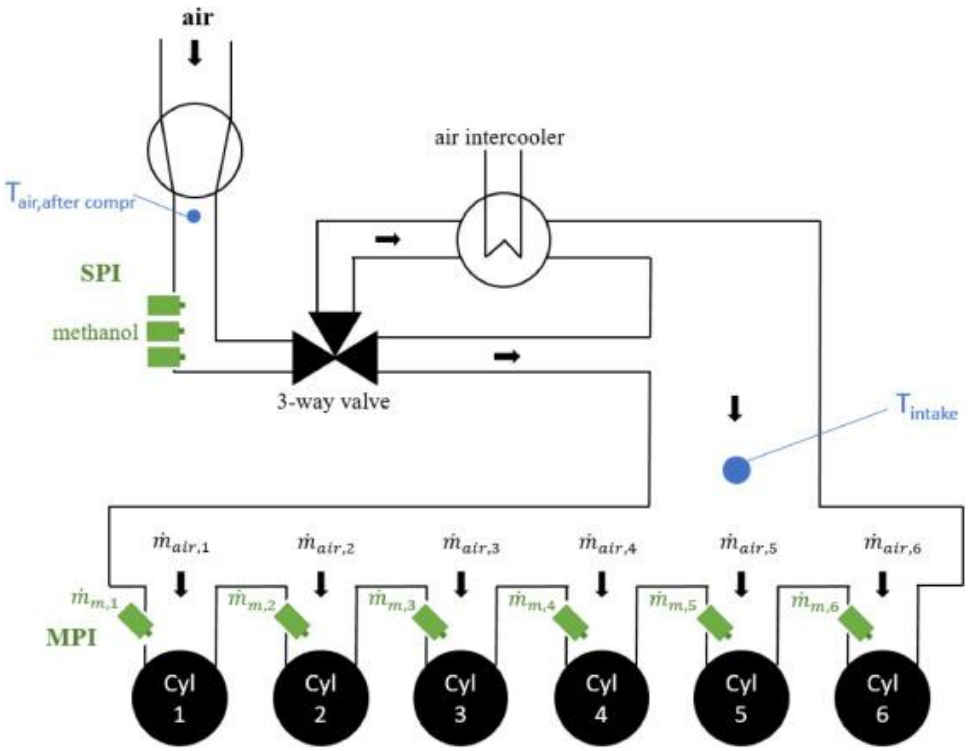

Figure 18:Intake air manifold and the methanol injector positions.

Retrieved from: https://www.sciencedirect.com/science/article/pii/S2666052021000030.

Fig.18 illustrates the technical design requirements of such an engine configuration based on the Multiple Point Injection (MPI) concept. In this arrangement, several modifications to the intake system are required in order to accommodate the methanol fuel supply system. For example, the position of the intercooler may be adjusted to create the necessary space for the installation of the low-pressure methanol injection components within the intake system.

In the MPI configuration, methanol is injected at multiple points in the intake port rather than directly into the cylinder. This allows the fuel to mix with the incoming air before entering the combustion chamber, forming a premixed air–fuel mixture. One of the important advantages of this concept is that it enables the engine to benefit from a key property of methanol, namely its high latent heat of vaporization. As the methanol evaporates, it produces a cooling effect on the intake charge, which can improve mixture formation and influence the thermodynamic conditions inside the cylinder.

The same figure also presents the configuration of a single-point injector system. In this design, a single injector is positioned at a suitable location within the intake duct, allowing sufficient distance for the injected methanol to mix effectively with the incoming air. This placement facilitates the formation of a more homogeneous air–fuel mixture before the mixture enters the cylinder and participates in the combustion process [46].

As methanol possesses several characteristics that make it a promising alternative fuel for the maritime sector and capable of contributing significantly to the reduction of the environmental footprint of shipping, research in this field continues in order to achieve the most efficient and reliable technological solutions. Despite the considerable progress that has been made so far, the most suitable combustion system for methanol-fueled marine engines remains a subject of ongoing investigation and development.

In general, the current technological developments indicate that further research is still required in order to determine the optimal engine configuration and combustion strategy for methanol utilization in marine propulsion systems. Consequently, the question of which combustion concept is ultimately preferable for marine engines remains open and continues to attract significant scientific and industrial interest.

In summary, the two main technological approaches that currently dominate both the academic literature and the development efforts of engine manufacturers can be outlined as follows:

- The high flame propagation velocity of methanol, combined with its strong evaporative cooling effect, promotes rapid premixed combustion under an Otto-cycle operating mode when port injection is applied. This combustion behavior generally occurs at lower temperatures and demonstrates a high resistance to knocking. However, these same characteristics may also increase the likelihood of surface ignition under certain operating conditions. Previous studies have highlighted several performance advantages of methanol compared with conventional fuels such as gasoline and natural gas, particularly in passenger car engines.
- The fact that methanol remains in liquid form under standard conditions, together with its ignition characteristics described by Arrhenius-type kinetics, makes it suitable for high-pressure injection strategies within diffusion-controlled combustion systems. In such configurations, a small quantity of pilot diesel fuel is first injected and combusted, initiating the ignition process before the methanol fuel burns. This concept is commonly applied in direct injection compression ignition systems, similar to those already used in low- and medium-speed marine engines operating on liquid biofuels.

Despite these promising characteristics, further investigation is still required in order to determine whether the advantages observed in larger, lower-speed engines or in smaller, high-speed engines can be effectively transferred to the intended marine applications. For this reason, the most relevant technological alternatives have been selected for further evaluation and analysis [47].

3.5 Ammonia-Fueled Dual Fuel Marine Engines

Ammonia has the potential for widespread use in the maritime industry, as its combustion does not produce carbon dioxide. In addition, ammonia can be stored in liquid form under relatively moderate conditions, which makes it easier to handle and transport compared with fuels that require cryogenic storage. These characteristics make ammonia an attractive candidate as an alternative marine fuel.

Ammonia is produced through the Haber–Bosch process, in which hydrogen and nitrogen react under high pressure and temperature in the presence of a catalyst to form ammonia:

$$N_2 + 3H_2 \rightarrow 2NH_3$$

This industrial process has been widely used for decades, mainly for the production of fertilizers, and therefore the technological infrastructure for ammonia production and distribution is already well established. To date, ammonia has been widely used in the agricultural sector, primarily in the production of fertilizers, significantly supporting global food production and supply chains.

With regard to ammonia as a fuel, its volumetric energy density is approximately half that of conventional diesel fuel. In liquid form, ammonia has an energy density of about 15.6 MJ/L, compared with approximately 38 MJ/L for diesel. This implies that a significantly larger volume of ammonia would be required in order to produce the same amount of energy as conventional marine fuels. Consequently, vessels operating on ammonia would require larger fuel storage capacities compared with those using diesel.

Another important characteristic of ammonia is its relatively high vapor pressure, which is around 8.5 bar at ambient conditions. This means that ammonia storage tanks must be designed to withstand pressures of at least about 10 bar in order to safely contain the fuel in its liquid form. In addition, the auto-ignition temperature of ammonia is considerably higher than that of diesel fuel under atmospheric conditions. At the same time, its flammability limits are relatively narrow. These properties offer certain safety advantages in terms of storage and handling, but they also make the combustion process more difficult to initiate and sustain.

The high auto-ignition temperature mentioned above makes ammonia more suitable for spark-ignition engines. However, due to its low flame propagation speed, hydrogen is often added to the fuel mixture in order to enhance and stabilize the combustion process. This requirement represents one of the main technical challenges associated with the use of ammonia as a marine fuel.

In particular, the high auto-ignition temperature of ammonia presents difficulties for its application in compression-ignition engines, which are the most commonly used propulsion systems in the maritime sector. This is mainly due to the fact that ammonia exhibits a very low cetane number (and correspondingly high octane rating), together with a relatively low heating value. As a result, when ammonia is injected into the cylinder it can produce a cooling effect, which may further complicate the ignition and combustion process in compression-ignition engine configurations [48].

With regard to the environmental footprint of ammonia combustion, although carbon dioxide is not produced during its combustion, NOx can still be emitted. These compounds contribute to several environmental and health-related problems, including acid rain formation, tropospheric ozone generation, and potential adverse effects on human health, particularly cardiovascular and respiratory conditions. For this reason, the use of ammonia as a marine fuel must also consider the regulatory limits imposed in ECAs, where the Tier I, Tier II and Tier III standards establish strict limits on NOx emissions.

