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“Shipping in Energy Transition Pathways to Meet IMO 2050 Greenhouse Gas Reduction Targets”

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Diploma Thesis

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Acronyms & Abbreviations	
AC	Alternative Current
AE	Auxiliary Engines
AER	Annual Efficiency Ratio
CCUS	Carbon Capture, Utilization, and Storage
CI	Carbon Intensity
CI	Compression Ignited
CII	Carbon Intensity Indicator
COP	Conference of the Parties
DC	Direct Current
DCS	Data Collection System
DF	Dual Fuel
DWT	Deadweight
EC	European Commission
ECA	Emission Control Area
EEA	European Economic Area
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EGR	Exhaust Gas Recirculation
EP	European Parliament
ESD	Energy Saving Devices
ESS	Energy Storage Systems
ETS	Emissions Trading System
EU	European Union
EUAs	EU Allowances
FAME	Fatty Acid Methyl Ester
FLL	Fuel Lifecycle Label

GD	Direct Gas Injection
GFS	GHG Fuel Standard
GHG	Greenhouse Gas
GT	Gross Tonnage
GWP	Global Warming Potential
HVSC	High Voltage Shore Connection
HVO	Hydrotreated Vegetable Oil
HFO	Heavy Fuel Oil
IAPP	International Air Pollution Prevention
ICE	Internal Combustion Engines
IEE	Initial Environmental Examination
IGC	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF	International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels
IMDG	International Maritime Dangerous Goods
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
ISWG-GHG	Intersessional Working Group on Reduction of GHG emissions
LCA	Lifecycle assessment
LHV	Lower Heating Value
Li-on	Lithium-ion
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MBM	Market-Based Measures
MDO	Marine Diesel Oil
ME	Main Engines
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil

MN	Methane Number
MRV	Monitoring, Reporting and Verification
OCCS	Onboard Carbon Capture and Storage
OCCUS	Onboard Carbon Capture, Use and Storage
OPS	Onshore Power Supply
PM	Particulate matter
PPE	Personal Protective Equipment
ppm	parts per million
PCC	Pure Car Carrier
PV	Solar Photovoltaic
R&D	Research & Development
RES	Renewable Energy Sources
RFNBOs	Renewable Fuels of Non-Biological Origin
RO	Recognized Organization
ROPAX	Roll-on/roll-off Passenger vessel
Ro-Ro	Roll-on/Roll-off vessel
RPM	Revolution Per Minute
SCR	Selective Catalytic Reduction
SECA	Sulphur Emission Control Area
SEEMP	Ship Energy Efficiency Plan
SFC	Specific Fuel Consumption
SI	Spark Ignited
SMR	Steam Methane Reforming
SOLAS	International Convention for the Safety of Life at Sea
STCW	Standards of Training, Certification & Watchkeeping for Seafarers)
TtP	Tank-to-Propeller
TtW	Tank-to-Wake
UNCLOS	United Nations Convention on the Law of the Sea
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change

VLCC	Very Large Crude Carrier
WAPS	Wind-Assisted Propulsion System
WMO	World Meteorological Organization
WtT	Well-to-Tank
WtW	Well-to-Wake

Methodology/Abstract

This thesis, entitled “Shipping in Energy Transition Pathways to Meet IMO 2050 Greenhouse Gas Reduction Targets” was developed as part of the postgraduate programme in Sustainability and Quality in Marine Industry at the Department of Maritime Studies, University of Piraeus, under the supervision of Assistant Professor Stefanos Chatzinikolaou.

The objective of this thesis is to examine the development of alternative fuels and their adoption by the shipping industry in response to the International Maritime Organization's (IMO) Greenhouse Gas (GHG) Reduction Strategy and the targets set for 2050. This master's thesis adopts a systematic and well-organized approach to investigate the landscape of emissions from shipping and the evolution of IMO GHG Reduction Strategy. As the maritime sector faces increasing pressure to reduce greenhouse gas emissions, the adoption of alternative fuels presents a viable pathway toward achieving the reduction targets and promoting sustainability. This central theme of thesis investigates the role of alternative marine fuels in the shipping industry, focusing on their application in internal combustion engines and analyzing their uptake trends in the newbuild orderbook.

The primary scope is to comprehend the evolution of IMO's GHG Reduction Strategy, exploring regulations, and measures geared towards reducing greenhouse gas emissions in international shipping. The study also delves into mid- and long-term market-based measures discussed by the IMO, while emphasis is placed on the promotion of research and development for sustainable marine fuels.

This study provides a comprehensive literature review of various alternative marine fuels (LNG, Methanol, Ammonia and Hydrogen), examining their production processes, emissions profiles, safety considerations, and regulatory frameworks. Additionally, the thesis provides insights into existing marine internal combustion engine technology and alternative propulsion technologies. The objective is to comprehend the interplay between IMO GHG Strategy, evolving regulations, and ship technologies, offering a comprehensive understanding of the potential of alternative marine fuels. The research scope extends to outlining the limitations associated with the alternative marine fuels.

Furthermore, this thesis is concluding with a descriptive data analysis of the adoption of alternative marine fuels by examining the global shipping newbuild orderbook during the period 2019-2024. The analysis aims to assess the uptake of alternative fuels and identify key trends in the shipping industry, revealing significant shifts in fuel preferences among different fleet types, highlighting the shipping industry's energy transition pathways.

This research contributes to the understanding of how alternative marine fuels can facilitate compliance with the IMO 2050 targets and support the shipping industry's efforts to achieve its decarbonization goals.

(Key words: Energy Transition, Alternative Fuels, Sustainability, Shipping Industry)

Μεθοδολογία/Περίληψη

Η διπλωματική εργασία, με τίτλο "Η Ναυτιλία στην Πορεία της Ενεργειακής Μετάβασης για την Επίτευξη των Στόχων Μείωσης των Εκπομπών Αερίων του Θερμοκηπίου του IMO για το 2050", αναπτύχθηκε στο πλαίσιο των μεταπτυχιακών σπουδών στο Τμήμα Ναυτιλιακών Σπουδών του Πανεπιστημίου Πειραιώς, υπό την επίβλεψη του Επίκουρου Καθηγητή Στέφανου Χατζηνικολάου.

Ο στόχος αυτής της διπλωματικής εργασίας είναι να εξετάσει την ανάπτυξη εναλλακτικών καυσίμων και την υιοθέτησή τους από τη ναυτιλιακή βιομηχανία σε απάντηση στη Στρατηγική Μείωσης των Εκπομπών Αερίων του Θερμοκηπίου του Διεθνούς Ναυτιλιακού Οργανισμού (IMO) και τους στόχους που έχουν τεθεί για το 2050. Αυτή η μεταπτυχιακή εργασία υιοθετεί μια συστηματική και καλά οργανωμένη προσέγγιση για να διερευνήσει το τοπίο των εκπομπών από τη ναυτιλία και την εξέλιξη της Στρατηγικής Μείωσης των Εκπομπών Αερίων του Θερμοκηπίου του IMO. Καθώς ο ναυτιλιακός τομέας αντιμετωπίζει αυξανόμενη πίεση για τη μείωση των εκπομπών αερίων του θερμοκηπίου, η υιοθέτηση εναλλακτικών καυσίμων παρουσιάζει μια βιώσιμη διαδρομή προς την επίτευξη των στόχων μείωσης και την προώθηση της βιωσιμότητας. Το κεντρικό θέμα της διπλωματικής εργασίας διερευνά τον ρόλο των εναλλακτικών ναυτιλιακών καυσίμων στη ναυτιλιακή βιομηχανία, εστιάζοντας στην εφαρμογή τους σε κινητήρες εσωτερικής καύσης και αναλύοντας τις τάσεις υιοθέτησής ως προς τις παραγγελίες νεότευκτων πλοίων.

Ο κύριος σκοπός είναι να κατανοηθεί η εξέλιξη της Στρατηγικής Μείωσης των Εκπομπών Αερίων του Θερμοκηπίου του IMO, εξερευνώντας κανονισμούς και μέτρα που στοχεύουν στη μείωση των εκπομπών αερίων του θερμοκηπίου στη διεθνή ναυτιλία. Η μελέτη εξετάζει επίσης τα μεσοπρόθεσμα και μακροπρόθεσμα μέτρα που συζητούνται από τον IMO ενώ ιδιαίτερη έμφαση δίνεται στην προώθηση της έρευνας και ανάπτυξης για βιώσιμα ναυτιλιακά καύσιμα.

Αυτή η μελέτη παρέχει μια εκτενή ανασκόπηση της βιβλιογραφίας για τα διάφορα εναλλακτικά ναυτιλιακά καύσιμα (Υγροποιημένο Φυσικό Αέριο (ΥΦΑ) , Μεθανόλη, Αμμωνία και Υδρογόνο), εξετάζοντας τη διαδικασία παραγωγής τους, τα προφίλ εκπομπών, τα ζητήματα ασφάλειας και τα κανονιστικά πλαίσια. Επιπλέον, η διπλωματική

εργασία παρέχει πληροφορίες για την υπάρχουσα τεχνολογία κινητήρων εσωτερικής καύσης και εναλλακτικές τεχνολογίες πρόωσης. Ο στόχος είναι να κατανοηθεί η αλληλεπίδραση μεταξύ της Στρατηγικής Μείωσης των Εκπομπών Αερίων του Θερμοκηπίου του IMO, των εξελισσόμενων κανονισμών και των τεχνολογιών πλοίων, προσφέροντας μια ολοκληρωμένη κατανόηση των δυνατοτήτων των εναλλακτικών ναυτιλιακών καυσίμων. Το ερευνητικό πεδίο επεκτείνεται στην περιγραφή των εμποδίων που σχετίζονται με τα εναλλακτικά ναυτιλιακά καύσιμα.

Επιπλέον, αυτή η διπλωματική εργασία καταλήγει με μια περιγραφική ανάλυση δεδομένων για την υιοθέτηση εναλλακτικών ναυτιλιακών καυσίμων, εξετάζοντας το παγκόσμιο βιβλίο παραγγελιών νεότευκτων πλοίων κατά την περίοδο 2019-2024. Η ανάλυση στοχεύει στην αξιολόγηση της υιοθέτησης εναλλακτικών καυσίμων και στον εντοπισμό βασικών τάσεων στη ναυτιλιακή βιομηχανία, αποκαλύπτοντας σημαντικές αλλαγές στην επιλογή καυσίμων μεταξύ διαφορετικών τύπων στόλων, υπογραμμίζοντας την πορεία της ενεργειακής μετάβασης της ναυτιλιακής βιομηχανίας.

Αυτή η έρευνα συμβάλλει στην κατανόηση του πώς τα εναλλακτικά ναυτιλιακά καύσιμα μπορούν να διευκολύνουν τη συμμόρφωση με τους στόχους του IMO για το 2050 και να υποστηρίξουν τις προσπάθειες της ναυτιλιακής βιομηχανίας να επιτύχει τους στόχους της για την απανθρακοποίηση.

(Λέξεις κλειδιά: Ενεργειακή Μετάβαση, Εναλλακτικά Καύσιμα, Βιωσιμότητα, Ναυτιλία)

1. Introduction: Global Warming and An Overview of Global Initiatives Addressing Climate Change

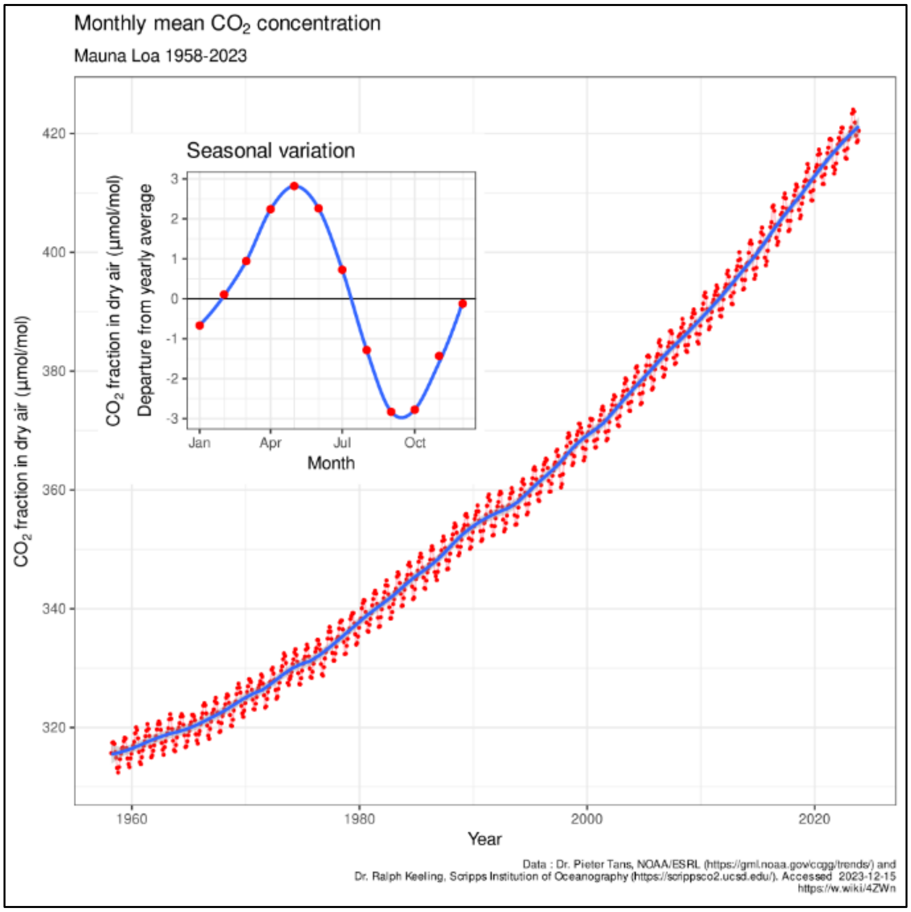
1.1. The Greenhouse effect and Global Warming

The greenhouse effect is a natural atmospheric phenomenon that plays a crucial role in maintaining Earth's temperature and making it suitable for life. It occurs when certain gases in the Earth's atmosphere, known as greenhouse gases, such as carbon dioxide, methane, and water vapor, trap and absorb outgoing infrared radiation from the sun. Instead of allowing this heat to escape back into space, the greenhouse gases re-radiate some of it back to the Earth's surface, effectively warming the planet. This process is essential for maintaining a habitable climate; without the greenhouse effect, the Earth’s average surface temperature would be about -18°C, while the recent average has been about 14-15°C.