The formation of NOx during ammonia combustion is mainly associated with high combustion temperatures. At the same time, when combustion temperatures are relatively low, incomplete combustion may occur, leading to the presence of unburned ammonia (commonly referred to as ammonia slip). A major challenge in ammonia-fueled engines is therefore the difficulty of identifying operating conditions that simultaneously minimize both NOx formation and unburned ammonia emissions.

To mitigate nitrogen oxide emissions in large marine engines, exhaust gas after-treatment systems are typically required. One of the most widely used technologies is Selective Catalytic Reduction (SCR), in which ammonia itself can be used as a reducing agent to convert NOx into nitrogen (N_2) and water vapor (H_2O). In addition, emissions of nitrous oxide (N_2O), another nitrogen-based greenhouse gas that may be produced under certain combustion conditions, can be reduced by maintaining sufficiently high combustion temperatures and by optimizing the catalytic after-treatment process.

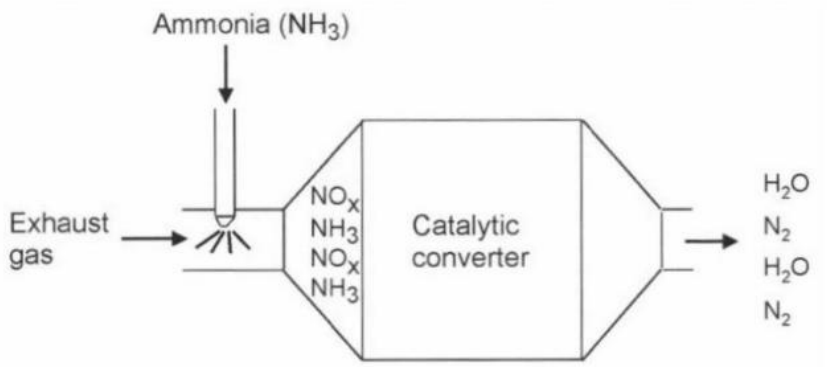

Figure 19:Operating process of an active SCR system.

Retrieved from: B. R. van and S. Fred, "Internal Combustion engine Handbook," in 14. Combustion, 2016, pp. 589-605.

Overall, by operating engines under appropriately controlled combustion temperatures and employing catalytic after-treatment technologies, it is possible to significantly reduce both nitrogen oxide emissions and other nitrogen-related pollutants associated with ammonia combustion in marine propulsion systems [49].

With regard to safety considerations in the handling of ammonia, this substance is characterized as a colorless and corrosive gas. At very low concentrations, typically below approximately 5 ppm, it may not be easily perceived, while exposure to higher concentrations can cause irritation to the eyes, skin and throat. At very high concentrations, exceeding roughly 2500 ppm, ammonia exposure may become extremely dangerous and can even lead to fatal consequences.

Due to its toxicity and the potential hazards associated with its handling, ammonia can present several safety risks, including poisoning, asphyxiation, and in certain cases fire or explosion hazards. Historical data from industrial accidents related to ammonia handling indicate that many incidents have been associated with leaks, fires, or explosions. For this reason, classification societies and regulatory bodies have focused on establishing strict requirements regarding system design, material selection,

operational procedures and inspection regimes. Particular emphasis is also placed on continuous training of personnel and proper maintenance of the fuel handling systems.

When compared with other gaseous fuels, ammonia can in some respects be considered a relatively manageable alternative fuel, provided that appropriate safety measures are implemented. Several characteristics contribute to this assessment. First, ammonia is lighter than air under certain conditions, allowing it to disperse relatively quickly into the atmosphere in the event of a release. Second, its strong and distinctive odor at moderate concentrations allows leaks to be detected more easily. In addition, ammonia is relatively difficult to ignite and has a narrower flammability range compared with many hydrocarbon fuels, which can reduce the likelihood of accidental explosions.

Furthermore, ammonia has been widely produced and handled for decades in various industrial sectors, particularly in the fertilizer industry. As a result, significant operational experience and established safety practices already exist for its storage, transport and handling.

In general, the safe use of ammonia as a marine fuel requires the implementation of strict safety measures. These include adequate ventilation of engine rooms and fuel handling areas, storage of ammonia in properly designed and ventilated compartments, and the use of electrical equipment that complies with applicable explosion-protection standards. Such precautions are essential in order to minimize the risks associated with ammonia handling and to ensure safe engine room operation [50].

Special attention has also been given by DNV (Det Norske Veritas) to the appropriate selection of materials used in systems intended for ammonia handling and storage. According to the guidance provided by DNV, certain materials such as zinc and copper should be avoided, as they may react adversely when exposed to ammonia. Materials considered more compatible with ammonia include aluminum, carbon steel and stainless steel. However, even when such materials are used, their mechanical properties must be carefully considered. In particular, materials with excessively high yield strength should be avoided, as they may be more susceptible to stress corrosion cracking when exposed to ammonia under certain operating conditions. Proper material selection is therefore essential in order to ensure the structural integrity and long-term reliability of ammonia fuel systems [51].

Operating Principle

According to the operating principle of diesel engines, the fuel is atomized into fine droplets inside the combustion chamber after being injected at high pressure through the fuel injectors. In combination with the compressed air present in the cylinder under high temperature and pressure conditions, the temperature rises further above the ignition threshold, leading to auto-ignition of the fuel.

Compression ignition (CI) engines typically operate with compression ratios in the range of approximately 14:1 to 25:1 and achieve thermal efficiencies between 45% and 55%. The introduction of ammonia as a fuel significantly affects engine operation due to its inherent properties, as discussed previously. In particular, ammonia is characterized by a high auto-ignition temperature, rapid evaporation behavior, and combustion characteristics that differ substantially from those of diesel fuel. As a result,

if ammonia were to be used as the sole fuel in a CI engine, much higher compression ratios, in the range of approximately 35:1 to 100:1, would be required to achieve reliable ignition. Such values are considered impractical for conventional marine engines.

For this reason, in dual-fuel engine configurations currently under development and already applied in some marine applications, diesel serves as the primary ignition source. In such systems, the required compression ratio can be maintained at more conventional levels, typically around 15:1, as the ignition process is initiated by the pilot diesel fuel. It should be noted that the minimum required compression ratio is closely related to the cetane number of the pilot fuel, which directly influences ignition characteristics. Experimental studies have also shown that stable engine operation can be achieved when ammonia is injected into the combustion chamber sufficiently early, typically around 40 crank angle degrees or more before the completion of diesel injection. Delayed ammonia injection, on the other hand, may lead to unstable combustion or misfiring. Furthermore, research on the development and optimization of ammonia-fueled engines indicates that spark-ignition engine concepts may offer certain advantages over compression ignition engines, particularly in terms of combustion stability and overall performance when operating with ammonia [52].

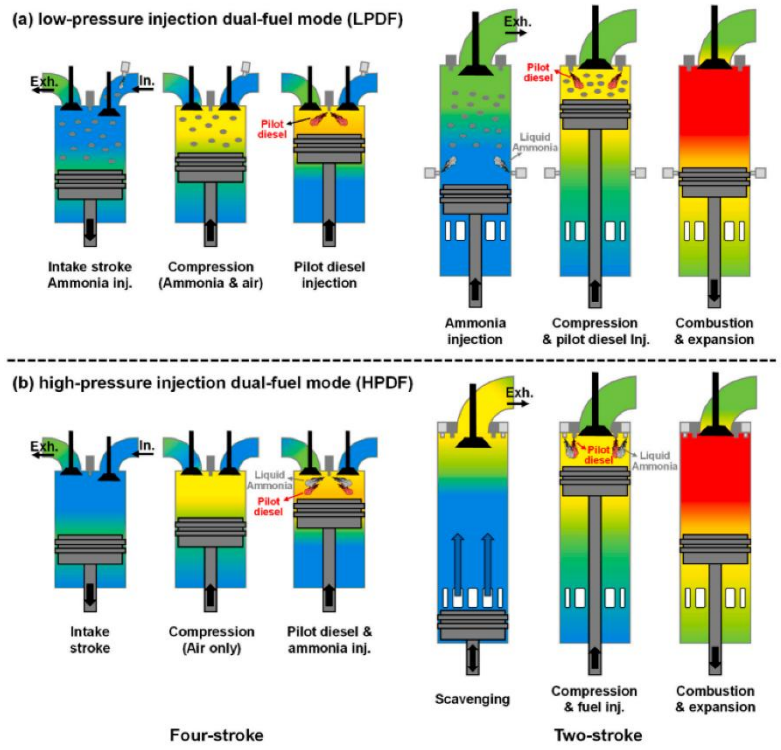

Figure 20: Schematic Comparison of Low-Pressure and High-Pressure Dual-Fuel Ammonia Injection Modes in Marine Engines (Four-Stroke and Two-Stroke Configurations).

Retrieved from: https://www.mdpi.com/1996-1073/17/12/3046

As illustrated in Fig. 20, regardless of whether ammonia is supplied to the engine in liquid or gaseous form, typical levels of thermal efficiency and overall performance can be achieved when ammonia is used in combination with a pilot fuel such as diesel. The heat release rate is, however, higher in the case of liquid ammonia. On the other hand,

the use of gaseous ammonia results in slower combustion, accompanied by lower heat release and reduced in-cylinder pressure. It is also observed that, under gaseous ammonia operation, NOx emissions may exceed the limits set by Tier III regulations [53].

To address these challenges, high-pressure fuel injection has been proposed as a potential solution. Compared to conventional low-pressure injection systems, high-pressure injection can lead to a reduction in NOx emissions of up to approximately 50%, while maintaining comparable thermal efficiency. A key finding is that the proportion of ammonia in the fuel mixture should not exceed approximately 40%. Beyond this threshold, ignition delay increases, air–fuel mixing deteriorates, leading to unstable combustion, and NOx emissions rise significantly [54].

Overall, ammonia represents a feasible alternative fuel for maritime applications, offering the potential to significantly reduce CO_2 emissions, while NOx emissions can be effectively mitigated through the use of appropriate after-treatment systems, such as catalytic converters. Ammonia is further considered an attractive option due to its already widespread industrial use and the existence of an established supply chain.

However, several challenges remain associated with its utilization. These include its toxicity, corrosive nature, and certain unfavorable thermodynamic characteristics, such as its high auto-ignition temperature and narrow flammability limits, which complicate its application in conventional marine engines. Therefore, it becomes evident that further research and a deeper understanding of ammonia's properties are essential to support the optimal design, safe handling, and efficient operation of ammonia-fueled engine systems [55].

3.6 Comparative Assessment of Marine Engine Technologies

Following the analysis of the previously presented technologies related to dual-fuel marine engines, which incorporate innovative solutions and enable the gradual introduction of alternative fuels in the maritime sector, it is appropriate to provide a comparative assessment. Such a comparison enhances the understanding of how each technology and fuel type responds to evolving environmental regulations, as well as their implications for fuel consumption and overall performance.

The comparative analysis indicates that conventional diesel engines, despite their technological maturity and widespread availability, face significant limitations in meeting increasingly stringent emission requirements. LNG dual-fuel engines provide a transitional solution with reduced emissions; however, they do not fully eliminate carbon output. Methanol emerges as a promising alternative, offering lower emissions alongside relatively manageable safety considerations and infrastructure demands. In contrast, ammonia, while achieving zero carbon emissions at the point of use, remains at an early stage of technological development and presents considerable safety and operational challenges.

Overall, the selection of the most suitable technology is not straightforward and depends on a careful balance between environmental performance, economic viability, and technological readiness, all of which will shape the future pathway of the maritime

energy transition. Following the key comparison criteria outlined above, the table below summarizes the main findings.

Parameter	**Conventional Diesel**	**LNG DF**	**Methanol DF**	**Ammonia**
CO_2 emissions	High	Medium	Low	Zero (tank-to-wake)
NO_x emissions	High	Low (Tier III)	Low	Potentially high
SO_x emissions	High (unless scrubber)	Very Low	Very Low	Zero
Fuel availability	Very High	High	Medium (developing)	Low (emerging)
Infrastructure	Fully developed	Developed	Limited	Very limited
CAPEX	Low	High	Medium	Very High
OPEX	Medium	Medium	High	Unknown/high
Safety	High	High	Medium (toxic)	Low (high toxicity)
Technology maturity	Mature	Mature	Emerging	Early stage
FuelEU Compliance	Poor	Good	Very good	Excellent

4.FuelEU Compliance Mechanism

In order to initiate the process of calculating the potential penalty that may be imposed on a vessel, depending on whether it complies with the environmental performance targets related to emissions, the calculation methodology is analyzed in detail. The necessary equations and relationships are presented in order to provide a comprehensive understanding of the calculation procedure.

To calculate the GHG intensity, the following formula is used:

$$GHG\ intensity = f_{wind} * (WtT + TtW)$$

Where GHG intensity is expressed in gCO_2eq/MJ.

The parameter f_{wind} is a reward factor applied in cases where wind-assisted propulsion systems are installed on the vessel. Such systems can contribute, according to various studies, up to approximately 5% reduction in fuel consumption.

It takes the following values:

f_{wind}	P_{wind}/P_{prop}
1	$P_{wind}/P_{prop} < 0.5$
0.99	$0.05 \leq P_{wind}/P_{prop} < 0.1$
0.97	$0.1 \leq P_{wind}/P_{prop} < 0.15$
0.95	$0.15 \leq P_{wind}/P_{prop}$

Where,

- P_{wind} It represents the effective power available from wind-assisted propulsion systems and is defined as the product of the efficiency factor and the effective power $f_{eff} * P_{eff}$. This parameter is determined in accordance with the 2021 guidelines for the treatment of innovative energy efficiency technologies in the calculation and verification of the attained EEDI and the Energy Efficiency EEXI, as outlined in MEPC.1/Circ.896.

- P_{prop} represents the propulsion power of the vessel and is equivalent to PME, as defined in the 2018 guidelines for the calculation of the attained EEDI for new ships (IMO resolution MEPC.364(79)) and the 2021 guidelines for the calculation of the attained EEXI (IMO resolution MEPC.333(76)). In cases where shaft motor(s) are installed, the corresponding contribution is also taken into account in the propulsion power.

With regard to WtT and TtW emissions, the following definitions apply:

WtT emissions refer to the emissions associated with fuel extraction, production, processing, and transport up to the point where the fuel is delivered onboard the vessel.

These emissions are calculated based on the following relationship:

$$WtT = \frac{\sum_i^{n\,fuel} M_i x CO_2 eq_{WtWi} x LCV_i + \sum_k^c E_k x CO_{2eq\ electricity,k}}{\sum_i^{n\,fuel} M_i x LCV_i x RWD_i + \sum_k^c E_k} \quad (1),$$

where the term $\sum_k^c E_k x CO_{2eq\ electricity,k}$ shall be set to zero according to Annex I.

Therefore, the overall resulting expression is:

$$WtT = \frac{\sum_i^{n\,fuel} M_i x CO_2 eq_{WtWi} x LCV_i}{\sum_i^{n\,fuel} M_i x\, LCV_i x RWD_i + \sum_k^c E_k} \quad (2)$$

According to Equation (2), the variables involved are as follows:

- $M_{i,j}$ It represents the mass of fuel type iii consumed by consumer j, expressed in grams of fuel (g fuel)
- $CO_2 eq_{WtWi}$ represents the WtW greenhouse gas emission factor for fuel i, expressed in units of: $gCO_2 eq/MJ$.
- LCV_i represents the lower calorific value of fuel i, expressed in: MJ/g fuel.
- RWD_i represents the reward factor, which is equal to 2 and applies from 1 January 2025 until 31 December 2033 when RFNBO fuels are used; otherwise, it is equal to 1.
- $\sum_k^c E_k$ represents the total electrical energy supplied to the ship from shore, expressed in MJ.

TtW emissions: emissions resulting from combustion or onboard usage, including methane slip and other fugitive discharges.

They are calculated based on the following formula:

$$TtW = \frac{\sum_i^{n\,fuel} \sum_j^{engine} M_{i,j} x [\left(1 - \frac{1}{100} C_{slip,j}\right) x \left(CO_{2eq,TtW,i,j}\right) + \left(\frac{1}{100} C_{slip,j} x CO_{2eq,TtW,slip,i,j}\right)]}{\sum_i^{n\,fuel} M_i x LCV_i x RWD_i + \sum_k^c E_k} \quad (3)$$

According to equation (3),

- $C_{slip,j}$ represents the dimensionless factor of unburned fuel, expressed as a fraction of the mass of fuel consumed by consumer j. This factor also accounts for emission slip losses.
- $CO_{2eq,TtW,i,j}$ describes the equivalent grams of CO_2 emissions produced from the fuel used for combustion by the consumer j in units of $g\frac{CO_2 eq}{g} fuel$.
- $CO_{2eq,TtW,slip,i,j}$ represents the equivalent CO_2 emissions associated with the slipped fuel.