The enhanced greenhouse effect is defining the increased concentration of greenhouse gases in the atmosphere due to human activities, intensifying the natural greenhouse effect and contributing to global warming. Global warming is posing serious environmental challenges, including rising temperatures, sea-level rise, and changes in weather patterns, with far-reaching impacts on ecosystems and human societies.

The increase in the concentration of greenhouse gases over the last century, particularly since the late 19th century, has been substantial and is primarily attributed to anthropogenic activities. The burning of fossil fuels, deforestation, industrial processes, and other human-related activities have led to a significant rise in the levels of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), among other greenhouse gases.

Before the Industrial Revolution in the mid-18th century, the concentration of carbon dioxide in the atmosphere was approximately 280 parts per million (ppm). As of 2022, it had surpassed 421 ppm, representing a substantial increase. Methane and nitrous oxide concentrations have also risen significantly over the past century.

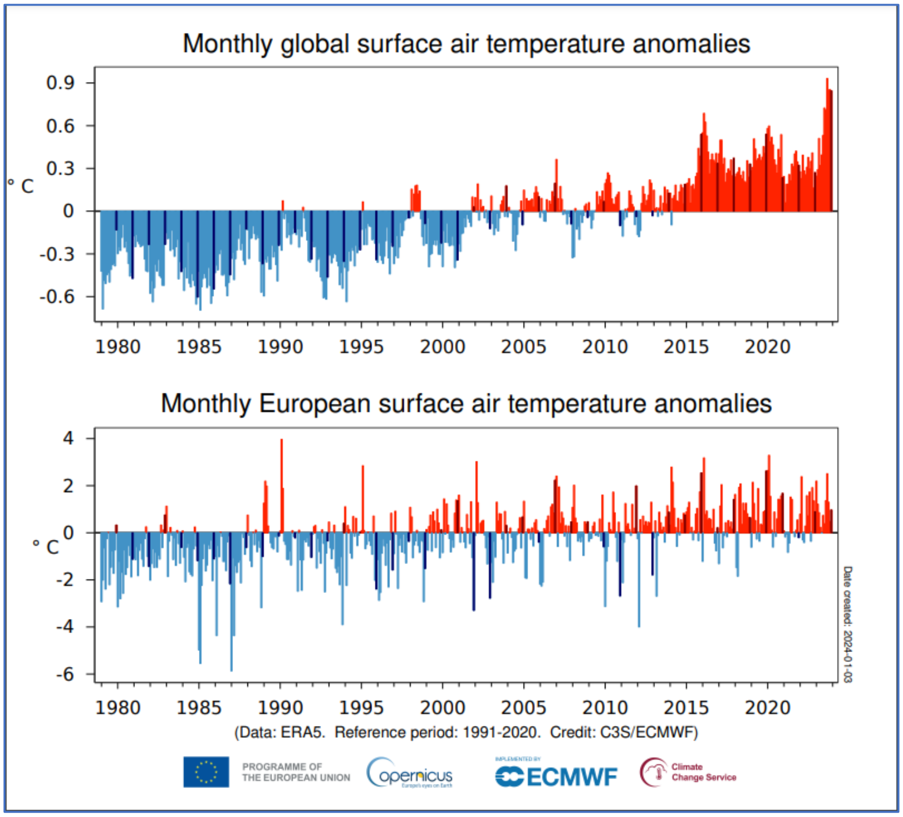


Picture 1: Trends in Atmospheric Carbon Dioxide Source: (Tans, 2023)

The Intergovernmental Panel on Climate Change (IPCC) and other scientific bodies have attributed the observed global warming and climate changes to this enhanced greenhouse effect. The consequences include rising global temperatures, more frequent and severe heatwaves, altered precipitation patterns, and various impacts on ecosystems and human societies. Efforts to mitigate climate change often focus on reducing greenhouse gas emissions to limit further warming and its associated effects.

According to IPCC's report, in all scenarios and modelled pathways for the future, global warming is projected to continue to raise in the coming years (2021-2040) due to the increased accumulation of CO_2 emissions in the atmosphere. Global warming is likely to exceed 1.5°C during the 21st century, and consequently being unavoidable to be limited below 2°C.

The below graph illustrates the global-mean and European-mean surface air temperature anomalies relative to 1991-2020 for all months from January 1979 to December 2023 with the darker colored bars denoting the December values. Year 2023 has been confirmed as the warmest calendar year in global temperature data records going back to 1850 (Copernicus EU, 2024).



Picture 2: Monthly Global Surface Air Temperature Anomalies (Data source: ERA5. Credit: Copernicus Climate Change Service/ECMWF)

1.2. Global Initiatives for Climate Change

Over the last decades there have been several initiatives addressing the problem and the challenges posed by global warming and climate change, reflecting a growing global awareness of the urgent need for proactive measures to mitigate these environmental threats.

The first global action addressing the greenhouse gas effect was the foundation of the IPCC by the United Nations Environment Programme (UNEP). The IPCC was established by the

UNEP and the World Meteorological Organization (WMO) to assess scientific information related to climate change and its potential impacts. This marked the first global effort to systematically evaluate and synthesize scientific knowledge about the greenhouse gas effect and its implications for the Earth's climate. The IPCC's assessments have since become crucial references for policymakers worldwide and have informed subsequent international negotiations and agreements aimed at addressing climate change.

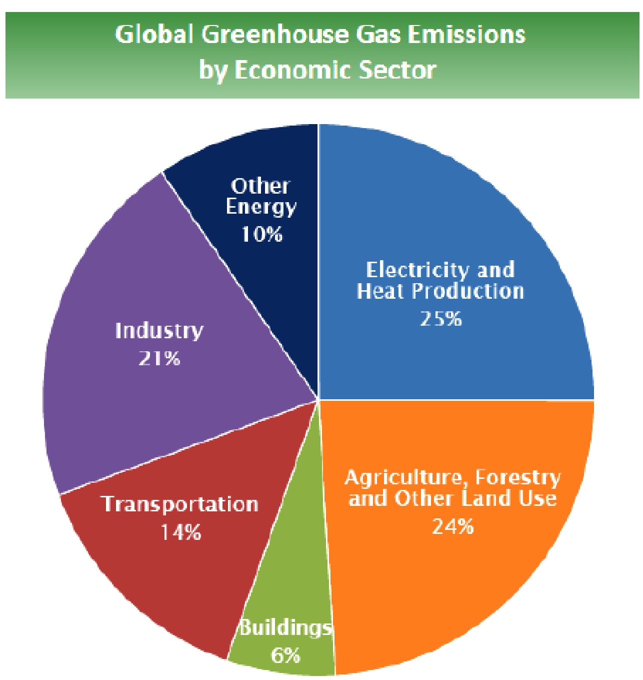
Following the same direction, in 1992, 154 countries signed the United Nations Framework Convention on Climate Change (UNFCCC), which is an international treaty with the primary objective to stabilize greenhouse gas concentrations in the atmosphere, thereby preventing dangerous anthropogenic interference with the climate system. The convention serves as a framework for international cooperation The UNFCCC provides a platform for regular negotiations and meetings among member countries, known as the Conference of the Parties (COP), to assess progress, negotiate agreements, and adopt measures aimed at mitigating climate change and adapting to its impacts. The UNFCCC played a crucial role in laying the groundwork for subsequent international climate agreements including the Kyoto Protocol and the Paris Agreement and remains a central framework for global efforts to combat climate change and achieve sustainable development.

The Kyoto Protocol was adopted in Japan in 1997, has been the first significant action and global effort to address climate change. The Protocol has been designed as an extension of UNFCCC and has established legally binding emission reduction targets for developed countries. These targets aimed to reduce their greenhouse gas emissions, particularly carbon dioxide, methane, and nitrous oxide, by an average of 5.2% below 1990 levels during the commitment period of 2008 to 2012. While the Kyoto Protocol marked an essential step forward in recognizing the need for global action on climate change, its effectiveness faced challenges, including the absence of binding commitments for developing nations and the withdrawal of some key countries. Despite its limitations, the protocol laid the groundwork for subsequent international climate agreements and set the stage for more inclusive and ambitious efforts to mitigate the impacts of climate change, as exemplified by the Paris Agreement in 2015.

Recognizing the urgency of addressing climate change, representatives from nearly 200 countries came together for the UNFCCC Conference of the Parties (COP21) in Paris in December 2015. The result of this historic gathering was the Paris Agreement, a landmark international accord aimed at limiting global warming to well below 2 degrees Celsius above pre-industrial levels, with efforts to limit it to 1.5 degrees Celsius. Under the agreement, each participating country committed to specific emission reduction targets and outlined plans to achieve them. The Paris Agreement marked a significant milestone in global efforts to combat climate change, emphasizing collective responsibility and cooperation to address one of the most pressing challenges facing the planet.

1.3. Emissions from Shipping

The Paris Agreement recognized the importance of all sectors, including international shipping and aviation to contribute to global efforts to limit temperature increases. The global transportation sector in 2010 was accountable for the 14% of the global greenhouse gas emissions according to the IPPC's report.



Picture 3: Global Greenhouse Gas Emissions by Economic Sector Source: based on global emissions from 2010. Source: (IPCC, 2014)

The shipping industry is a relatively small contributor to the total volume of emissions deriving from the transport sector and it is recognized as the most efficient form of commercial transport in terms of CO_2 emissions per ton of cargo transported per mile. In 2018, global emissions deriving from shipping industry represented 1 076 million tons of CO_2 and were responsible for around 2.9% of global emissions caused by anthropogenic activities (EC, 2023).

Year	Global anthropogenic CO_2 emissions	Total shipping CO^2	Total shipping as a percentage of global
2012	34,793	962	2.76%
2013	34,959	957	2.74%
2014	35,225	964	2.74%
2015	35,239	991	2.81%
2016	35,380	1,026	2.90%
2017	35,810	1,064	2.97%
2018	36,573	1,056	2.89%

Table 1: Total shipping and voyage-based and vessel-based international shipping CO_2 emissions 2012-2018 (million tonnes) Source: 4th IMO GHG Study (IMO, 2020)

It is crucial to recognize that even this seemingly modest percentage represents a significant absolute volume of emissions, given the vast scale of global shipping activities. As international trade continues to grow, there is an increasing acknowledgment of the need for the shipping industry to further reduce its carbon footprint. Efforts within the sector, such as those led by the International Maritime Organization (IMO), aim to implement measures that enhance energy efficiency, promote the use of cleaner fuels, and ultimately contribute to the broader global goal of mitigating climate change.

1.4. IMO Initial Strategy on Reduction of GHG from International Shipping

In 2018, the IMO adopted the initial strategy on reduction of greenhouse gas emissions from seagoing vessels in consistence with the targets set in the 2015 Paris Agreement. The Paris Agreement's goal is to mitigate climate change and limit global warming below 2°C, above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C. The IMO Initial Strategy, in general, includes a broader frame of Law of the Sea, UNCLOS and International Climate Law. The strategy constitutes of the IMO's response to climate change following the United Nations 2030 Agenda for Sustainable development and in particular SDG 13: "*Take urgent action to combat climate change and its impacts*".

Undoubtfully, shipping is the most cost-effective and energy efficient mode of transportation for mass cargo. However, taking into consideration the 4th IMO GHG study, which was published in 2020, the share of emissions coming from international shipping was 2,89% of the global GHG from anthropogenic activities and based on the business-as-usual scenario, the same study projects that there will be a 90% to 130% increase by 2050, despite all efforts for improved energy efficiency measures on vessels (IMO, 2020) (Chircop, 2019).

By adopting the initial strategy, IMO was aiming to advance its contribution to the global efforts to reduce GHG emissions from international shipping. As global trade growth and maritime transport services are heavily relying on international shipping, it has been a necessity for IMO to address the actions to be taken by the shipping sector and further introduce measures and incentives for research and development and monitoring of GHG emissions from international shipping.

Thereupon the 62nd Meeting of the Marine Environment Protection Committee (MEPC), a body which addresses environmental issues under IMO's remit, IMO had adopted revisions on MARPOL Annex VI, with new regulations on Energy Efficiency for Ships by introducing the EEDI (Energy Efficiency Design Index) for new ships and Ship Energy Efficiency Plan (SEEMP) for all ships. These measures have been identified as the first attempt by IMO to regulate and impact the CO_2 emissions deriving from vessels, with effective date the 1st of January 2013 (Lloyd's Register, 2011).

In the course of MEPC's 70th session, in October 2016, an important milestone has been set by IMO when addressing GHG emission reduction. A roadmap (2017 through 2023) has been approved for the development of IMO's Strategy to reduce GHG emissions from seagoing vessels and continuing with the adoption of the Strategy in 2018 and as a way forward its revision in 2023.

The roadmap will be in line with the committee's three step-approach, Data Collection, Data Analysis and following Policy/Decision Making. As first step, a new mandatory requirement for ships to record their fuel oil data has been introduced. The MEPC initiated a Data Collection System (DCS) for fuel oil consumption, which has been included in the MARPOL Annex VI requirements.

Under these amendments, vessels above 5,000 GT are required to collect data on their fuel consumption, per each fuel type, and data related to transport work. These data will have to be collected, reported to flag States and annually to be transferred to an IMO Ship Fuel Consumption Database. The Data Collection System will support IMO with decision making, additional measures and future steps by enhancing its inclusive policy while using firm, transparent and evidence-driven data (IMO, 2016).

In line with the roadmap, and as part of the future activities, the Committee has recognized that intersessional work will be required with clear timelines and alignment with the ongoing work. An Intersessional Working Group on Reduction of GHG emissions from ships has been introduced by MEPC 70 (ISWG-GHG), as the responsible body for the development of IMO's Strategy, taking into consideration the current work and finally submitting a report by the next session (ISWG-GHG 1, FEB 2017).

The first draft of the Strategy was shaped during ISWG-GHG 2 (October 2017) including a refined vision for IMO and an agreed timeline for the candidate short-, mid- and long-term measures, which would be finalized by the Marine Environment Protection Committee (MEPC).

In April 2018, MEPC 72 has adopted the Initial Strategy for the Reduction of GHGs from international ships in accordance with the agreed roadmap. The Initial Strategy declared the organization's vision and commitment to reduce GHG emissions from international shipping, and over the end of the century, as a matter of urgency, to accomplish the decarbonization of the industry (T. H. JOUNG, ET AL., 2020).

Regarding the identified "levels of ambition", the Strategy envisions to minimize the total annual volume of GHG emissions from international shipping, even though they are projected to peak, aiming to at least 50% decline by 2050 compared to 2008 levels and total elimination of the emissions by the end of the century. The targets set will be achieved by the reduction of Carbon Intensity (CI) on ship basis, and further implementation and reinforcement of EEDI and aiming to an average reduction of CO_2 emissions per transport work, at least 40% by 2030 and respectively 70% by 2050 compared to the 2008.

To implement these plans and targets, the Strategy provides a framework for Member States which includes guiding principles, a list of the candidate short, mid, and long-term measures with proposed timetables and their impacts on States. The Committee has recognized the key barriers and supportive measures, the necessity for capacity building, technical cooperation and research and development (R&D) (IMO, 2018).

In 2018, the 4th GHG Working Group and MEPC 73 approved a program of the follow-up actions of the IMO's Initial Strategy planned until 2023 and towards the adoption of its revision. This action plan includes the improvement of the EEDI and SEEMP, speed reduction for ships, voyage optimization, candidate market-based-measures and R&D for alternative fuels (T. H. JOUNG, ET AL., 2020).

During MEPC 73, further work was assigned for the fifth intersessional working group meeting, among of the tasks was firm proposals to evaluate the candidate measures and their impacts on States and furthermore proposals for candidate short-term measures (IMO, 2018).

In 2019 the 5th ISWG-GHG and MEPC 74 introduced approach methods and possible time frames for the GHG reduction as a list of candidate measures. The Committee agreed to continue discussions for various short-term measures, with emphasis on improving the energy efficiency requirements for the existing ships from both technical and operational approach and approved amendments to strengthen the existing mandatory EEDI requirements. In accordance with the roadmap, MEPC 74 initiated the 4th IMO GHG Study and agreed to set up a multi-donor trust fund for GHG. Additionally, as an adopted resolution, MEPC invited the Member States to encourage cooperation between ports and the shipping industry to contribute to GHG emissions reduction from ships (Class NK, 2019).

As future work for the ISWG, concrete proposals for candidate short-term measures had to be considered and evaluated, giving priority to proposals for energy efficiency improvements for the existing ships. Mid and long-term measures proposals were discussed, with focus on the uptake of alternative low-carbon and zero-carbon fuels (IMO , 2019).

In November 2020 and in line with the ambition of the Initial IMO GHG Strategy, draft new mandatory regulations addressing the reduction of Carbon Intensity for the existing ships, were approved by IMO during MEPC 75. The ships will be required to implement a plan with both technical and operation approach, to monitor and decrease their carbon intensity. (IMO, 2020)

As an addition to the existing requirements for EEDI, the set of amendments for MARPOL Annex VI includes both a technical and an operational approach for carbon intensity reduction. The Energy Efficiency Existing Ship Index (EEXI) was introduced as a new technical requirement for the existing fleet, in combination with the Carbon Intensity Indicator (CII) as the new operational requirement.

The additional requirements have been included as amendments to the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI and officially adopted during the MEPC 76 session. The existing ships will be required to measure and improve their Energy Efficiency Existing Ship Index (EEXI) from a technical perspective and to calculate their annual Carbon Intensity Indicator (CII) and improve their CII rating from the operation approach, as Carbon Intensity indicates the amount of cargo transported over the distance travelled (IMO, 2021). Both measurements are expected to be into force in November 2022, following the IMO's ambition for 40% reduction of carbon intensity by year 2030.

The requirements for EEXI and CII certification will take into effect from 1 January 2023 and consequently the first annual reporting on carbon intensity will be completed in 2023, and first rating will be given to the ships in 2024. As agreed under the held session, the effectiveness of the implementation of these measures as an emissions reduction mechanism, will be examined, and if needed, revised in 2026.

The committee has provided guidance documents to support the EEXI and CII frameworks. The guidelines refer to Calculation Methods, Survey and Certification for the verifiers and reference lines for the indicators. In addition, with the above requirements and guidelines, which are considered as short-term measures, the committee recognized the urgent need to progress with the development of mid- and long-term measures and agreed to establish a working plan towards this end. The work plan sets out a three-phase approach, supporting the IMO's Initial Strategy and its follow-up actions, Phase I: Collection and Initial consideration of proposals of measures, Phase II: Assessment and Selection of the measures to be further developed and Phase III: Development and Finalization of the measure(s) with agreed timelines. Additionally, the committee adopted a revision to the Method of Calculation for the Attained EEDI for new ships (ABS , 2021).

IMO's MEPC held its 77^{th} session in November 2021, in view of the urgency to expedite the transformation of the sector and has acknowledged the demand to further strengthen the ambitions of IMO Strategy and agreed to initiate its revision in spring 2023, keeping in line with the initial timeline. The proposed mid- and long-term measures and next steps have been discussed and will be considered in the next sessions and intersessional working groups (DNV GL, 2021). Additional guidelines on calculating EEDI & EEXI were approved under the same session and also instructions were provided on how to treat innovative energy efficiency technologies, i.e., Wind propulsion as an alternative source of energy (Lloyd's Register, 2021).

In June 2022, MEPC 78 has finalized the guidelines for the Energy Efficiency Existing Ship Index (EEXI), the Carbon Intensity Indicator (CII) and SEEMP regulations, deploying these measures ready for implementation starting from January 2023. There have been extensive discussions and considerations about the scheduled revision of IMO's GHG strategy. Significant divergence in views, between countries which necessitate reaching full decarbonization by 2050, while others being more conservative, are addressing the need to re-assess the feasibility of the targets already set and their impacts on States, before proceeding with steps forward (DNV GL, 2022). A significant number of Member States aimed to support a complete phase-out of GHG emissions by 2050, comparing the current 50% reduction target. Other States supported the idea to additionally strengthen the level of ambition for 2030. However, there were also oppositions from other Member States, from a more realistic point of view, that complete phase-out by 2050 will not be possible. High emphasis was posed on the impacts on the developing States from energy transition costs. As the IMO's GHG Strategy will be revised in 2023, it is essential that decisions will be made based on evidence, rather than focusing only on the targets set.

As part of the mid- and long-term measures to reduce GHG emissions from international shipping, at this meeting the committee had extensively considered various proposals for market-based-measures. IMO in its Initial Strategy has addressed the Market-Based-Measures as feasible mid-term measures, which are to be finalized between 2023 and 2030 and as described in the Strategy: *"New/innovative emission reduction mechanism(s), possibly including Market-based Measures, to incentivize GHG emission reduction".* In addition, there have been discussions on a proposed technical measure in the form of a well-to-wake GHG intensity fuel standards, with a view to be further assessed in the next sessions.

During MEPC 79 in December 2022, the Committee have received and assessed various proposals related to the ongoing revision of the Initial IMO Strategy. The ambition levels of the initial strategy as well as the revision of the targets for 2030 and 2050 were extensively discussed. The Revised Strategy is projected to include further enhancements to the Energy Efficiency and Carbon Intensity and revised or/and additional checkpoints for the Levels of Ambition in GHG Reduction. The Member States discussed about an integrated basket of measures which will tackle the GHG emissions. These candidate measures will either have a direct impact on the emissions from ships or will act supportively on the GHG reduction. It was proposed to introduce a GHG Fuel Standard (GFS), a regulatory mechanism calculating the amount of carbon or GHG equivalent allowed in marine fuels for a given period. Also, it was highlighted that a standard methodology needs to be developed and agreed on quantifying both Well-to-Tank (WtT) and Tank-to-Wake (TtW). A Well-to-Wake (WtW) Lifecycle approach (LCA) is important as certain types of fuels might be attractive on a TtW approach but with an overall higher GHG footprint across their lifecycle. Apart from the GFS, the Member States discussed on proposed Market-Based Measures (MBMs), which will act as a financial mechanism to support first movers in the industry's energy transition. The Committee and the Member States have recognized the importance of Onboard Carbon Capture and Storage (OCCS) and Onboard Carbon Capture, Use and Storage (OCCUS) in relation to the EEXI/EEDI and CII regulations (ABS, 2022).

The IMO's Marine Environment Protection Committee held its 80th session (MEPC 80) in July 2023 and adopted a Revised GHG Strategy with strengthened ambitions. The revised targets as introduced by the Revised Strategy are aiming to reduce well-to-wake GHG emissions from international shipping by meeting the following checkpoints:

a. to reduce the total annual GHG emissions from international shipping by at least 20%, striving for 30% in 2030, compared to 2008; and
b. to reduce the total annual GHG emissions from international shipping by at least 70%, striving for 80% by 2040, compared to 2008.

The 2023 IMO GHG Strategy aims to reduce GHG emissions from ships. Compared to the Initial IMO Strategy on Reduction of GHG Emissions from Ships, the 2023 strategy has higher levels of ambition and indicative checkpoints. The levels of ambition and indicative checkpoints consider the Well-to-Wake (WtW) GHG emissions of marine fuels, as addressed in the Guidelines on lifecycle GHG intensity of marine fuels (LCA Guidelines). The overall objective is to reduce GHG emissions of international shipping without a shift to other sectors.

The updated levels of ambition are:

1. Reduce carbon intensity of ships through the further improvement of the energy efficiency for new ships.

2. The overall carbon intensity of international shipping to decline: to reduce CO_2 emissions per transport work, by at least 40% by 2030 (compared to 2008 levels)
3. Improve the uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources: these technologies to represent at least 5%, striving for 10% of the energy used by international shipping by 2030,
4. GHG emissions from international shipping to reach net-zero.

Year	Previous Targets	Revised Targets
2030	Reduce **carbon intensity** (CO_2 emissions per unit transport work) by **40%** vs 2008	+Reduce **carbon intensity** (CO_2 emissions per unit transport work) by **at least 40%** vs 2008 + Reduce **total annual GHG emissions** from international shipping (on a WTW basis see footnote) by at least **20%**, **striving for 30%**, vs 2008 + Zero/near-zero emission fuels (on a WTW basis) to account for **at least 5%, striving for 10%,** of the total energy used by the international shipping industry
2040	None	+ Reduce **total annual GHG emissions** from international shipping by **at least 70%, striving for 80%,** vs 2008
2050	Reduce **carbon intensity** (CO_2 emissions per unit transport work) by **70%** vs 2008 Reduce **total GHG** emissions from international shipping by 50% vs 2008	+ Reach **net-zero GHG emissions** from international shipping 'by or around' 2050 (accounting for differing national circumstances)

Table 2: Key revisions of the IMO GHG Strategy according to MEPC 80

The IMO GHG Strategy will be subject to a five-year review, with the next one happening in 2028. The Committee has agreed also to conduct a review of the Short-term GHG reduction measures in 2026. The evaluation will be done one the effectiveness and their enforcement based on the relevant IMO DCS data. On the other hand, IMO decided to implement a basket of measures as mid- and long-term measures to reduce GHG emissions keeping in line with the revised levels of ambition. This basket of measures consists of two different elements, a technical measure, meaning a goal-based marine fuel standard which will regulate the phased reduction of marine fuel GHG intensity and secondly an economic measure in a form of a maritime GHG emissions pricing mechanism. The development of these candidate measures will progress withing IMO and according to the agreed timeframe will be adopted in 2025 and will become effective by 2027.

The MEPC 80 has adopted the Resolution MEPC 376(80) which contains the Marine Fuel Lifecycle GHG Guidelines and sets out the methods for calculating well-to-wake and tank-to-wake GHG emissions for all fuels and other energy carriers (such as electricity) which are used for ship propulsion and power generation onboard a ship. These guidelines include the complete fuel life cycle from feedstock up until the fuel usage onboard. Additionally, the guidelines address sustainability topics/aspects marine fuels and define a Fuel Lifecycle Label (FLL), which provides the information for the fuel type, feedstock, conversion/production process, GHG emission factors, information on fuel blends and sustainability aspects. It is important to highlight that these guidelines are only intended to support the development of the GHG Fuel Standard, and they are not yet to be applicable or acting as a requirement.
Similar result to MEPC 79, the importance of carbon capture and storage was identified but the work in progress has been postponed for the next intersessional meeting of the Working group on GHG reductions (DNV, 2023).

Following the adoption the 2023 IMO Strategy in July 2023, the committee reconvened in March 2024 for its 81st session (MEPC 81) and emphasized on significant advancements in maritime environmental policies, particularly in the areas of greenhouse gas emissions, energy efficiency, and the development of new marine fuels. Central to the discussions was the implementation of the 2023 IMO Strategy on the Reduction of GHG Emissions from Ships, which aims for net-zero emissions by around 2050. This strategy includes the development of an "IMO net-zero framework" that proposes a marine fuel standard and economic mechanisms to incentivize the transition to net-zero emissions. Additionally, MEPC 81 adopted updated guidelines for SEEMP (Resolution MEPC.388(81)) and reinforcing measures to enhance the energy efficiency of ships. This is a critical step towards reducing the carbon footprint of the maritime industry. Furthermore, the committee endorsed a work plan for developing guidelines for new alternative fuels, such as hydrogen and ammonia, which are seen as pivotal in achieving long-term sustainability goals. These initiatives underscore MEPC 81's commitment to fostering a more sustainable and environmentally responsible maritime sector.

In September 2024, at MEPC 82, key discussions focused on enhancing energy efficiency, reviewing short-term measures, and developing mid-term measures to reduce GHG emissions. The committee commenced to review the short-term GHG measures (CII, SEEMP and EEXI) by examining gaps and challenges. The review found no challenges with EEXI. For CII and SEEMP, the committee decided to address the gaps and challenges using a two-stage approach. The first phase, to be completed before January 1, 2026, will focus on enhancing the SEEMP framework, addressing idle time and port waiting time, improving the CII metric for cruise ships, and considering CII reduction factors for 2027-2030. The second phase, to be addressed after January 1, 2026, will tackle more complex issues such as adverse weather impacts, the use of bow thrusters, and life-cycle GHG emissions (DNV, 2024).

To achieve the goals of the 2023 IMO GHG Strategy, MEPC 80 in 2023 decided on a two-part approach: a technical element involving a goal-based marine fuel standard to gradually reduce marine fuel GHG intensity, and an economic element featuring a GHG emissions pricing mechanism, either linked to the GHG intensity mechanism or as a standalone measure. For mid-term measures, the committee continued developing a global marine fuel standard and a GHG emissions pricing mechanism, with further convergence among member states but no final agreement. The comprehensive impact assessment of these measures was completed, but additional work is needed to address concerns, particularly regarding food security. These measures are set for adoption in 2025 and implementation by mid-2027. At MEPC 82, the net-zero framework was refined, incorporating various design options for both elements, though consensus on the entire package was not reached. Discussions included a GHG fund and revenue distribution, but alignment was limited. A comprehensive impact assessment was completed, but further work is needed before MEPC 83, particularly on the potential impact on food security. Significant work remains, necessitating intersessional efforts before MEPC 83 (April 2025) to ensure successful adoption (IMO, 2024).