For the factor $CO_{2eq,TtW,i,j}$, which is associated with the combustion process, it is calculated in accordance with the regulation as follows:

$$CO_{2eq,TtW,i,j} = (C_{fCO_{2,j}} x GWP_{CO_2} + C_{fCH_{4,j}} x GWP_{CH_4} + C_{fN_2O_j} x GWP_{N_2O})_i$$

Where, for the above calculation, the TtW values are:

- $CO_2 = 1$
- $CH_4 = 25$
- $N_2O = 298$

While for the factor: $\frac{1}{100} C_{slip,j} x CO_{2eq,TtW,slip,i,j}$

$$\frac{1}{100} C_{slip,j} x CO_{2eq,TtW,slip,i,j} = (\frac{1}{100} C_{slip,j} x \left(C_{sfCO_{2,j}} x GWP_{CO_2} + C_{sfCH_{4,j}} x\, GWP_{CH_4} + C_{sfN_2O_j} x GWP_{N_2O}\right))_i$$

Where, $C_{sfCO_{2,j}} = C_{sfN_2O_j} = 0$ $\kappa\alpha\iota$ $C_{sfCH_{4,j}} = 1$ are applied.

For the calculation of WtT and TtW emissions for fossil fuels, the values are taken from the data provided in the annex, as shown in Figure 15, in accordance with the FuelEU regulation.

1	2	3	4	5	6	7	8	9
			WtT	TtW				
Fuel Class	Pathway name	LCV [MJ/g]	$CO_{2eq\ WtT}$ [gCO2eq/MJ]	Fuel Consumer Unit Class	$C_{f\,CO_2}$ [gCO2/gFuel]	$C_{f\,CH_4}$ [gCH4/gFuel]	$C_{f\,N_2O}$ [gN2O/gFuel]	C_{slip} As % of the mass of the fuel used by the engine

Figure 21:FuelEU Annex II references.

Retrieved from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1805

Beyond fossil fuels, the regulation also provides for the use of biofuels as well as RFNBOs. As discussed extensively in previous chapters, the use of these fuels requires certification in accordance with the RED. Under these conditions, the WtT emissions are determined based on the corresponding values provided in Annex II (Appendix A), using the following equation:

$$WtTCO_2eq = E - \frac{c_f CO_2}{LCV} \quad (4)$$

Where,

E represents the total greenhouse gas emission intensity (gCO_2eq/MJ) associated with both the production and utilization of the fuel, as documented through the relevant PoS or PoC for certified biofuels. In cases where such certification is not available, or where the biofuel fails to comply with the established sustainability and greenhouse gas emission saving criteria, or is derived from food and feed crops as specified in FuelEU Article 10(1)(a), the calculation must instead be based on the emission factors (WtT and TtW) corresponding to the least favourable fossil fuel pathway applicable to that specific fuel category.

For RFNBOs, the WtT emissions indicated in column 4 of Annex II of the FuelEU regulation are aligned with the provisions of the RED. According to the relevant

supplementary Delegated Regulation, the certified E value, as documented in the PoS or PoC, is used to define the overall greenhouse gas emission intensity of the fuel.

In order to determine the WtT emissions of RFNBOs or e-fuels, it is necessary to exclude the emissions associated with the combustion phase of the fuel e_u. These emissions are already accounted for separately under the TtW component, and their subtraction ensures that double counting within the FuelEU framework is avoided. Unlike the approach applied to biofuels, no additional CO_2 deduction is required.

Accordingly, the WtT emissions for RFNBOs are calculated using the following expression:

$$CO_2eq_{WtT} = E - e_u \quad (5)$$

where E represents the total greenhouse gas eemission intensity (gCO_2eq/MJ) covering both fuel production and use, as specified in the PoS or PoC certification, and e_u corresponds to the emissions generated during the combustion of the fuel.

4.1 Case Studies

For a clearer understanding of the regulation, a number of case studies are presented, applying the methodology described above. These examples aim to illustrate how vessel emissions are quantified and under which conditions they exceed the prescribed limits, thereby triggering the imposition of penalties.

With regard to the compliance balance, it determines whether a vessel meets the requirements to avoid penalties. A positive balance indicates compliance and therefore no penalty is imposed, whereas a negative balance results in a penalty. In the latter case, the vessel may utilize certain flexibility mechanisms in order to offset the deficit and avoid penalties. These include mechanisms such as banking, where a vessel can use previously accumulated surplus compliance from earlier periods, and pooling, where vessels with positive and negative balances participate in a common scheme. Within such a mechanism, a vessel with a deficit can effectively compensate its shortfall by using surplus compliance from other vessels, typically in exchange for a financial arrangement.

As stated in the FuelEU regulation,

$$compliance\ balance\ [gCO_{2eq}] = (GHGIE_{target} - GHGIE_{actual})\ x\ [\sum_i^{n\ fuel} M_i x LCV_i + \sum_k^c E_k] \quad (6)$$

Where,

- $GHGIE_{target}$: It refers to the emission limit that a vessel must meet in order to comply with the regulation.
- $GHGIE_{actual}$: It refers to the actual emission levels produced by the vessel during a given reporting year.

Therefore, the difference between these two determines whether the vessel has a positive balance, in which case no penalty is imposed, or a negative balance, which results in a penalty.

The penalty is calculated based on the following equation:

$$FuelEU\ Penalty\ [EUR\ €] = \frac{|Compliance\ Balance|}{GHGIE_{actual} x 41{,}000} x 2{,}400 \quad (7)$$

Where,

- 41,000 MJ/tfuel : It is used as a constant and represents the lower heating value of VLSFO, which is applied to convert the compliance balance and the $GHGIE_{actual}$ into an equivalent emissions deficit expressed in tonnes.
- 2,400 €/tfuel : It represents the penalty imposed per metric tonne of VLSFO-equivalent emissions deficit.

An important provision of the regulation is that, if a penalty is imposed on a vessel and is not offset through the previously mentioned flexibility mechanisms, but instead is paid, then in the following year—should the vessel again incur a penalty—it will be calculated differently. Specifically, the penalty is increased by 10% for each consecutive year in which the vessel fails to comply with the regulation and continues to rely on penalty payments instead of corrective measures.

$$Total\ Penalty = FuelEU\ Penalty\ x\ (1 + (n-1)x0.10) \quad (8)$$

Where, n represents the number of consecutive years during which the vessel has failed to comply with the regulation.

Before presenting the case studies, an overview of the compliance balance calculation is provided. The first step involves determining the $GHGIE_{target}$, as the limit is progressively reduced at regular intervals, leading to a gradual tightening of the regulatory requirements. The corresponding limits are presented in Fig. 22.

Timeline	Reduction Percentage	GHGIE target
From 1 January 2025	-2%	89.33680 gCO_2e/MJ
From 1 January 2030	-6%	85.69040 gCO_2e/MJ
From 1 January 2035	-14.5%	77.94180 gCO_2e/MJ
From 1 January 2040	-31%	62.90040 gCO_2e/MJ
From 1 January 2045	-62%	34.64080 gCO_2e/MJ
From 1 January 2050	-80%	18.23200 gCO_2e/MJ

Figure 22:Maximum allowable GHG intensity for shipboard energy under FuelEU regulation.

The second step involves calculating the total fuel consumption of the vessel over a given reporting period, including both voyages and port operations. For each fuel consumed, the following equation is applied:

$$\sum_{i}^{n\ fuel} M_i x LCV_i$$

If electrical energy is supplied through Onshore Power Supply (OPS), the following term is also included:

$$\sum_{c}^{k} E_k$$

Subsequently, the $GHGIE_{actual}$ is calculated in accordance with Annex I, and finally the compliance balance is determined.

It is important to note that voyages between ports within the EU are fully covered by the regulation, meaning that 100% of the associated emissions are accounted for. In contrast, for voyages involving ports outside the EU, where the vessel departs from or arrives at an EU port, only 50% of the emissions are considered under the regulation.

4.1.1 Conventional-Fueled Crude Oil Tanker

In this case study, an Aframax crude oil tanker is considered, with the following characteristics:

LOA 245.07m

LBP 233m

Deadweight 108,926 mt

Main Engine: MAN B&W 6S60MC-C

MCR 13560 KW AT 105 RPM

NCR 12204 KW AT 101,4 RPM

The vessel carried out a voyage between Ruwais in the United Arab Emirates and Antwerp, covering a distance of 6,523 nautical miles. It should be noted that this voyage involves a route between a non-EU port and an EU port. Therefore, in accordance with the regulation, only 50% of the total emissions will be considered in the calculation of the final compliance balance.

During this voyage, the vessel consumed 750 metric tonnes of HFO and 220 metric tonnes of MGO.