1.5. EU Initiatives in Tackling Shipping Emissions

The EU has an important role and many European countries which are leading the IMO GHG Reduction Strategy, have been questioning if the IMO targets can be reached with the current technology and taking countermeasures. Maritime transport is one of the most energy efficient modes of transport and it is recognized to have an essential role in the EU economy. However, it is still a growing source of greenhouse gas emissions and according to the 4th IMO GHG Study and emissions are projected to increase from 90% to 130%, comparing to 2008 emission levels by 2050. From an EU perspective, maritime transport is considered as a significant CO_2 emitter, representing 3-4% of the EU's total emissions or over 144 million tons of CO_2 in 2019 (EC, 2021). The reduction of maritime transport's emissions falls under the Paris Agreement and the EU's emissions reduction commitment. EU has an increased climate ambition, although it has acknowledged that up to date there are no adequate measures either on global level or in the EU, that can contribute to emission's reduction from maritime transport (European Comission, 2022).

The International Maritime Organization is responsible to address the greenhouse gas emissions from international shipping from a global perspective. However, EU had recognized a relatively slow progress from the IMO, which triggered EU to take countermeasures and prepare proposals for the maritime transport to meet climate neutrality by 2050.

The EU acted as a leading party to promote CO_2 emissions reduction from maritime transport and the Commission, in 2013, introduced a Strategy towards the reduction of GHG emissions from maritime transport. The strategy included the following key elements (EU, 2015):

- Monitoring and Reporting: The proposal called for the development of a system to monitor, report, and verify CO_2 emissions from maritime transport. This laid the groundwork for the later adoption of the EU MRV Regulation in 2015.
- Setting intermediary reduction targets. While legislation already exists for all other industrial sectors and forms of transport to contribute to the EU's target of cutting GHG emissions by at least 40 % below 1990 levels by 2030. The reduction target

of 40 % (if feasible, 50 %) by 2050, compared to 2005, as an aspirational goal for maritime shipping.

- Market-Based Measures (MBMs): The Commission considered exploring the potential use of market-based measures to incentivize emission reductions in the maritime sector. This could include mechanisms such as emissions trading systems or other economic instruments.

It's important to note that while the 2013 strategy outlined these measures, the specific regulations and initiatives, such as the EU MRV Regulation, were developed and implemented in subsequent years. The focus on reducing GHG emissions from the maritime sector aligns with broader global efforts to address climate change and promote sustainability in transportation.

1.5.1. EU Monitoring, Reporting and Verification

First step of the Strategy is the Monitoring, Reporting and Verification of CO_2 emissions from large ships calling EU ports, subsequently to set out Greenhouse Gas Reduction Targets for the maritime transport and in the mid-long term, to introduce Market-Based Measures. The European MRV Regulation entered into force in 2015, the first reporting period started in January 2018. It is mandatory for large ships over 5000GT which carry passengers or cargo for commercial purposes to or from ports in the European Economic Area (EEA), regardless of their flag, to monitor and report their related CO_2 emissions and other relevant information by 31 August 2017.

Following the adoption of the EU MRV Regulation, the IMO introduced the IMO Data Collection System. The DCS entered into force in March 2018 and data collection effectively started on 1 January 2019. In consequence, ships calling into EEA ports will have to report under both the EU MRV Regulation and the IMO Data Collection System.

While the discussion for MBMs had been set aside from IMO side, the EU continued into that direction with the European Green Deal. The EU with this effort introduced a package of policy initiatives, aiming to set a path to a green transition, with the goal of reaching climate neutrality by 2050. Achieving this objective, EU would be required to reduce its

CO_2 emissions by at least 55% by 2030, compared to 1990 levels (European Comission, 2022).

In 2021 the European Commission adopted a package of legislative proposals known as “Fit for 55” with the goal to make the EU’s climate, energy, land use, transport and taxation policies effective in reducing its GHG emissions by at least 55% by 2030, compared to 1990 levels. This comprehensive climate policy package includes also the emissions coming from maritime transport, especially with the proposal for the review of the EU Emissions Trading System (ETS) and the proposal for FuelEU Maritime, a regulation for the use of renewable and low-carbon fuels in the shipping industry. The ETS proposal incorporates maritime transport into the existing scheme of EU ETS, meanwhile the proposal for FuelEU Maritime establishes emissions requirement levels for the energy used by ships (Nelissen, et al., 2022)

1.5.2. EU Emissions Trading System

The European Union Emissions Trading System (EU ETS) is a market-based instrument established by the European Union to tackle climate change by reducing greenhouse gas emissions. It was firstly introduced in 2005, the EU ETS is the world's first and largest cap-and-trade system, covering a broad spectrum of industries, including power generation, manufacturing, and aviation. The core principle involves placing a cap on the total amount of greenhouse gas emissions allowable within the system and allocating or auctioning emission allowances to regulated entities. These allowances serve as tradable permits, allowing companies to buy or sell them based on their individual emission levels. The EU ETS operates on the principle of gradually reducing the overall cap, incentivizing emission reductions over time. This innovative market mechanism incentivizes companies to invest in cleaner technologies and practices, fostering a transition to a low-carbon economy while contributing to the EU's broader climate goals The system has undergone various phases and revisions to enhance its effectiveness in addressing climate challenges, showcasing the EU's commitment to sustainable environmental policies.

In September 2020, based on the data collected from the first two operated years under the MRV regime, the European Parliament decided to take a vote for including maritime transport in the EU ETS (Lagouvardou, et al., 2020).

There has been an imperative force from the European Commission (EC) and the European Parliament (EP), to strengthen the EU ETS by incorporating the emissions from shipping industry and up to the end of 2022 this proposal was under debate. Finally on 17 December 2022, the EU's legislative bodies have reached to a provisional agreement on including maritime sector into ETS. By adopting this agreement EU is becoming the first jurisdiction on applying a carbon price on the emission from maritime sector (European Comission, 2022). Subject to final adoption, as of 2024, ships over 5000 GT carrying cargo or passengers for commercial purposes in the EU will be required to obtain and hand over emission allowances for their CO_2 emissions (DNV GL, 2023).

On 16th of May 2023 the Commission adopted the amendments to the ETS Directive and came into force on June 5th, 2023. Starting from January 2024 the maritime emissions will be included in the EU ETS. This means that CO_2 emissions from all large ships (of 5 000 gross tonnage and above) entering EU ports, regardless their flag state. The EU ETS system covers:

- 50% of the emissions from voyages starting or ending outside the EU
- 100% of the emissions deriving from voyages between two EU ports and when ships are within EU ports.

The system includes the following greenhouse gas emissions: CO_2 (carbon dioxide), CH_4 (methane) and N_2O (nitrous oxide), however the two latter only will be accounted for starting from 2026. The emissions scope of the EU ETS is covering only tank-to-wake emissions (approximately one ton of diesel produces 3 tons of CO_2).

The ETS cap sets out the maximum amount of greenhouse gas emissions that can be emitted under this system. The cap will be reduced over time in order to make sure that all sectors under ETS are taking actions towards the EU's climate objectives. The inclusion of maritime transport in the EU ETS is incentivizing energy efficiency, low-carbon solutions and technologies and aims to close the gap between alternative fuels and traditional maritime fuels. In practical terms, the shipping companies will have to purchase and use the allowances for each ton of reported CO_2 (or CO_2 equivalent) emissions in the scope of the EU ETS system. The EU Allowances (EUAs) are a permit to emit a certain amount of

CO_2 equivalents. These allowances can be bought or sold on the market, with a variable market price which reflects the cost of reducing the emissions. The scheme will be coming into force in a gradual manner so as to ensure a smooth transition. Shipping companies will have to surrender their allowances for a portion of their emissions during an initial three-year phase-in period (Commission, 2023):

- 2025: for 40% of their emissions reported in 2024;
- 2026: for 70% of their emissions reported in 2025;
- 2027 onwards: for 100% of their reported emissions.

The revenue from these allowances will be dedicated to innovations related to the maritime sector. Currently, ETS is the world's biggest carbon market (EC , 2023).

1.5.3. FuelEU Maritime

The second proposal for FuelEU Maritime was adopted by the European Parliament and the Council of the European Union in July 2023. The FuelEU Maritime will come into force from January 1st, 2025. The main objective of this proposal is to reduce the GHG intensity of the vessels travelling within, to and from EU while promoting the deployment of renewable and low-carbon fuels, to promote the mandatory use of Onshore Power Supply (OPS) for containerships and passenger ships in EU ports and lastly incentivize the production and use Renewable Fuels of Non-Biological Origin (RFNBOs).

FuelEU Maritime will be applicable for all ships above 5000GT that transport passengers or cargo for commercial purposes in the terms of:

- 100% of the energy used on voyages between EU port of calls;
- 100% of the energy used at berth in EU port;
- 50% of the energy used on voyages departing from or arriving to a port of call under the jurisdiction of a member State.

The regulation has set a tightening requirement on the well-to-wake GHG intensity expressed in gCO_2eq/MJ. The upper reference limit, which was set at 91.16 grams of **CO_2e** per MJ, was based on the energy used on board by ships in 2020, determined by the reported data in the framework of Regulation (EU) 2015/757, EU MRV. To ensure that the energy used onboard will be less intensive over the time, the GHG intensity limit will be gradually reduced as follows:

Effective Date	Reduction Percentage	Carbon Intensity Limit (g CO_{2e}/MJ)
01 January 2025	2%	89.34
01 January 2030	6%	85.69
01 January 2035	14.5%	77.94
01 January 2040	31%	62.90
01 January 2045	62%	34.64
01 January 2050	80%	18.23

Table 3: Reduction of energy's GHG intensity used on board Source: (ABS, 2023)

Each reporting period, the energy consumption onboard must be below the reference GHG intensity limit. In the event that the actual GHG intensity is higher, a penalty will be imposed. If a ship fails to be compliant for two or more consecutive reporting years, the remedial penalty will be subject to multiplication by an escalating factor for each year of non-compliance.

In an instance that a ship demonstrates a surplus in compliance for a given reporting period, the shipping company can reserve the surplus amount and utilize in the subsequent reporting period, under the following two conditions: the amount is less than 2% of the reference GHG intensity multiplied by the energy consumption and the amount can be used only for once consecutive year.

Furthermore, it is feasible for one or more vessels from the same or different companies to establish a compliance pool, provided the following conditions are met:

1. The cumulative compliance within the pool is positive.
2. A vessel with compliance deficit does not have a higher compliance deficit after the allocation of the pooled compliance.
3. A vessel with compliance deficit does not have a higher compliance deficit after the allocation of the pooled compliance.

Starting from January 1, 2030, containerships and passenger ships must utilize onshore power supply (OPS) for all energy requirements while docked in a port governed by a Member State. However, there are several scenarios in which a vessel may be exempt from OPS, including instances where it is at berth for less than two hours, its electrical power needs are met by zero-emission technologies, it makes an unscheduled port call for safety reasons, or it is unable to connect to OPS due to unavailable or incompatible connection points.

Vessels that fail to comply to the OPS mandate will receive a remedial penalty, calculated proportionally based on the rounded-up hours spent at berth in non-compliance with the established total electrical power demand of the ship at berth.

FuelEU Maritime encourages the adoption of Renewable Fuels of Non-Biological Origin (RFNBOs) and mandates member States to guarantee the availability of RFNBOs in ports under their jurisdiction. The European Commission will oversee the market availability of RFNBOs starting in 2025. Should the utilization of RFNBOs by 2031 fall below 1%, a renewable fuels usage target of 2% will be established for the year 2034.

2. IMO GHG Strategy and Its Measures for GHG Emission Reduction

The IMO has taken significant steps to address greenhouse gas emissions in the maritime industry through its initial GHG strategy. It has introduced a comprehensive framework encompassing short, medium, and long-term measures. In the short term, the strategy focuses on optimizing operational energy efficiency, promoting energy-efficient technologies, and implementing technical and operational measures. Medium-term & long-term measures include the pursuit of innovative technologies, alternative fuels, and the development of zero-emission ships as well as establishing a framework of market-based measures, aiming for a 50% reduction in total annual GHG emissions from the international shipping sector by 2050 compared to 2008 levels. This phased approach reflects the IMO's commitment to addressing climate change progressively while considering the unique challenges and opportunities of the maritime industry.

2.1. Short Term Measures

In the short term, the IMO has introduced several crucial measures to reduce GHG emissions from ships. The first implemented measures were the introduction of the Energy EEDI, which mandates new-build ships to meet specific energy efficiency standards and the SEEMP in 2013. The IMO has also established mandatory data collection systems for fuel consumption and energy efficiency measures, enabling better monitoring and assessment of emissions. These short-term measures demonstrate the IMO's commitment to fostering a more sustainable and environmentally responsible maritime sector while laying the foundation for further reductions in GHG emissions in the mid-long term.

The IMO progressed quickly with the development of new short-term measures (2018-2023) as an implementation of its GHG strategy. These measures were the conclusion that derived from the ISGW-GHG 7, aiming to combine a technical and an operational approach to reduce ship’s carbon intensity, which were introduced under the following two categories:

1. Technical: The Energy Efficiency Existing Ship Index (EEXI), which was an adjustment of the already implemented EEDI that will be implemented for the existing vessels.
2. Operational: The binding Carbon Intensity Indicator (CII) applying to all existing ships of a significant size, following a rating system from A to E.

The EEXI and CII indexes were introduced to achieve additional reductions in GHG emissions from the existing global fleet. These measures aim to enhance the energy efficiency of ships promptly, as they do not require substantial changes to the existing fleet's technology or design, by setting specific energy efficiency standards. EEXI and CII are considered cost-effective and feasible measures for reducing emissions because they primarily involve optimizing operational and maintenance practices rather than extensive capital investments. The introduction of CII, which rates a ship's energy efficiency in relation to its transport work, promotes transparency and encourages shipowners and operators to continuously improve their vessels' performance based on real data. These short-term measures serve as a foundation for achieving the IMO's long-term GHG reduction goals, as they create a culture of energy efficiency within the maritime industry and pave the way for more advanced technologies and practices in the future.

2.1.1. The Energy Efficiency Design Index (EEDI)

The Energy Efficiency Design Index (EEDI) is one of the first and important regulatory tool for the reduction of GHG emissions from international shipping. This index is designed to measure the amount of carbon dioxide that a ship emits per unit of transport work. The EEDI requirements set a level for a minimum energy efficiency for a new ship depending on factors like ship type and size and technologies improving the ship's energy efficiency. The formula provides a figure for each ship design, and it is indicating the grams of CO_2 emissions per ship's transport work. The smaller the EEDI figure is interpreted that the ship is more energy-efficient and emits less CO_2 (Zheng, et al., 2013).