Proceeding with the calculation,

Initially, the quantity corresponding to the EEA–non-EEA voyage is determined as follows:

Step 1: HFO: $750 * 0{,}5 = 375 MT$ *and* $MGO: 220 * 0.5 = 110 MT$

Based on these quantities, namely 375 metric tonnes of HFO and 110 metric tonnes of MGO, the compliance balance will be calculated.

The lower calorific values (LCV) of the fuels are:

Step 2: $0.0405\ MJ/g$ *and* $0.0427\ MJ/g$, respectively.

Taking the above data into account, the fuel quantities must be converted into energy expressed in million MJ (i.e., units of 10^6MJ). Therefore,

Step 3: $375x0{,}0405x100\% =$
$15.1875x10^6 MJ$ *for HFO and for MGO* $110x0{,}0427x100\% = 4.697x10^6 MJ$

From Annex II, column 4 from Fig 17, for the specific fossil fuels considered, the following values for WtT GHG emissions are obtained:

Step 4: 13.5 gCO_2eq/MJ for HFO and 14.4 gCO_2eq/MJ for MGO.

1	2	3	4	5	6	7	8	9
			WtT	TtW				
Fuel Class	Pathway name	LCV [MJ/g]	$CO_{2eq\ WtT}$ [gCO2eq/MJ]	Fuel Consumer Unit Class	$C_{f\ CO_2}$ [gCO2/gFuel]	$C_{f\ CH_4}$ [gCH_4/gFuel]	$C_{f\ N_2O}$ [gN_2O/gFuel]	C_{slip} As % of the mass of the fuel used by the engine
	HFO ISO 8217 Grades RME to RMK	0,0405	13,5	ALL ICEs	3,114	0,00005	0,00018	-
	MDO MGO ISO 8217 Grades DMX to DMB	0,0427	14,4	ALL ICEs	3,206	0,00005	0,00018	-

Figure 23: Annex II Fossil Fuel default values.

Retrieved from: European Sustainable Shipping Forum (ESSF), Sustainable Alternative Power for Shipping, FuelEU Calculation Methodologies Workstream.

Again, from Annex II, the TtW emission values are obtained from columns 6 to 9, and more specifically for:

Step 5: TtW_{CO_2} : $3.114/0.0405 = 76.88889\ gCO_2eq/$
MJ *for HFO and for* $MGO: 3.206/0.0407 = 75.08197\ gCO_2eq/MJ$

$$TtW_{CH_4} : 0.00005 / 0.0405\ x\ 25\ =\ 0.03086\ \frac{gCO_2eq}{MJ}\ \ and\ 0.00005/$$
$$0.0427\ x\ 25\ = 0.03086\ \frac{gCO_2eq}{MJ}$$

$$TtW_{N_2O} : 0.00018/\ 0.0405\ x\ 298\ =\ 1.32444\ \frac{gCO_2eq}{MJ}\ \ and\ 0.00018/$$
$$0.0427\ x\ 298\ =\ 1.25621\ \frac{gCO_2eq}{MJ}.$$

$TtW_{CH_4\ slip}$ 0% for both fuels.

Therefore, the total emissions attributed to TtW GHG are: TtW_{HFO}=78.24420 $\frac{gCO_2eq}{MJ}$ and TtW_{MGO} = 76.36745$\frac{gCO_2eq}{MJ}$.

With regard to the reward factor, RWD, for the use of RFNBOs, it is set equal to 1.

Hence, for the five-year period 2025–2029,

Step 6: GHG intensity target: $91.16\ (which\ is\ the\ reference\ value)\ x\ (1 - 0.02)\ =\ 89.33680\ \frac{gCO_2eq}{MJ}$.

Step 7: Energy use in scope: 15,187,500 + 4,697,000 = 19,884,500 MJ

Step 8: WtT GHG intensity: $((13.5x15{,}187{,}500) + (14.4x4{,}697{,}000))/ 19{,}884{,}500\ =\ 13.71259\ \frac{gCO_2eq}{MJ}$.

Step 9: TtW GHG intensity: $((78.24420x15{,}187{,}500) + (76.36745\ x\ 4{,}697{,}000))/$ 19,884,500 = 77.80089 $\frac{gCO_2eq}{MJ}$.

Step 10: $GHGIE_{actual}$ = 13.71259+77.80089 = 91.51348$\frac{gCO_2eq}{MJ}$.

Step 11: Compliance balance: $(89.33680 - 91.51348)x19{,}884{,}500$ = -43,282,193.46 gCO_2eq.

Step 12: Penalty: $\frac{|-43{,}282{,}193.46|}{(91.51348x41000)}\ x\ 2400\ =\ 27{,}685.45$ €.

4.1.2 LNG Dual-Fuel Crude Oil Tanker

For the purposes of this case study, an Aframax tanker of 114,598 DWT is considered, equipped with a dual-fuel engine using natural gas as its primary fuel. More specifically, the vessel is powered by a main engine operating on a dual-fuel LNG Otto-cycle configuration (low-pressure, four-stroke), intended for low-speed operation. This engine primarily uses LNG, while MDO is employed as pilot fuel to initiate and stabilize combustion. In addition, the vessel is fitted with auxiliary engines capable of operating on LNG, which are assumed to function under medium-speed conditions.

Further technical particulars cannot be disclosed, in accordance with the company's request to preserve anonymity.

Accordingly, proceeding with the calculation methodology and explaining each step separately, it should be emphasized that, in this case, natural gas is used as the main fuel and the vessel performs a voyage between EU ports.

Therefore,

Step 1: LNG (dual Fuel slow speed) 750 MT, LNG (Dual Fuel medium speed) 75MT and MGO: 125MT

The lower calorific values (LCV) of the fuels are:

Step 2: 0.0491 MJ/g $for\ LNG\ and$ 0.0427 MJ/g, for MDO respectively.

Taking the above data into account, the fuel quantities must be converted into energy expressed in million MJ (i.e., units of 10^6MJ). Therefore,

Step 3: $750x0.0491x100\% = 36.825x10^6\ MJ$ for LNG slow speed,
$75x0.0491x100\% = 3.6825x10^6\ MJ$ for LNG medium speed and
$125x0.0427x100\% = 5.3375x10^6\ MJ$ for MDO.

From Annex II, column 4 from for the specific fossil fuels considered, the following values for WtT GHG emissions are obtained:

Step 4: 18.5 gCO_2eq/MJ for LNG and 14.4 gCO_2eq/MJ for MGO

From Annex II, the TtW emission values are obtained from columns 6 to 9, and more specifically for:

Step 5: TtW_{CO_2}= 2.750 / 0.0491 = 56.00815 gCO_2eq/MJ for LNG and for MGO:
$3.206/0.0407 = 75.08197\ gCO_2eq/MJ$

$TtW_{CH_4} = 0 / 0.0491\ x\ 25 = 0$ for LNG and for MGO: $0.00005/0.0427\ x\ 25 = 0.03086\ \frac{gCO_2eq}{MJ}$.

TtW_{N_2O} : $0.00011/ 0.0491\ x\ 298$ = 0.66762 $\frac{gCO_2eq}{MJ}$ and $0.00018/0.0427\ x\ 298$ = 1.25621 $\frac{gCO_2eq}{MJ}$.

$TtW_{CH_4\ slip}$ = 1.7% for slow speed και 3.1% for medium speed LNG while on MGO is 0%.

Therefore, the total emissions attributed to TtW GHG are:

$TtW_{LNG\ slow\ speed}$ =

$$(1 - 0.017)x(56.00815 + 0 + 0.66762) + (0.017x25)/0.0491 = 64.36808 \frac{gCO_2eq}{MJ},$$

$$TtW_{LNG\ medium\ speed} = (1 - 0.031)x\ (56.00815 + 0 + 0.66762) + (0.031x25)/ 0.0491 = 70.70293\ \frac{gCO_2eq}{MJ}$$

$$TtW_{MGO} = 76.36745 \frac{gCO_2eq}{MJ}.$$

With regard to the reward factor, RWD, for the use of RFNBOs, it is set equal to 1.

Hence, for the five-year period 2025–2029,

Step 6: GHG intensity target: $91.16\ (which\ is\ the\ reference\ value)\ x\ (1 - 0.02)$ = $89.33680 \frac{gCO_2eq}{MJ}$.

Step 7: Energy use in scope: 36,825,000 + 3,682,500+5,337,500 = 45,845,000 MJ

Step 8: WtT GHG intensity: $((18.5x36{,}825{,}000) + (18.5x3{,}682{,}500) + (14.4x5{,}337{,}500))/\ 45{,}845{,}000$ = $18.02270\ \frac{gCO_2eq}{MJ}$.