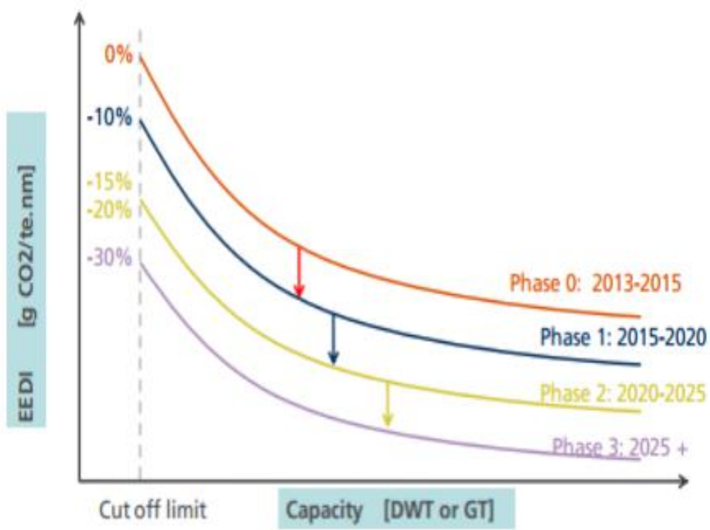
A reference line has been established for each ship type, which provides a basis for a fair comparison and to promote the efficiency improvement. The reference line is a curve that represents and average index value for a specific ship category (IMO, 2013).

The EEDI requirements have been addressed in three phases, as newbuild ships will enter the global fleet meeting the EEDI criteria, the total CO_2 emissions will gradually decrease by 3% in Phase 1, 13% by the time of phase 2 and accordingly 30% by phase 3. (Zheng, et al., 2013)

The EEDI phases are divided as per below:

1. Phase 1 (2013-2020): The first phase of the EEDI established a baseline for the calculation of the index and set the initial reduction targets for new-built ships.
2. Phase 2 (2021-2025): The second phase of the EEDI increases the targets and applies to a wider range of ship types and sizes.
3. Phase 3 (2026 onwards): The third phase of the EEDI poses a further increase on the reduction targets and aims to achieve significant improvements in the energy efficiency of new ships.

Each phase of the EEDI has different targets and timelines for reducing the carbon emissions of ships, with the goal of promoting more energy-efficient and environmentally friendly shipping practices. In the next phases, new ship designs will be increasingly more efficient, with a goal to reach a 30% reduction between 2025 and 2030 for applicable ship types. The Reduction factor is the % reduction in Required EEDI relative to Reference Line.



Picture 4: EEDI Phases and Cut-off Limits Source: (IMO, 2010)

The Energy Efficiency Design Index has been the first regulatory measure imposed by IMO since 2011 to reduce the greenhouse gases from ships. EEDI was the first legally binding measure which was established since the Kyoto Protocol and was mandated for new ships during the 62nd session of the IMO's Marine Environment Protection Committee through the adoption of amendments to the MARPOL Annex VI.

The EEDI's adoption promotes the use of more energy-efficient, and thus less CO_2 emitting, equipment, and engines onboard ships. The index sets a minimum energy efficiency lever per capacity mile (tone mile) for different vessel type and size. The initial phase 0 (2 years) starting from January 1st 2013, each new build design is required to meet the reference level per ship type. The reference level will be strengthened incrementally by 10% every 5 years. The EEDI regulation has the intention to incentivize continuous technical development and innovation for all the ship equipment which has an impact on the fuel efficiency of a ship from its design stage.

The EEDI can be considered as a performance-based mechanism that provides room for choice of technologies without being prescriptive. Ship designers and builders have a level of freedom to use cost-efficient solutions as long as the required energy efficiency level is obtained, and the ship is compliant with the regulations. The EEDI is designed to drive continuous improvement in ship design and increase vessel's energy efficiency and reduce total emission through the use of newer technologies and less emitting equipment and engines. It is a goal-oriented technical standard and will act as a benchmark of comparison for the energy efficiency of ships and sets a minimum required level of efficiency per ship type and size. (Polakis, et al., 2019)

The EEDI provides a numerical value for an individual ship design, expressed in grams of CO_2 per ships capacity mile (smaller the EEDI, the more energy efficient is the ship).

The general formula is: EEDI = $\frac{CO_2 Emissions}{Transport\ Work}$ (1)

In more detailed expression EEDI=$\frac{Engine\ Power \times SFC \times C_F}{DWT \times Speed}$ (g CO_2/ton-mile) (2)

The detailed formula below (3) is based on the technical design parameters for a given ship:

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

(3)

The formula (3) is expressed as per below: EEDI = (CO_2 from Propulsion System + CO_2 from Auxiliary System – CO_2 Emission Reduction) / DWT x Speed

In where:

- $P_{ME/AE}$: Main Engine Power / Auxiliary Engine Power (kW);
- $SFC_{ME/AE}$: Specific fuel consumption for main / auxiliary engine (g/kW);

- $Peff(i)$: Innovative mechanical energy efficient technology for main engine
- $PAEeff$ Innovative mechanical energy efficient technology for auxiliary engine
- C_F: Fuel to CO_2 factor (g CO_2/ g Fuel);
- Capacity: for Cargo ships DWT, for Passenger ships GT;
- V_{ref}: Reference speed (nm/hour);
- f_i: Correction factor for technical/regulatory limitation on capacity;
- f_w: Correction factor for speed reduction at sea;
- f_j: Correction factor for general cargo ships equipped with cranes and cargo-related gear;
- f_c :Cubic capacity correction factor for chemical tankers, gas carriers, ro-ro passenger ships, bulk carriers

According to the amendments released by IMO, the mandatory reporting of Attained EEDI value and below related information need to be reported (IMO, 2021):

1. Applicable EEDI Phase (e.g. Phase 1, Phase 2, etc.)
2. Identification number
3. Ship Type
4. Common Commercial Size Reference
5. DWT or GT
6. Year of Delivery
7. Required EEDI Value
8. Attained EEDI Value
9. Dimensional Parameters (Length L_{pp} (m), Breadth B_s (m), Draught (m))
10. V_{ref} (knots) and P_{ME} (kW)
11. Use of Innovative Technologies (4th and 5th terms in the EEDI equation, if applicable)
12. Short Statement describing the principal design elements or changes employed to achieve the attained EEDI
13. Type of Fuel used in the calculation of attained EEDI, and for dual-fuel engines, the f_{DFgas} ratio
14. Ice Class Designation (if applicable)

The following ship types are currently required to comply with the Attained EEDI regulation:

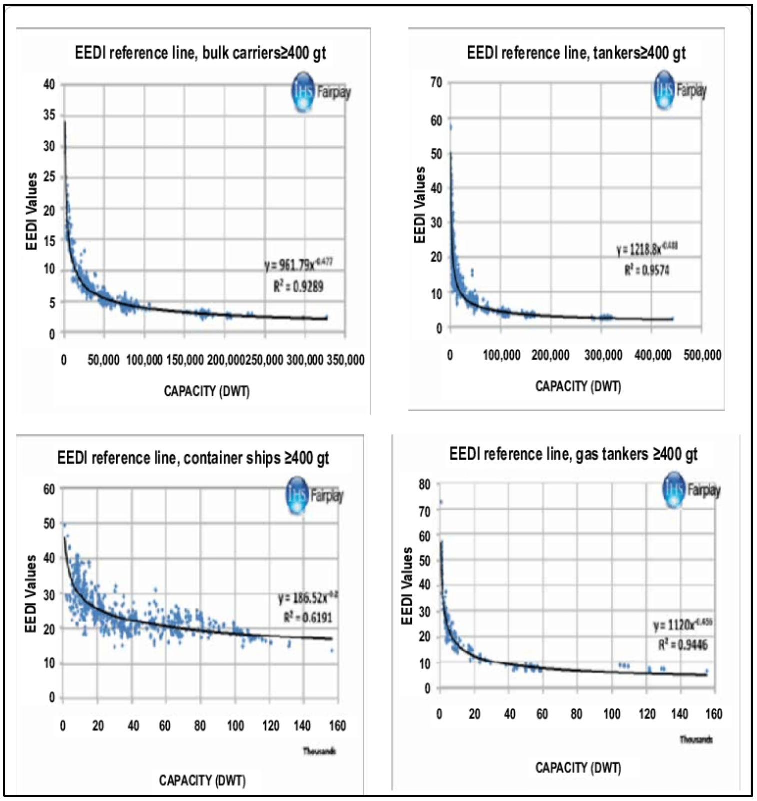
1. Bulk carrier
2. Gas carrier
3. Tanker
4. Containership
5. General cargo ship
6. Refrigerated cargo ship

7. Combination carrier
8. Passenger ship
9. Ro-Ro cargo ship (vehicle carrier)
10. Ro-Ro cargo ship
11. Ro-Ro passenger ship
12. LNG carrier
13. Cruise passenger ship

Reg.	Ship Type	Definition
2.25	Bulk carrier	A ship which is intended primarily to carry dry cargo in bulk, including such types as ore carriers as defined in SOLAS Chap. XII, Regulation 1 but excluding combination carriers
2.26	Gas carrier	A cargo ship, other than an LNG carrier as defined in paragraph 38 of this regulation, constructed, or adapted and used for the carriage in bulk of any liquefied gas
2.27	Tanker	An oil tanker as defined m MARPOL Annex I, Regulation 1 or a chemical tanker or an NLS tanker as defined in MARPOL Annex II, Regulation 1
2.28	Container ship	A ship designed exclusively for the carriage of containers in holds and on deck
2.29	General cargo ship	A ship with a multi-deck or single deck hull designed primarily for the carriage of general cargo. This definition excludes specialized dry cargo ships, which are not included in the calculation of reference lines for general cargo ships, namely, livestock carrier, barge carrier, heavy load carrier, yacht carrier, and nuclear fuel carrier
2.30	Refrigerated cargo carrier	A ship designed exclusively for the carriage of refrigerated cargoes in holds
2.31	Combination carrier	A ship designed to load 100% deadweight with both liquid and dry cargo in bulk
2.32	Passenger ship	A ship which carries more than 12 passengers
2.33	Ro-ro cargo ship (vehicle carrier)	A multi-deck roll-on-roll-off cargo ship designed for the carriage of empty cars and trucks
2.34	Ro-ro cargo ship	A ship designed for the carriage of roll-on-roll-off cargo transportation units
2.35	Ro-ro passenger ship	A passenger ship with roll-on-roll-off cargo spaces
2.38	LNG carrier	A cargo ship constructed or adapted and used for the carriage in bulk of liquefied natural gas (LNG)
2.39	Cruise passenger ship	A passenger ship not having a cargo deck, designed exclusively for commercial transportation of passengers in overnight accommodations on a sea voyage

Table 4: Definition of each type of ship as defined in Regulation 2 of MARPOL ANNEX VI, Chap. 4 Source: (ClassNK, 2015)

The EEDI uses a reference line to set reduction targets for each ship type. The reference line is based on the average performance of the best performing ships of each type that were built in a specified reference year, usually the year of the adoption of the relevant EEDI phase. The reduction targets for each ship type are calculated as a percentage reduction of the reference line for that ship type. For example, in Phase 2 (2021-2025), the reduction targets for each ship type are set as a percentage reduction of the reference line established for that ship type in the year 2021.The attained EEDI which is calculated based on the above formula indicates the estimated performance for each ship in terms of energy efficiency. According to the procedure, an EEDI technical file must be prepared for each new ship. The technical file shall include all relevant terms and definitions and the calculation methodology which was applied and then has to be submitted for certification to a recognized organization by its Flag State. The EEDI Verification is conducted in two stages, the preliminary stage, and the final stage. The preliminary stage is carried-out before construction for the ship’s initial design and the final verification is executed during sea trials. The EEDI technical file is necessary to be kept on board and acts as an addition to the International Energy Efficiency Certificate (Polakis, et al., 2019).



Picture 5: EEDI Reference Lines as developed by the IMO using techniques in Resolution MEPC 231 65 Source: (Tran, 2016)

2.1.2. Ship Energy Efficiency Management Plan (SEEMP)

The Ship Energy Efficiency Management Plan (SEEMP) was introduced by the IMO as an essential tool to enhance energy efficiency in the maritime industry. The SEEMP was initially adopted by the IMO in 2011 and later came into force on January 1st, 2013. The implementation of SEEMP is mandatory for all ships over 400 gross tonnages (Resolution MEPC.203(62)). Since its introduction, this guideline has undergone several updated and amendments in order to reflect the new guidelines suggested by IMO (IMO Resolution MEPC. 282(70), 2016).

The primary objective of SEEMP is to provide ship operators with a comprehensive framework to improve the energy efficiency of their vessels. It encourages the implementation of operational measures that optimize ship performance, reduce fuel consumption, and subsequently decrease carbon emissions. The SEEMP impact is significant as it fosters a culture of continuous improvement, requiring ship operators to regularly assess and update their energy efficiency strategies. By promoting best practices and technological advancements, SEEMP contributes to the overall goal of achieving a more energy-efficient maritime industry.

The SEEMP is a cost-effective measure and if implemented effectively by all those who are obliged, will have an important impact in the short and medium term. Both EEDI and SEEMP since their introduction, have been expected to develop an energy-efficiency culture in shipping industry.

SEEMP is consisting of three parts (DNV, 2023):

- Part I: Ship management plan to improve energy efficiency
- Part II Ship fuel oil consumption data collection plan
- Part III: Ship Operational carbon intensity plan

The first part is mandatory and must be found on board all ships above 400 GT which are engaged in international voyages effective from 2013 (Safety4Sea, 2022). According to the amendments to MARPOL Annex VI, adopted in 2016, all ships are mandated to collect and report their fuel oil consumption data to the Administration or a Recognized Organization (RO) from the year 2019 (IMO DCS). The second part (SEEMP Part II) instructs that all ships subject to the IMO DCS must develop a ship fuel oil consumption data collection plan, which will have to be reported and confirmed by an Administration or a Recognized Organization. The verified Part II is required for all ships of 5,000 GT and above. Moving forward, as adopted by MEPC 76, all ships that are subject to CII rating starting from January 2023 will have to develop also SEEMP Part III and to be verified by an Administration or a RO. This part has to include (ClassNK, 2022):

- CII calculation methodology
- Required CII values over the next 3 years
- implementation plan for achieving the required CII
- Procedures for self-evaluation and improvement

This plan is essential for documenting the strategies and measures the vessel intends to achieve its Carbon Intensity Indicator (CII) targets.