Step 9: TtW GHG intensity: $((64.36808x36{,}825{,}000) + (70.70293x3{,}682{,}500) + (76.36745\ x\ 5{,}337{,}500))/45{,}845{,}000$ = $66.27395\ \frac{gCO_2eq}{MJ}$.

Step 10: $GHGIE_{actual}$ = 18.02270+ 66.27395 = $84.29665\ \frac{gCO_2eq}{MJ}$.

Step 11: Compliance balance: $(89.33680 - 84.29665)x\ 45.845.000 = 231{,}065{,}676.75\ gCO_2eq$ or $231.0660\ tnCO_2eq.$

Step 12: Penalty: It is not applicable, as the vessel has a surplus. In this case, the vessel may either bank the surplus for use in future years in the event of non-compliance, or utilize it within a pooling mechanism, allowing the surplus to be transferred to other vessels.

4.1.3 Alternative Low-Carbon Fuels

Methanol-Fueled Configuration

The use of methanol as a fuel represents a significant innovation for the global maritime sector. As discussed previously, its application has a positive impact not only on the environment through the reduction of emissions, but also on regulatory compliance. This reduction in emissions can result in a positive compliance balance, which may be utilized through banking for future years or through pooling mechanisms.

The use of methanol is further incentivized through a RWD equal to 2, while the WtT emissions are determined based on the PoS in accordance with RED Annex VI Part D.

Ammonia-Fueled Configuration

The use of ammonia as a fuel contributes positively to the overall compliance balance of the vessel under the regulation, as it is incentivized through the RWD, which in this case takes a value of 2. However, ammonia is associated with increased TtW emissions, particularly in relation to N_2O.

With respect to WtT emissions, these are determined based on the PoS, in accordance with RED Annex VI Part D. In all other respects, the calculation methodology remains unchanged, and depending on the extent of ammonia utilization, the vessel may achieve a lower penalty or a more favorable compliance balance.

4.2 FuelEU-Based Economic Assessment of Alternative Marine Fuels

As illustrated in Figure 22, the GHG emission limits are progressively reduced over time, resulting in increasingly stringent regulatory requirements. Consequently, the economic dimension becomes a critical factor in the evaluation of alternative marine fuels. This section assesses the economic viability of alternative fuels within the context of the progressively tightening FuelEU Maritime framework. Given that the regulation imposes increasingly demanding greenhouse gas intensity reduction targets, the economic attractiveness of each fuel cannot be evaluated solely based on its current price or availability. Instead, it must be examined in a broader context that includes future compliance costs, potential penalties, fuel availability, infrastructure readiness, and the level of technological maturity.

Based on the FuelEU compliance calculation methodology presented in the previous section, along with the corresponding case studies, the following tables illustrate the progression of compliance penalties as GHG emission limits become increasingly stringent over time.

For the case study presented in Section 4.1.1, involving a conventional diesel engine, the progressive reduction of the emission limits results in the following table:

Timeline	Reduction Percentage	GHGIE target	Penalty
From 1 January 2025	-2%	89.33680 $\frac{gCO_2eq}{MJ}$	27,685.45€
From 1 January 2030	-6%	85.69040$\frac{gCO_2eq}{MJ}$	74,064.45€
From 1 January 2035	-14.5%	77.94180$\frac{gCO_2eq}{MJ}$	172,619.8€
From 1 January 2040	-31.5%	62.90040$\frac{gCO_2eq}{MJ}$	363,933.14€
From 1 January 2045	-62%	34.64080$\frac{gCO_2eq}{MJ}$	723,370.32€
From 1 January 2050	-80%	18.23200 $\frac{gCO_2eq}{MJ}$	932,075.78€

As illustrated in the table, the penalty associated with the use of conventional fuels becomes extremely high by 2050. It should be noted that this does not account for the additional cost incurred if the company chooses to pay the penalty, in which case it will be further increased in subsequent years.

With regard to the use of an LNG dual-fuel engine, as calculated in Case Study 4.1.2:

Timeline	Reduction Percentage	GHGIE target	Penalty	Surplus
From 1 January 2025	-2%	89.33680 $\frac{gCO_2eq}{MJ}$	N/A	231.0660 $tnCO_2eq$
From 1 January 2030	-6%	85.69040$\frac{gCO_2eq}{MJ}$	N/A	63.89 $tnCO_2eq$
From 1 January 2035	-14.5%	77.94180$\frac{gCO_2eq}{MJ}$	202,308.62€	N/A
From 1 January 2040	-31.5%	62.90040$\frac{gCO_2eq}{MJ}$	681,156.19€	N/A
From 1 January 2045	-62%	34.64080$\frac{gCO_2eq}{MJ}$	1,580,809.24€	N/A
From 1 January 2050	-80%	18.23200 $\frac{gCO_2eq}{MJ}$	2,103,188,43€	N/A

In the case of LNG, it is evident that the fuel remains a viable option up to approximately 2034. As shown, a vessel operating with an LNG dual-fuel engine achieves a compliance surplus during this period, which can either be traded to other vessels through the pooling mechanism or banked for future use.

However, from 2035 onwards, the vessel begins to exhibit a compliance deficit, leading to the imposition of penalties. Depending on the FuelEU parameters, these penalties may become significant and, in certain cases, even higher than those associated with conventional engines over the same time horizon. For this reason, the global maritime industry has expressed concerns regarding the regulation, arguing that investments in LNG are not sufficiently recognized or incentivized under the current framework.

With regard to the use of methanol and ammonia, the corresponding calculations are performed depending on their application, ensuring compliance with the FuelEU framework. However, these fuels introduce a degree of uncertainty, particularly in relation to their future pricing, the availability of bunkering infrastructure, and the extent of their widespread adoption. More specifically, the key question remains whether the maritime industry will fully adopt these fuels, based on their ability to ensure operational safety, demonstrate economic viability, and effectively contribute to the reduction of the environmental footprint.

The cost of marine fuels, both at present and in the future, constitutes one of the most critical factors influencing the viability of the transition towards a low-emission shipping sector. In order for this transition to be effectively realized, it is essential to establish a robust supply chain that ensures the widespread availability and accessibility of alternative fuels on a global scale. Furthermore, the production of these fuels is closely linked to the availability of renewable energy sources, as well as to the level of investment directed towards their development. At the same time, geopolitical factors introduce a significant degree of uncertainty, as they can strongly influence both fuel availability and price dynamics. Consequently, the future cost and accessibility of alternative marine fuels will be determined by a complex interaction between technological progress, energy policies, market forces, and geopolitical developments.

Conventional oil fuels and natural gas, both of which are fossil fuels, currently remain the driving force of the maritime industry, as their production, distribution networks,

and global infrastructure are already well established. Their prices are largely influenced by major decision-making centers that regulate production levels according to market conditions. Consequently, geopolitical developments play a significant role in determining fuel prices and availability, rather than limitations associated with infrastructure development or fuel production capacity. However, it becomes increasingly evident that, due to the continuously tightening environmental regulations aimed at reducing emissions, both fuels may gradually become economically disadvantageous for long-term maritime use.

Turning to alternative fuels, and more specifically methanol and ammonia, their future adoption and establishment within the maritime sector can largely be summarized through three key factors: fuel availability, infrastructure development, and energy cost.

In the case of methanol, the most significant barrier to its widespread adoption remains the cost of energy. According to market data from the ARA region (Amsterdam–Rotterdam–Antwerp), the price of bio-methanol was approximately 3,500 USD/tMGOe in 2022, decreasing to around 2,500 USD/tMGOe in 2025, based on data reported by Argus Media (via AFI.com). For e-methanol and blue methanol, reliable market price information remains limited. Due to the relatively short pricing history available for bio-methanol, it is still unclear whether the observed reduction in prices between 2020 and 2025 reflects a long-term decrease in production costs or is simply associated with fluctuations in fossil methanol prices. Fossil methanol prices were estimated at approximately 1,000 USD/tMGOe in 2022 and around 700 USD/tMGOe in 2025, based on prices in Rotterdam, Southeast Asia, and the US Gulf region. Consequently, fossil methanol remained approximately three times cheaper than green methanol during this period. At the same time, MGO prices fluctuated at levels relatively close to those of fossil methanol.

Future cost projections are considered equally important for decision-makers, although they remain subject to considerable uncertainty. According to estimates published by DNV, the production and distribution cost of bio- and e-methanol could range between approximately 1,200 and 2,050 USD/tMGOe by 2050. Other organizations, such as IRENA and the Methanol Institute (2021), provide broader projections, estimating future methanol costs within a range of approximately 490 to 1,900 USD/tMGOe by 2050.