In June 2022, MEPC 78 approved the final templates for SEEMP Part I, Part II & Part III and the methodology of calculations.

The SEEMP is a management tool introduced by the IMO to enable ship operators improve the energy efficiency of their ships through the implementation of various operational and technical measures. It is a proactive plan designed to optimize ship performance and reduce fuel consumption, thereby decreasing greenhouse gas emissions. Some examples of improving operational efficiency and carbon intensity are:

- Speed optimization
- Weather routing
- Hull monitoring and maintenance
- Installation of heat recovery systems

In general, SEEMP Parts I and III are structured in a way that they have a goal, a plan and implementation of the measures, a monitoring method, and a self-assessment/improvement process.

A successful implementation of SEEMP includes methods and measures which will improve the ship's energy efficiency, translated to a lower energy consumption and consequently less carbon emissions. An effective implementation of SEEMP will support operators and shipowners to achieve savings from fuel costs and decrease in general their operational costs. The successful implementation of SEEMP can be achieved by following a continuous improvement approach. First plan your SEEMP, execute the plan and implement the energy efficiency measures, collect the data, monitor the results and evaluate the effectiveness of the measures.

Picture 6: SEEMP Steps

2.1.3. Energy Efficiency Existing Ship Index (EEXI)

On 17June 2021 (MEPC 76), the IMO adopted amendments to MARPOL Annex VI, based on changes drafted at MEPC 75 in November 2020. Under these amendments was the introduction of the Energy Efficiency Existing Ship Index (EEXI) and the requirement to evidence the operational carbon intensity reduction through the Carbon Intensity Indicator (CII).

The EEXI is a technical efficiency indicator that follows the same concept with EEDI, and its main purpose is the CO_2 emissions reduction coming from the existing vessels. The EEXI is a measure related to the technical design of the ship, as the regulation sets minimum requirements for technical efficiency. The existing ships must be granted an EEXI approval once in their lifetime. This is a one-time certification. The planned requirements entered into force on the 1st of January 2023. Under the EEXI regulation, all vessels above 400 GT falling under MARPOL Annex VI must undergo an assessment of their energy efficiency. The aim of this assessment is to determine the ship's energy efficiency rating, which must meet new minimum requirements set out by the IMO (IMO, 2021).

The EEXI estimates the grams of Co2 emissions per transport work (g of co2 per ton-mile).

The concept of the formula (4) is detailed below:

$$EEXI = \frac{CO_2\ emissions}{Transport\ work} =$$

$$= \frac{Main\ engine\ emissions + Auxiliary\ engine\ emisisons + (PTI - Innovative\ electrical\ energy\ technologies) - Innovative\ propulsion\ energy\ technologies}{Capacity * Reference\ Speed * Reduction\ Factors}$$

The concept is to promote the application of innovative technologies that contribute to the ship's energy efficiency.

The required EEXI value is determined by the ship type, the ship's capacity and principle of propulsion and is the maximum acceptable attained EEXI value. The attained EEXI must be calculated for the individual ship, which falls under the regulation. For the ships are required to calculate the EEXI (i.e. attained EEXI) and the value shall be equal to or less than the allowable maximum value (i.e. required EEXI).

Attained EEXI ≤ Required EEXI

If the attained EEXI cannot satisfy the required EEXI, the ship has to implement countermeasures in order comply, such as shaft/engine power limitation and other energy saving devices.

The IMO has specified the below important parameters which are with accordance of the EEDI calculation guidelines:

- Power of main engines
- Power of Auxiliary engines
- The reference speed of the vessel
- The Certified specific fuel consumption

As stated by the IMO, verifying compliance with the EEXI will usually be carried out by an authorized Administration or organization, such as a classification society acting on behalf of the flag state. If a ship does not meet the required standards, technical adjustments must be made to enhance the ship's EEXI. In other case, not compliance may result in the imposition of penalties.

Depending on the technical adjustments, if changes are affecting the vessel's structure or any important components and systems on board, then relevant documentation must be submitted for approval to class societies. Upon approval, a survey shall take place and a surveyor will verify the changes.

Verification that the ship's attained EEXI and technical file is in accordance with the requirements shall take place at the first annual, intermediate or renewal survey after 1st January 2023.

The survey is part of the scope of the IAPP (International Air Pollution Prevention) survey, which is designed to ensure compliance with the air pollution prevention requirements of MARPOL Annex VI, and the compliance is documented by issuance of the Initial Environmental Examination (IEE) certificate.

The EEXI technical file contains the EEXI calculation as well as accompanying documentation and must be submitted to a class society prior to the International Energy Efficiency survey. The IEE Certificate is issued once per vessel, and it is valid through its lifetime. This document confirms that the ship complies with the environmental regulations and has undergone an environmental assessment. The assessment is carried out by a recognized organization or classification society, which is authorized by the ship's flag state to carry out the assessment. The assessment considers factors such as the ship's energy efficiency, emissions, waste management, and ballast water management.

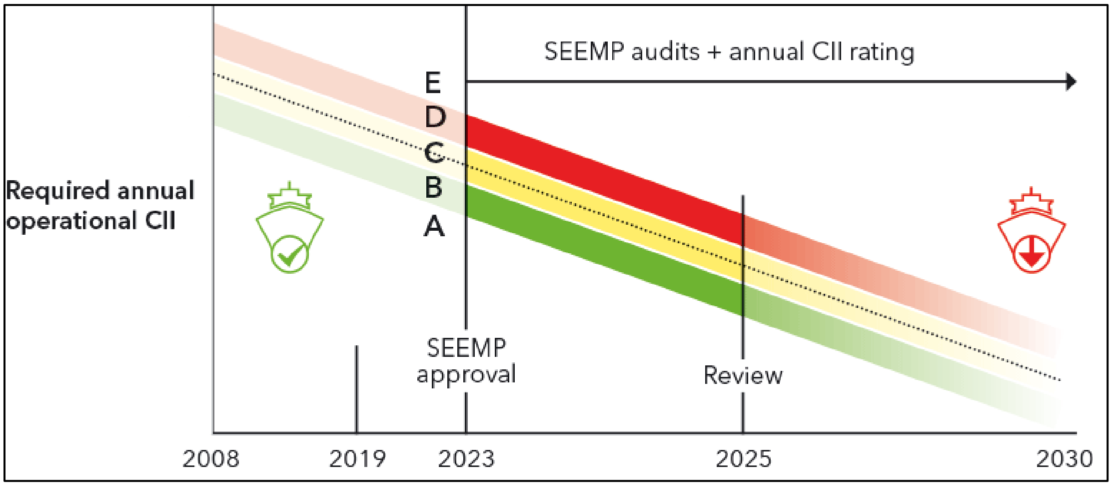
2.1.4. Carbon Intensity Indicator (CII)

In June 2021, the Marine Environment Committee (MEPC 76) of the IMO implemented additional obligatory measures, aligning with the targets which were introduced by the Initial IMO Strategy Among these actions is the carbon intensity indicator (CII), which assesses the carbon emissions per unit of transportation work for each individual vessel (Shuaian, et al., 2021).

New measures were introduced, ships would be obliged to show their operational carbon intensity indicator (CII) and CII rating annually. The carbon intensity refers to the link between the amount of GHG emissions and the amount of cargo carried out over the distance travelled (IMO , 2019). The CII is expressed in grams of CO_2 per deadweight-nautical mile, and it is an operational measure of a ship's efficiency of CO_2 emitted in transporting cargo or passengers. The CII applies to all cargo, RoPax, and cruise vessels with a gross tonnage of more than 5,000 GT and trading internationally.

The measure is mandatory under MARPOL Annex VI and came into force on the 1st of January 2023, meaning that the first annual reporting will be completed in 2023, and the first initial ratings would be appointed in 2024. The actual annual operational CII achieved would need to be documented and verified against the required annual operational CII, enabling the calculation of the operational carbon intensity rating to be determined on a scale of A, B, C, D or E, indicating a major superior, minor superior, moderate, minor inferior, or inferior performance level (IMO, 2022). The level of the performance is necessary to be documented in the ship's SEEMP. Based on their energy efficiency results each ship will receive a rating of A (major superior), B (minor superior), C (moderate), D (minor inferior) or E (inferior performance level), where A is considered the best performer and considering that the rating thresholds standards would become increasingly strict, towards 2030 (DNV GL, 2022).

If a ship is rated with D for three consecutive years, or E, it would be mandatory to revert with a corrective action plan, providing an outline of how the ship will achieve the required C (or higher) rating. IMO has set these guidelines to urge administrators, port authorities and other relevant stakeholders, to incentivize ships rated as A or B.



Picture 7: CII Rating Source: DNV

The MEPC 76 has determined that each vessel should attain an annual reduction of 1% until 2023, followed by 2% from 2023 to 2026, while the necessary reductions until 2030 remain undefined. It should be noted that 2030 represents the year of the interim objective, which requires a reduction of CII of no less than 40% in 2030 compared to the 2008 baseline (Shuaian, et al., 2021).

In other words, the CII determines the annual reduction factor required to continuously improve the ship's operational carbon intensity within a certain rating level. This indicator is comprised in the short-term measures, following IMO's initial GHG emissions strategy, and aiming to achieve carbon intensity reductions (Mallouppas & Yfantis, 2021).

The CII is a measure of how efficiently a ship transports goods or passengers in terms of emissions per transport work. This index is measuring operational efficiency and is has followed the concept of the Annual Efficiency Ratio (AER), which is expressed in grams of CO2 per DWT tone-mile

$$AER = \frac{\sum_i C_i}{\sum_i DWT\ D_i} (5)$$

AER is a metric for carbon intensity introduced by the Poseidon Principles organization and it is an approximation of the cargo which has been carried in correlation with the vessel's design DWT and its cargo capacity. This metric assumes that the vessels is continuously caring cargo or passengers, however ships are not always fully utilized in terms of capacity . The method for calculating AER is underestimating the carbon intensity.

Where:

- Ci (computed using the fuel consumption and carbon factor for each type of fuel) is the carbon emissions for a voyage,
- DWT is the design deadweight tons of the vessel,
- Di is the distance travelled over a voyage, summed for all laden, ballast and other voyages in the year

The data for the AER is collected through the IMO's Data Collection System (DCS).

The CII unit is expressed in grams of CO_2 emitted per cargo-carrying capacity and nautical mile, where cargo capacity is either deadweight or gross tonnage depending on ship type. In addition, there are correction factors and voyage adjustments that can be applied to the basic CII calculations based on special ship designs and operational circumstances (DNV, 2022).

Carbon Intensity Indicator Calculation Method

The CII calculation is conducted in a step-by-step approach. The first step is to calculate the Reference CII. The Reference CII is the initial value from 2019. The year 2019 is the first year where the verified DCS data were reported to IMO and it is the reference year for the CII. The reference line has to be established based on the vessels IMO DCS data and according to the Reference Line guidelines (G2), the guidance for the Reduction factor (G3) and the Rating guideline (G4) Resolution MEPC.337(76) (IMO, 2021).

The reference line for CII is defined as a curve which represents the median attained operational carbon intensity performance, as a function of Capacity, of a defined group of ships in year of 2019. For a defined group of ships, the reference line is formulated as follows:

$$CII_{ref\_2019} = a\ Capacity^{-c} \quad (6)$$

Ship Type		Capacity	a	c
Bulk Carrier	DWT ≥ 279,000	279,000	4745	0.622
	DWT < 279,000	DWT	4745	0.622
Gas Carrier	DWT ≥ 65,000	DWT	144050000000	2.071
	DWT < 65,000	DWT	8104	0.639
Tanker		DWT	5247	0.61
Container ship		DWT	1984	0.489
General cargo ship	DWT ≥ 20,000	DWT	31948	0.792
	DWT < 20,000	DWT	588	0.3885
Refrigerated cargo carrier		DWT	4600	0.557
Combination carrier		DWT	40853	0.812
LNG Carrier	DWT ≥ 100,000	DWT	9.827	0
	100,000 > DWT ≥ 65,000	DWT	144790000000000	2.673
	DWT < 65,000	65,000	144790000000000	2.673
Ro-ro cargo ship (VC)		GT	5739	0.631
Ro-ro cargo ship		DWT	10952	0.637
Ro-ro passenger ship		GT	7540	0.587
Cruise passenger ship		GT	930	0.383

Table 5: Parameters for calculating the 2019 CII reference lines.

The second step is the calculation of the Required CII, which is the new CII that the vessel needs to comply with. The value of the Required CII is dependent on the reduction factor for each specific year.

The required annual operational CII is calculated by the following formula:

$$Required\ annual\ operational\ CII = \left(1 - \frac{Z}{100}\right) \times CII_{Ref} \quad (7)$$

The Reduction factor Z (%) for the CII is relative to the 2019 reference line Year. The reduction factor will be calculated as 5% from 2023 and 2% will be added on a yearly basis. The reduction factors for the years of 2027 to 2030 are expected to be strengthened and developed taking into account the review of the short-term measures.

Year	Reduction Factor (Z)
2023	5%
2024	7%
2025	9%
2026	11%
2027	**
2028	**
2029	**
2030	**

Table 6: CII Reduction Factor

The third step is the calculation of the actual CII (Attained CII) of the vessel for each year. The simplified annual attained CII Formula:

$$Attained\ CII = \frac{Annual\ Fuel\ Consumption * CO2\ Emissions\ Factor}{Transport\ Work{:}Distance\ Sailed\ annually * Capacity} * Correction\ Factors \quad (8)$$

The attained CII is calculated in accordance with the calculation guidelines (G1) based on the IMO DCS fuel reporting data and on the guidelines on correction factors and voyage adjustments (G5) (IMO, 2022) (IMO, 2021).

CII Rating

The performance rating of the index is demonstrating the deviation from the annual attained CII from the required value for each vessel type.

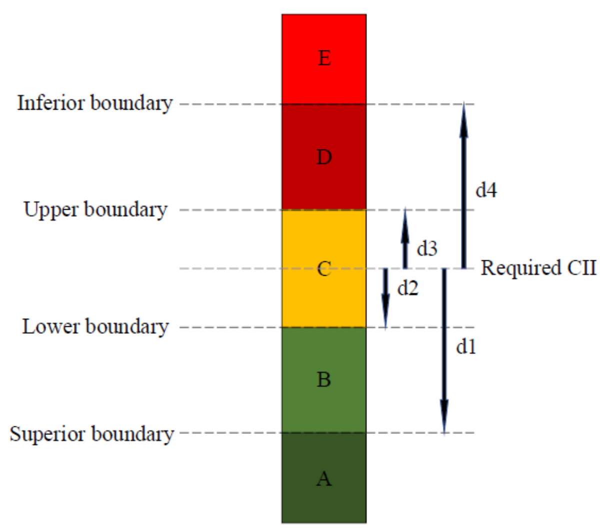
$$CII\ Rating = \frac{Attained\ CII}{Reference\ CII} \quad (9)$$

The rating is compared according to the following table and determines the vessel grade.

Ship type		d1	d2	d3	d4
Bulk Carrier		0.86	0.94	1.06	1.18
Gas Carrier	>=65,000DWT	0.81	0.91	1.12	1.44
	<65,000DWT	0.85	0.95	1.06	1.25
Tanker		0.82	0.93	1.08	1.28
Container ship		0.83	0.94	1.07	1.19
General cargo ship		0.83	0.94	1.06	1.19
Refrigerated cargo carrier		0.78	0.91	1.07	1.20
Combination carrier		0.87	0.96	1.06	1.14
LNG Carrier	>= 100,000DWT	0.89	0.98	1.06	1.13
	<100000DWT	0.78	0.92	1.10	1.37
Ro-ro cargo ship (VC)		0.86	0.94	1.06	1.16
Ro-ro cargo ship		0.76	0.89	1.08	1.27
Ro-ro passenger ship		0.76	0.92	1.14	1.30
Cruise passenger ship		0.87	0.95	1.06	1.16

Table 7: dd vectors for determining the rating boundaries of ship types

The performance rating and boundaries are determined based on the CII rating guidelines, G4.



Picture 8: CII Rating Boundaries Source: (Zincir, 2023)

2.2. Medium and Long-Term Measures

The IMO has taken significant strides towards addressing the maritime industry's environmental impact through the implementation of its GHG reduction strategy. The strategy, developed in response to growing concerns about climate change, outlines a comprehensive set of medium and long-term measures aimed at mitigating greenhouse gas emissions from the shipping sector. The proposed mid (2023-2030) and long-term (2030-2050) measures are a continuation of the implemented short-term measures. This course of action is taking into consideration the introduction and enforcement of market-based-mechanisms as a practice to incentivize the reductions of emissions. However, these kinds of mechanisms require the formation of synergies between technical, political, and infrastructural measures (Balcombe, et al., 2019).

2.2.1. Market Based Measures

The MEPC has proceeded with several attempts of bringing potential Market-Based Measures into the discussion. It has been identified that measures from technical and operational approach would not be adequate to reduce sufficiently the amount of GHG emissions from international shipping aligning with the projections for world trade growth and the level of ambition of IMO’s strategy.

Market-Based Measures are an economic variable, that through carbon pricing could create an impetus and aiming:

1. To provide an economic incentive for the maritime industry to invest in more green/innovative technologies and more fuel-efficient ships and to operate the ships more energy efficiently (in-sector reductions)
2. To offset in other sectors of growing emissions (out-of-sector reductions)

Starting from 2010, the committee has evaluated various proposals for MBMs from governments and observer organizations. All proposed programs and procedure were aiming GHG reduction either by focusing on ‘in-sector’ emissions reduction or ‘out-of-sector’ by gathering funds which would be utilized for different objectives, including adaptation and transfer of technology. The submitted proposals can be divided into two categories by either supporting an emissions trading system or a levy system (carbon tax).

However, the discussion around the market-based mechanism was suspended by IMO in May 2013. (Psaraftis, et al., 2020)

In 2017, the shipping industry faced increased international pressure when the European Parliament proposed including shipping in the European Union's onshore Emission Trading System (ETS) by 2023. Although the EU did not proceed immediately with this plan, it continued to monitor the progress of the IMO towards adopting market-based measures (Metzger, 2021).

Since, MBMs are considered as medium-term measures based on IMO's initial strategy on GHG emissions, they have been back also on IMO's agenda in the ISWG-GHG groups, however up to now the discussions are inconclusive. Prior MEPC 79, in the working groups there was a partial agreement around the discussions for introducing a levy scheme, by setting a carbon price on well-to-wake or tank-to-wake GHG emissions. This scheme was discussed in combination with a rebate system where the earnings would be returned to ships and covering the price difference between fossil and low/zero-carbon fuels. The discussion for MBMs and maybe a conclusion has been expected in 2023 in MEPC 80, with the revision of IMO's GHG strategy (DNV GL, 2022).

It is important that the introduction of MBMs requires global governing rules as there are risks of that carbon levies would be applied multiple times on emissions. Shipping companies are facing the challenge to estimate the reduction of CO_2 emissions, considering that the current available models could not examine the amount of investment needed in capacity and the extent of the effort required to improve energy efficiency. A global enforcement of an ETS would be a promising scenario (Mallouppas & Yfantis, 2021).

2.2.2. Research and Development for the Deployment of Alternative Fuels

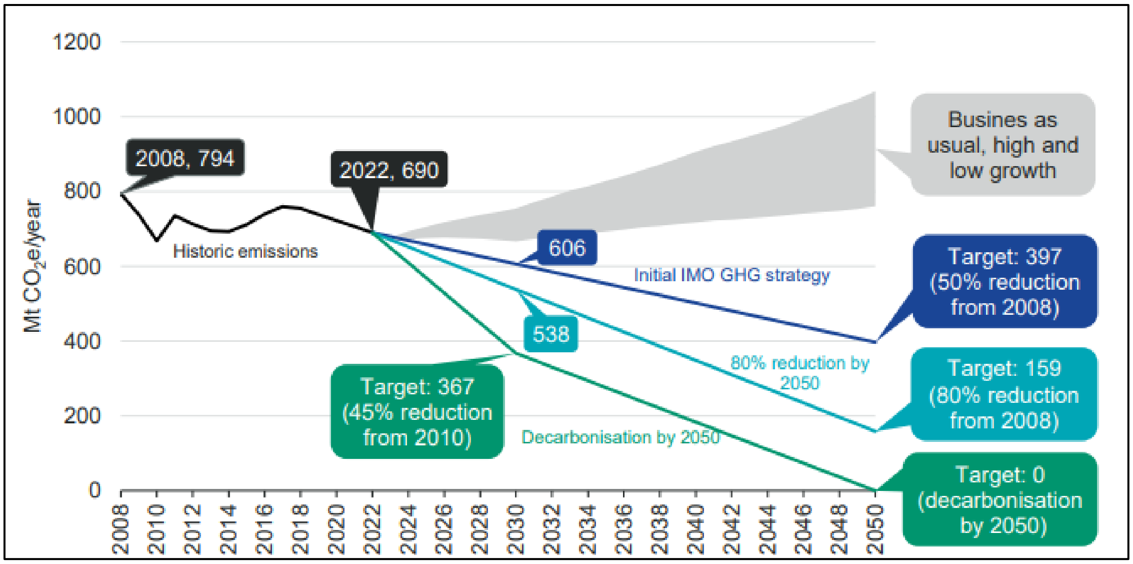
The IMO has undertaken a comprehensive approach to address the long-term reduction of GHG emissions in the shipping industry. Building upon its initial GHG reduction measures, the IMO recognizes the crucial role of research and development in fostering sustainable solutions. In pursuit of this objective, the organization continues to actively support and promote the exploration of alternative fuels. The IMO's long-term measures encompass the encouragement of innovation in propulsion technologies, such as hydrogen fuel cells, ammonia, and synthetic fuels. By fostering collaborative research initiatives and incentivizing the adoption of cleaner energy sources, the IMO seeks to accelerate the transition towards a low-carbon and environmentally responsible maritime sector. These concerted efforts not only contribute to the mitigation of climate change but also position the shipping industry as a leader in sustainable practices, aligning with the global commitment to reduce overall carbon emissions and promote a cleaner, greener future.

By mid-2023, the IMO had committed to establishing a revised and reinforced 2023 IMO GHG Strategy. To facilitate this endeavor, the IMO initiated the "Future Fuels and Technology for Low- and Zero-Carbon Shipping Project (FFT Project)" in September 2022. The primary aim of this project is to conduct a comprehensive assessment of the current state of readiness and availability of low- and zero-carbon ship technology and marine fuels. This assessment is intended to provide valuable insights to Member States involved in the development of IMO instruments designed to mitigate GHG emissions in international shipping. Acknowledging the imperative for enhanced information, the 78th session of the IMO MEPC 78 in June 2022 emphasized the necessity for supporting data in revising the Initial GHG Strategy. Consequently, the FFT Project conducted a study to evaluate the feasibility of achieving various decarbonization scenarios and to assess the readiness and availability of technologies and fuels essential for decarbonizing international shipping. It is important that the shipping industry will embrace technological innovation and along with the transition to low- and zero-carbon fuels and alternative energy sources in order to meet the IMO’s ambition towards 2050. The project is being implemented with funding from the Republic of Korea in three main phases and is expected to run until 2025. The phases are:

- A study of the current situation and the projected deployment, and the information/knowledge sharing among the industry for the low- and zero-carbon marine technology and fuels
- Identification and promotion of incentives and regulatory mechanisms that facilitate the deployment of alternative fuels and technology
- Promotion of technological cooperation among maritime stakeholders - for example, through pilot projects and reinforcing mutual understanding and collaboration between developed and developing countries and the global shipping industry.

The study is examining three scenarios as shown in Picture 9:

- The Initial IMO GHG Strategy reducing total annual Greenhouse Gas emissions by 50% by 2050 compared to 2008.
- 80% reduction by 2050 approximately aligned to IEA's 'Net Zero Emissions by 2050' scenario and IRENA's '1.5°C pathway scenario', In this scenario other sectors reduce GHG emissions more than the maritime sector or even achieve negative emissions to enable global net-zero emissions in 2050.
- A decarbonisation by 2050 scenario which represents international shipping reaching zero GHG emissions in 2050. This would be in-line with other sectors' reduction goals according to IPCC enabling no or limited overshoot of the 1.5°C target.



Picture 9: Three decarbonisation scenarios with targets compared to business-as-usual GHG emissions Source: (IMO, DNV, Ricardo, 2023)

Under the umbrella of this project a dedicated website was launched to serve as an online information hub. This platform aims to promote and share the latest developments in future fuels and technologies for reducing GHG emissions from international shipping in the mid- and long-term. The website is particularly focused on facilitating access to information for developing States, providing insights into the decarbonization of shipping, and guiding participation in a just and equitable transition.

The related IMO collaboration projects and initiatives are outlined here:

1. NORWAY-IMO GREEN VOYAGE 2050 Project
2. EU-IMO GMN Project
3. The Republic of Korea -IMO GHG SMART Project
4. IMO CARES
5. NEXT GEN
6. FIN-SMART
7. Zero and Low-Emission Innovation Forum

3. Alternative and Future Fuels in Shipping

In 2021, emissions from international shipping were reported to grow by 5%, despite the decrease which occurred in 2020 (IEA, 2022). The shipping sector, in comparison with road transport and aviation, is still relying on heavy or not processed fuels as bunkers. Bunker fuel is any fuel used on marine diesel engines for ship propulsion. Bunker fuels A, B, and C are respectively degrading quality-classifications of fuel oil, specified by their boiling points, carbon-chain lengths, and viscosities. Currently, the most widely used type heavy fuel oil (HFO) or Bunker C, with very high viscosity and contains big amounts of sulfur, which when combusted is emitting important amount of GHG, Sulphur oxides and other harmful substances that are negatively impacting environment and humans (Riley & Walker, 2019). Other fuels with lower viscosity levels and lower Sulphur percentage are Marine Gas Oil (MGO) which is a distillate fuel oil, classified as Bunker A and Marine Diesel Oil (MDO) which is a blend of MGO & HFO under bunker B category.

Presently, the global commercial fleet relies on fossil fuels as its primary energy source. The selection of fuel type has historically been driven by factors such as fuel availability and accessibility, energy density, and other economic considerations.

Traditionally, marine fuels have been categorized based on their kinematic viscosity, which was considered a reliable measure of oil quality, as long as the oil is produced by atmospheric distillation. Nowadays, all marine fuels predominantly originate from advanced refinery processes and the viscosity alone is an inadequate indicator of fuel quality. Despite this, international bunker markets continue to reference marine fuels with their maximum viscosity determined by ISO 8217, aligning with the diverse viscosities for which marine engines are designed. The fuel oil density also holds significance since marine fuels are purified before use to remove water and dirt. Consequently, the oil's density must sufficiently differ from water.

The IMO aims to achieve a decrease of no less than 50% in the maritime sector's overall annual GHG emissions by 2050. However, reaching this target necessitates the implementation of alternative zero-carbon fuels and carbon-neutral fuels produced from sustainable sources. Emissions reduction in shipping is twofold way. The first step is to improve the vessel's energy efficiency and thus reducing its fuel consumption; and second deploying low- and zero-emission fuels. To ensure meaningful emission reduction, it is important to account all the emissions of a fuel throughout its complete lifecycle. IMO has committed to promote research and development for new technologies and alternative fuels that would reduce the GHG emissions from ships while currently working towards the development and deployment of zero-emission ships, powered by clean energy sources.

Alternative fuels could be distinguished into two categories, carbon-neutral and zero-emission fuels. The main difference between carbon-neutral and fossil fuels is how they are produced and their effect on the environment. Carbon-neutral fuels result to net-zero emissions, meaning that their production and use does not increase carbon emissions and achieves carbon reduction through offsets, i.e. synthetic fuels and some biofuels. While zero-carbon fuels produce no CO_2 emissions when used as they do not contain any carbon. However, for example hydrogen can be considered as a zero-carbon but it is contingent on the method used for its production.

The use of alternative fuels for ship propulsion has the potential to result in lower or zero net emissions. Currently, there are many efforts on investigating a variety of fuels such as ammonia, hydrogen, methanol, and biofuels. The discussion around alternative fuels raises still a lot of uncertainties, emphasizing on the timeline, availability, safety, and their cost. The shipping sector is now facing this challenge and owner companies and the industry needs to invest into their future, while fuel flexibility seems to be a necessary step in the transition.

3.1. Liquefied Natural Gas (LNG)

LNG stands for Liquefied Natural Gas and it is a mixture of hydrocarbons. It consists almost entirely of methane (CH_4), which is the simplest hydrocarbon compound, ranging from 80-99% (SGMF, 2021). Other substances included with a few percentages, are some alkanes as ethane, propane and butane. Sometimes some small amounts of nitrogen (up to 1%) can be traced. It is a colorless and odorless liquid.