With regard to infrastructure related to the handling and distribution of methanol, the existing network can be considered relatively well developed, since methanol is already a widely used chemical product with extensive industrial applications beyond the maritime sector. As a result, methanol storage facilities are currently available in more than 115 ports worldwide. Furthermore, compared to LNG, ammonia, and hydrogen, methanol offers the significant advantage of remaining in liquid form under ambient temperature and pressure conditions, simplifying storage and transportation requirements.

According to MARPOL Annex II, methanol must be transported using chemical tankers. Nevertheless, existing fuel oil barges may also contribute to methanol bunkering operations following appropriate modifications and safety adaptations. Consequently, there remains additional potential for the development and expansion of dedicated methanol bunkering barges.

Regarding fuel availability, the current demand for low-greenhouse-gas methanol within the shipping sector remains relatively limited. To date, most methanol consumed onboard vessels has consisted of fossil methanol, primarily used on methanol carriers, while only small quantities of bio-methanol have been bunkered since 2023. According to the Maritime and Port Authority of Singapore, methanol bunker sales in Singapore increased from approximately 300 tonnes in 2023 to 1,600 tonnes in 2024. The volumes reported for 2023 are associated with green methanol, as the port conducted the world's first ship-to-containership green methanol bunkering operation during that year.

Similarly, the Port of Rotterdam reported increasing bio-methanol bunker volumes, from approximately 800 tonnes in 2023 to 4,000 tonnes in 2024, reaching nearly 11,800 tonnes by the third quarter of 2025. Additional methanol bunkering activities have also been reported at several other locations worldwide. Moreover, Maersk announced the first bunkering operations involving e-methanol in Denmark during 2025.

At present, global production capacity is sufficient to satisfy existing shipping demand for low-GHG methanol, particularly since shipping is not yet the dominant consumer of this fuel. According to AFI data, worldwide production capacity currently amounts to approximately 2.2 million tonnes annually, with nearly 98% corresponding to bio-methanol production and the remaining share to e-methanol. Production capacity is primarily concentrated in the United States, followed by China.

However, given the projected increase in future demand, production expansion becomes a critical factor. AFI project databases indicate that already approved projects could increase global methanol production capacity to approximately 14 million tonnes by 2030, with around 30% corresponding to e-methanol and 70% to bio-methanol production [56].

Turning to ammonia, which currently represents the least technologically mature solution among the alternative fuels examined, significant efforts are being made toward its gradual integration into the global maritime supply chain. Due to the high toxicity of ammonia, the first dedicated safety regulations and approvals were introduced in 2020. In parallel, amendments were implemented in the IGC Code (International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk), allowing the transportation of ammonia as fuel cargo. However, the corresponding modifications to the IGF Code are not expected to be finalized and fully implemented before approximately 2032.

With regard to fuel cost, green ammonia currently remains substantially more expensive than conventional marine fuels. In Europe, green ammonia prices are estimated at approximately 2,900 USD per tonne of marine gas oil equivalent (tMGOe), corresponding to nearly five times the price of conventional MGO. Blue ammonia has only recently entered the market and remains available in limited quantities. Nevertheless, future projections indicate that ammonia costs could decrease to approximately 1,000–1,900 USD/tMGOe by 2050, potentially approaching cost parity with MGO when carbon pricing mechanisms are considered. In this context, regulatory measures such as the EU Emissions Trading System (2024), FuelEU Maritime (2025), and potential future IMO market-based mechanisms may gradually shift the economic balance in favor of low-carbon fuels. Although the current cost gap remains significant, indications suggest that it may progressively narrow over time.

Regarding infrastructure, virtually no dedicated ammonia bunkering infrastructure existed prior to 2020. However, by 2025, countries such as Australia, China, Japan, Netherlands, and United Kingdom had already demonstrated safe ammonia transportation capabilities. In addition, major hubs within the global maritime supply chain, including Rotterdam and Singapore, are currently testing pilot projects and developing terminal infrastructure aimed at supporting future ammonia bunkering operations.

With regard to fuel availability, ammonia production is already established on a global scale due to its extensive use in the agricultural and chemical industries, particularly in fertilizer production. This existing industrial background provides an important advantage for its potential adoption as a marine fuel, as significant production know-how and transportation experience are already available. However, the majority of ammonia currently produced worldwide is derived from fossil fuels, resulting in substantial associated greenhouse gas emissions. Consequently, the future viability of ammonia as a sustainable marine fuel depends largely on the expansion of low-carbon production pathways, such as blue and green ammonia.

At present, the availability of low-GHG ammonia remains limited, mainly due to the high energy demand and investment costs associated with its production. Nevertheless, several large-scale projects are currently under development worldwide, aiming to increase production capacity and establish dedicated supply chains for the maritime sector. As environmental regulations become stricter and demand for carbon-neutral fuels increases, ammonia availability is expected to improve progressively over the coming decades [57].

Based on the analysis presented above, the following table provides a concise comparative overview of the examined fuels. It summarizes the principal parameters expected to influence the selection of future marine fuels, combining the technical, environmental, operational, infrastructural, and economic aspects that will ultimately determine the attractiveness and long-term viability of each investment option within the evolving regulatory framework of the maritime industry.

Parameter	**Conventional Fuels (HFO/MGO)**	**LNG**	**Methanol**	**Ammonia**
Infrastructure Availability	Fully established globally	Well-developed and expanding	Moderate to good	Limited but developing
Fuel Availability	Very High	High	Currently limited	Currently very limited
Storage Conditions	Ambient conditions	Cryogenic(-161℃)	Ambient conditions	Pressurised/ refrigerated
Operational Safety Challenges	Low	Methane leakage/ cryogenic risks	Toxicity/ flammability	High toxicity
Retrofit Potential	N/A	High	Moderate to high	Limited currently
Estimated Economic Viability until 2035	Increasingly expensive due to penalties	Economically attractive	Expensive but improving	Very expensive
Estimated Economic	Likely non-viable	Reduced competitiveness	Potentially competitive	Potentially competitive

Viability until 2050				
Main Barrier	FuelEU penalties	Methane slip & future compliance	Fuel cost	Technology maturity & safety
Main Advantage	Existing infrastructure	Immediate emissions reduction	Lower emissions & easier handling	Carbon-free combustion potential

4.3 Discussion

The FuelEU mechanism, as analysed in detail and supported by appropriate case studies covering both conventional and alternative fuels, is expected to significantly reshape the operational framework of the global maritime industry. The regulation systematically promotes the adoption of alternative fuels through progressively stricter requirements, driving a transition toward more sustainable practices. This transition aims to reduce exhaust gas emissions and ultimately minimize the environmental footprint of shipping.

From the perspective of the maritime community, the industry is making efforts to adapt to these new conditions; however, several concerns have been raised. These mainly relate to the rapid pace of implementation, which may not be adequately supported by sufficient financial incentives for investment in innovative vessels and technologies. In addition, certain technologies are still under development, leading to uncertainty even among engine manufacturers regarding their performance and long-term reliability. Furthermore, the global supply infrastructure for alternative fuels, particularly methanol, is not yet fully developed, although natural gas is gradually gaining ground in the global marine fuel market.

On the other hand, the European Union emphasizes that the transition toward a sustainable and low-carbon future is essential. It also highlights that revenues generated from penalties will be reinvested to support the development of green technologies, assist sectors most affected by the energy transition, and finance initiatives aimed at achieving long-term sustainability goals.

5.Conclusion

In concluding this thesis, it becomes evident that the international maritime community has actively addressed the challenge of decarbonization and the progressive reduction of its environmental footprint. Both the IMO and the European Union have established mechanisms to monitor and quantify vessel fuel consumption as well as their CO_2 equivalent emissions. In addition, structured frameworks have been introduced to ensure regulatory compliance, requiring shipping companies to systematically document and demonstrate how they meet the applicable environmental requirements.

The European Union, through the Fit for 55 package, has set a target of reducing greenhouse gas emissions by 55% by 2030. Within this framework, several regulatory instruments have been introduced. These include the EU ETS, which assigns an economic cost to carbon emissions within a market-based system; RED, which ensures the certification and sustainability of alternative fuels; AFIR, which promotes the development of the necessary infrastructure to support the use of such fuels; and the ETD, which encourages the uptake of alternative fuels through favorable taxation policies while imposing higher taxation on conventional fuels. All these measures are closely linked to the FuelEU mechanism, which integrates the aforementioned frameworks and provides the necessary tools for vessels to achieve compliance with the regulation.

Dual-fuel engines constitute a key enabler for the transition of shipping toward a more sustainable and low-carbon future. Both engine manufacturers and shipping companies have engaged in significant investment efforts, adopting innovative technologies and retrofit solutions to enable the use of alternative or transitional fuels, such as liquefied natural gas. This thesis has focused on dual-fuel engines operating on LNG, ammonia, and methanol, as substantial technological progress has been achieved in these areas compared with other emerging solutions, such as hydrogen-based systems or small modular nuclear reactors, which are still at an earlier stage of development.

The FuelEU mechanism, which ultimately leads to the determination of a compliance balance, has been analysed in detail based on Annex I of the regulation. To support this analysis, a series of case studies has been presented, illustrating how vessels operating on different fuel types may result in either a positive or negative compliance balance. A positive balance indicates compliance and may be utilized through mechanisms such as pooling or banking for future reporting periods. Conversely, a negative balance implies non-compliance, in which case the vessel must either rely on these flexibility mechanisms or be subject to penalties.

Shipping, as a global industry, has demonstrated its ability to adapt to the evolving regulatory landscape and environmental requirements. A significant number of companies have responded proactively through investments in more efficient vessels and technologies. Nevertheless, industry stakeholders express concerns not about the necessity of reducing emissions, but rather about the current limitations in infrastructure and the pace at which technological developments are expected to keep up with regulatory demands. In any case, these new regulations are now a reality. The transition period has effectively come to an end, and the maritime sector is entering a phase of full implementation, as emissions reported for 2026 will be fully accounted for in 2027.

This marks a decisive step toward a more structured and accountable regulatory environment, reinforcing the industry's commitment to achieving a sustainable and low-carbon future.

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Appendices

Appendix A- Extract from Annex II of Regulation (EU) 2023/1805 (FuelEU Maritime).

Default emissions factors

1	2	3	4	5	6	7	8	9
			WtT	TtW				
Fuel Class	Pathway name	LCV $\left[\frac{MJ}{g}\right]$	$CO_{2eq\ WtT}$ $\left[\frac{gCO2eq}{MJ}\right]$	Fuel Consumer Unit Class	$C_{f\ CO_2}$ $\left[\frac{gCO2}{gFuel}\right]$	$C_{f\ CH_4}$ $\left[\frac{gCH_4}{gFuel}\right]$	$C_{f\ N_2O}$ $\left[\frac{gN_2O}{gFuel}\right]$	C_{slip} As % of the mass of the fuel used by the engine
Fossil	HFO ISO 8217 Grades RME to RMK	0,0405	13,5	ALL ICEs	3,114	0,00005	0,00018	-
	LFO ISO 8217 Grades RMA to RMD	0,041	13,2	ALL ICEs	3,151	0,00005	0,00018	-
	MDO MGO ISO 8217 Grades DMX to DMB	0,0427	14,4	ALL ICEs	3,206	0,00005	0,00018	-

1	2	3	4	5	6	7	8	9
			WtT	TtW				
Fuel Class	Pathway name	LCV $\left[\frac{MJ}{g}\right]$	$CO_{2eq\ WtT}$ $\left[\frac{gCO2eq}{MJ}\right]$	Fuel Consumer Unit Class	$C_{r\ CO_2}$ $\left[\frac{gCO2}{gFuel}\right]$	$C_{r\ CH_4}$ $\left[\frac{gCH_4}{gFuel}\right]$	$C_{r\ N_2O}$ $\left[\frac{gN_2O}{gFuel}\right]$	C_{slip} As % of the mass of the fuel used by the engine
Fossil	LNG	0,0491	18.5	LNG Otto (dual fuel medium speed)	2,750	0	0,00011	3,1
				LNG Otto (dual fuel slow speed)				1,7
				LNG Diesel (dual fuel slow speed)				0,2
				LBSI				2,6
	LPG	0,046	7,8	ALL ICEs	3,030 Butane 3,000 Propane	TBM	TBM	N/A
	H2 (natural gas)	0,12	132	Fuel Cells	0	0	-	-
				ICE	0	0	TBM	
	NH3 (natural gas)	0,0186	121	Fuel Cells	0	N/A	TBM	N/A
				ICE	0	N/A	TBM	N/A
	Methanol (natural gas)	0,0199	31,3	ALL ICEs	1,375	TBM	TBM	-

1	2	3	4	5	6	7	8	9
			WtT	TtW				
Fuel Class	Pathway name	LCV $\left[\frac{MJ}{g}\right]$	$CO_{2eq\ WtT}$ $\left[\frac{gCO2eq}{MJ}\right]$	Fuel Consumer Unit Class	$C_{f\ CO_2}$ $\left[\frac{gCO2}{gFuel}\right]$	$C_{f\ CH_4}$ $\left[\frac{gCH_4}{gFuel}\right]$	$C_{f\ N_2O}$ $\left[\frac{gN_2O}{gFuel}\right]$	C_{slip} As % of the mass of the fuel used by the engine
Biofuels	Ethanol Production Pathways of Directive (EU) 2018/2001	Value as set out in Annex III of Directive (EU) 2018/2001	$E - \frac{C_{fCO_2}}{LCV}$	ALL ICEs	1,913	TBM	TBM	-
	Bio-diesel Production Pathways of Directive (EU) 2018/2001			ALL ICEs	2,834	TBM	TBM	-
	Hydrotreated Vegetable Oil (HVO) Production Pathways of Directive (EU) 2018/2001			ALL ICEs	3,115	0,00005	0,00018	-
	Liquefied Bio-methane as transport fuel (Bio-LNG) Production Pathways of Directive (EU) 2018/2001			LNG Otto (dual fuel medium speed)	2,750	0	0,00011	3,1
				LNG Otto (dual fuel slow speed)				1,7
				LNG Diesel (dual fuels)				0,2
				LBSI				2,6

1	2	3	4	5	6	7	8	9
			WtT	TtW				
Fuel Class	Pathway name	LCV $\left[\frac{MJ}{g}\right]$	$CO_{2eq\ WtT}$ $\left[\frac{gCO2eq}{MJ}\right]$	Fuel Consumer Unit Class	$C_{r\ CO_2}$ $\left[\frac{gCO2}{gFuel}\right]$	$C_{r\ CH_4}$ $\left[\frac{gCH_4}{gFuel}\right]$	$C_{r\ N_2O}$ $\left[\frac{gN_2O}{gFuel}\right]$	C_{slip} As % of the mass of the fuel used by the engine
Biofuels	Bio-methanol Production Pathways of Directive (EU) 2018/2001	Value as set out in Annex III of Directive (EU) 2018/2001	N/A	ALL ICEs	1,375	TBM	TBM	-
	Other Production Pathways of Directive (EU) 2018/2001			ALL ICEs	3,115	0,00005	0,00018	-
	Bio-H2 Production Pathways of Directive (EU) 2018/2001			Fuel Cells	0	0	0	-
				ICE	0	0	TBM	
Renewable Fuels of Non-Biological Origin (RFNBO) - e-Fuels	e-diesel	0,0427	Ref. to Directive (EU) 2018/2001)	ALL ICEs	3,206	0,00005	0,00018	-
	e-methanol	0,0199	Ref. to Directive (EU) 2018/2001)	All ICEs	1,375	TBM	TBM	-
	e-LNG	0,0491	Ref. To Directive (EU) 2018/2001)	LNG Otto (dual fuel medium speed)	2,750	0	0,00011	3,1
				LNG Otto (dual fuel slow speed)				1,7
				LNG Diesel (dual fuels)				0,2
				LBSI				2,6

1	2	3	4	5	6	7	8	9
			WtT	TtW				
Fuel Class	Pathway name	LCV $\left[\frac{MJ}{g}\right]$	$CO_{2eq\ WtT}$ $\left[\frac{gCO2eq}{MJ}\right]$	Fuel Consumer Unit Class	$C_{f\ CO_2}$ $\left[\frac{gCO2}{gFuel}\right]$	$C_{f\ CH_4}$ $\left[\frac{gCH_4}{gFuel}\right]$	$C_{f\ N_2O}$ $\left[\frac{gN_2O}{gFuel}\right]$	C_{slip} As % of the mass of the fuel used by the engine
	e-H2	0,12	Ref. to Directive (EU) 2018/2001)	Fuel Cells	0	0	0	-
				ICE	0	0	TBM	
	e-NH3	0,0186	N/A	Fuel Cells	0	N/A	TBM	N/A
				ICE	0	N/A	TBM	N/A
	e-LPG	N/A	N/A		N/A	N/A	N/A	N/A
	e-DME	N/A	N/A		N/A	N/A	N/A	-
Others	Electricity	-	EU ENERGY MIX	On-shore power supply (OPS)	-	-	-	-

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