LNG is natural gas that has been condensed through cooling into liquid state. In normal conditions, at atmospheric pressure natural gas liquifies at a temperature of -162 °C. Natural gas can be burned on in its vapor state. At ambient conditions, the liquid is boiling and creates vapor.

When natural gas is condensed, about 600 of gas volume turns to one volume of liquid. This property is important as it makes natural gas possible to be transported in big volumes on board ships. In general, LNG when is transferred to a pipeline grid or power station is first regasified by heating.

3.1.1. Production

LNG production is a sophisticated and energy-intensive process that involves the transformation of natural gas into a liquid form, allowing for easier transportation and storage. The production of LNG typically begins with the extraction of natural gas from underground reservoirs through drilling and extraction processes. The raw natural gas undergoes a series of treatments to remove impurities, water, and other components, ensuring that it meets the stringent quality standards for liquefaction. The liquefaction process takes place in large plants where the treated natural gas is cooled to extremely low temperatures, typically below -160 degrees Celsius (-260 degrees Fahrenheit), causing it to condense into a liquid state. This liquefied form reduces the volume of the gas significantly, making it more economical to transport over long distances via specially designed LNG carriers. The final product is then stored in LNG terminals before being distributed to end-users, such as power plants, industrial facilities, or residential consumers, where it can be regasified and utilized for various energy applications.

As of 2021, there are about twenty countries which produce LNG in large quantities and additional nine that produce in smaller quantities only for domestic use. As of 2023, the largest exporters of LNG are United States, Australia and Qatar.

3.1.2. Emissions

While LNG is considered a cleaner alternative to traditional marine fuels, its usage in marine engines does not eliminate emissions entirely. LNG combustion in marine engines primarily produces carbon dioxide (CO_2) but at lower levels compared to conventional marine fuels. However, LNG combustion may also lead to emissions of nitrogen oxides (NO_x) and particulate matter, still at reduced rates when compared to traditional marine fuels. While advancements in technology and the use of cleaner-burning engines and exhaust gas treatment systems aim to mitigate these emissions, challenges remain in achieving complete environmental sustainability.

The sulfur emissions when using LNG in marine engines are practically negligible. On the other hand, the NO_x emissions are dependent on the engine technology and engine loading. The NO_x emissions are a result of the combustion process and as the combustion temperature increases so is the level of NO_x emissions. Depending also on the engine type, LNG-fueled vessels might be required to install SCR/EGR technologies onboard in order to meet the IMO Tier III limits, same as traditionally fueled vessels. Particulate matter (PM) emissions are almost eliminated when deploying LNG, almost a 95% reduction if compared to HFO PM emissions.

There is a significant challenge associated with the combustion of LNG on marine dual fuel engines, known as the “Methane slip". This term refers to the unintended release of unburned methane during the combustion process, which occurs when the combustion efficiency is not optimal. In dual fuel engines, where a combination of LNG and diesel is used, achieving complete combustion of methane can be challenging. The slip occurs when a portion of the methane fuel does not fully combust and is emitted into the atmosphere. Methane is a GHG, with approximately 28 times higher 100-year global warming potential when compared to CO_2.

3.1.3. Storage

LNG is stored and transported at extremely low temperatures to maintain its liquid state. The storage properties of LNG are crucial for ensuring safety, efficiency, and the ability to transport natural gas over long distances. LNG is typically stored in cryogenic tanks, which are heavily insulated to minimize heat transfer and maintain the low temperatures required for liquefaction. These storage tanks are commonly constructed from materials such as stainless steel or aluminum to withstand the extreme conditions.

The temperature of LNG storage is typically around -160 degrees Celsius (-260 degrees Fahrenheit). At these low temperatures, the volume of natural gas is significantly reduced, making it more economical to store and transport. The insulation of LNG storage tanks prevents the ingress of heat and minimizes the "boil-off" phenomenon, where LNG gradually vaporizes due to heat exposure. Boil-off gas is usually captured and used for various purposes within the facility or, in some cases, reliquefied and returned to the storage system.

The fuel storage systems for an LNG vessel are different than the traditional ones. The requirements for the storage are regulated from the IGF Code as part of the International Convention for SOLAS which was published in 2015 and came into force in 2017.

Onboard LNG-powered vessels, storage tanks are essential for holding the liquefied natural gas. These tanks are specially designed to maintain extremely low temperatures. The tanks can be of different types, such as membrane tanks or independent tanks, depending on the vessel's design and size.

The LNG fuel supply system on vessels is a very important component of the technology needed to use LNG as a fuel. The fuel gas supply system is controlling the supply of LNG to the engines and also converts the LNG into gas mode before fed to the engines. Some vessels are also equipped with regasification units, particularly in vessels using LNG as a fuel but also requiring the option to transport and deliver LNG cargo.

3.1.4. Logistics and Infrastructure

Bunkering stations are facilities where ships receive LNG fuel. They can be located at ports, terminals, or on specialized bunkering vessels. Bunkering stations ensure a safe and controlled transfer of LNG from the storage infrastructure to the ship's fuel tanks. The transfer systems involve the equipment and technology used to transfer LNG from the bunkering station or LNG carrier to the ship's storage tanks. Cryogenic hoses, transfer arms, and other specialized equipment are employed to manage the transfer process safely. LNG infrastructure has ramped up, with a number of 185 ports globally with LNG bunkering (Mandra, 2023) .

3.1.5. Safety & Regulations

The adoption of liquefied natural gas as a marine fuel brings about safety challenges that require careful consideration. LNG-fueled vessels necessitate additional safety equipment onboard, including specialized storage tanks, vaporizers, and emergency shutdown systems, to handle the unique properties of LNG. Moreover, the use of LNG introduces additional regulations and guidelines, such as the IGF Code, which mandates specific safety measures and procedures. Ensuring compliance with these regulations becomes crucial for the safe operation of LNG-fueled vessels. Crew members also require specialized training to handle LNG-related equipment, emergency response protocols, and firefighting procedures. Proper training is essential to mitigate risks associated with the handling, transfer, and combustion of LNG, emphasizing the importance of a well-prepared crew to navigate the safety challenges posed by the adoption of LNG as a maritime fuel.

3.1.6. LNG as a Marine Fuel

The gas-fueled shipping fleet has expanded rapidly in the recent years. The transition to cleaner fuels will be easiest, fastest and more cost effective for ships which are already designed to be powered with LNG. The use of LNG as a fuel, can result to 5-21% less carbon emissions than heavy fuel oil. Moreover, bio and synthetic LNG can be utilized to existing marine engines as drop-in fuels to reduce carbon footprint, provided the availability of their supply. Bio LNG is available from different kinds of sustainable feedstock, ie manure or other types of waste. (Mallouppas & Yfantis, 2021)

Research and development for future fuels would take 10-20 years to be accepted by classification societies, while considering timelines for global development of fuel supply logistics, infrastructure, and bunkering facilities.

LNG is not the most optimal alternative fuel, mainly due to the so-called methane slip, meaning the methane leakages during production and combustion, which has a significantly negative impact on its GHG footprint.

LNG is a hydrocarbon fuel, composed mainly by 85-95% methane (CH_4) and contains the lowest carbon composition compared to other forms of fossil fuels. LNG compared to its gaseous form, requires up to 600 times less capacity of space for its storage and transportation, thus natural gas is condensed into a liquid at close to atmospheric pressure by cooling it to approximately −163 °C. As a result, LNG is requiring cryogenic technology and insulated tanks for its storage, which are in general more expensive that the conventional fuel storage and supply application.

Presently, LNG is considered as the cleanest available marine fuel that can be supplied in global scale volumes while also complying with the SO_x and NO_x emission requirements and producing up to 30% less CO_2 emissions than HFO. LNG as a marine fuel decreases the vessel's impact on air pollution as its combustion produces significantly less NO_x and PMs and almost 90% reduction in Sox emissions. Even though LNG contributes to significantly less CO_2 emissions, on the other hand, it contributes significantly to the release of methane gas, one of the main greenhouse gases, into the atmosphere. The so-called methane slip is a result of unburned methane leaking during combustion. The amount of methane slip differs per engine type and loading. LNG complies with SO_x emission limits and most of the engines types are also compliant NO_x with Tier III regulation.

The ships are required to have installed onboard the appropriate technology if shipowners and operators want to transition to LNG. The technology includes dual-fuel engines, LNG bunkering station, storage tanks and gas treatment plant. This technology for deploying LNG as marine fuel is widely available and mature. There are commercially developed solutions for low and high-pressure 2-stroke engines and low-pressure 4-stroke engines and as well different equipment for storage, process, and regasification (DNV GL, 2019).

LNG is considered as a transition fuel, taking into consideration the developing supply & bunker infrastructure globally. Additionally, the dual fuel engines provide fuel flexibility and an easier transition to future fuels as their technology is already developed to switch to a variety of fuels during operation.

The deployment of LNG as a fuel in shipping industry has been evidently slow. The oversupply of ships in certain trades has discouraged the investments in newer ships with more advanced technologies. The availability of a fuel globally is also an important factor that is driving the decisions for investments.

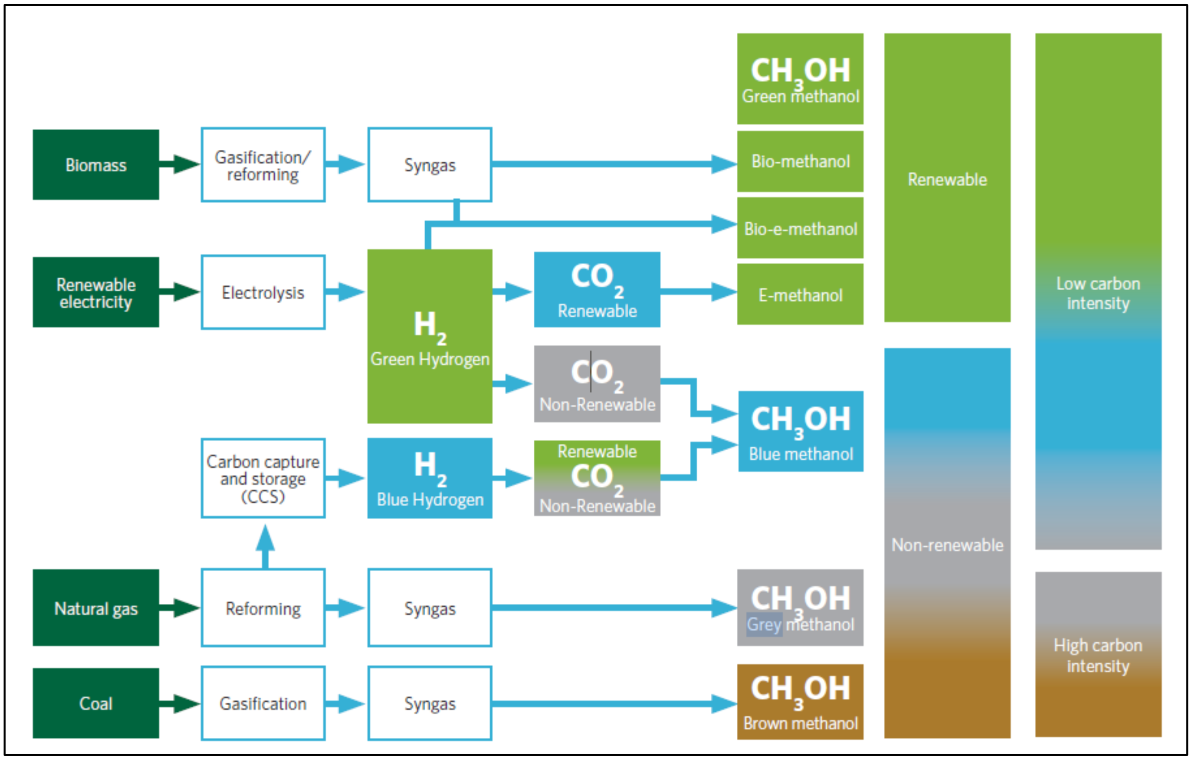
3.2. Methanol

Methanol is an organic chemical and the simplest aliphatic alcohol, with the formula CH_3OH. It is a light, volatile, colorless and flammable liquid with a distinctive alcoholic odour similar to that of ethanol. Methanol is a methyl alcohol, liquid in atmospheric pressure and it is one of the most widely produced chemicals globally. It is commonly used as a solvent, fuel, and antifreeze agent. In fact, it is the most widely used alcohol-based solvent in the world. Methanol as chemical has been used for industrial applications for many decades. Although its toxicity and high flammability, methanol could be dissolved in water and biodegrade. Energy density : Methanol 15.8 MJ/litre on an LH basis.

3.2.1. Production

Typically, methanol is produced by natural gas. Methanol could be characterized as a sustainable fuel, provided that renewable feedstocks are utilized for its production. Based on its origin methanol is grouped into the follow categories:

- Green methanol is produced from biomass or captured CO_2 and green hydrogen
- Blue methanol is produced from blue hydrogen along with carbon capture applications
- Grey methanol is the one made from natural gas
- Brown methanol is produced from coal



Picture 10: Methanol Production Pathways, Source: (Methanol Institute, 2023)

Grey and brown methanol are the most widely used today and produced by fossil fuel feedstocks, while blue and green methanol are more environmentally sustainable. The challenge lies in the production of hydrogen which is needed for green or blue methanol. The production of hydrogen deploying renewable electricity and usage of recaptured carbon could form green methanol and characterize it as a carbon neutral fuel. If compared to fossil fuels, green and blue methanol have significantly less well-to-tank CO_2 emissions, while all types of methanol could result to reduced tank-to-wake carbon emissions of about 7% compared to diesel fuel. Nevertheless, if it is examined from a well-to-wake approach, brown and grey methanol could have worse carbon footprint than diesel. (Bureau Veritas, 2023). Grey methanol is covering 95% of the total methanol used in the shipping industry. Marine engine manufacturers have reported that methanol emits up to 99% less sulfur emissions and up to 60% NO_x emissions, enabling methanol to be compliant also with the

IMO's 2020 SO_x emission regulations and the Tier III NO_x emission regulations. (Longspur, 2022)

3.2.2. Emissions

Methanol as an alcohol when combusted in engines, provide clean burning and emits low levels of soot during the combustion when compared with diesel or HFO (less than 0.01 g/kWh for methanol in heavy duty engines compared to more than 0.1 g/kWh for best diesel) (Tuner, 2015). Methanol releases low levels of nitrogen oxides and particulates and as it is sulfur-free, there are no sulfur oxide emissions. The low levels of nitrogen oxides are in line with Tier III Nox emissions (2-4g/kWh).

3.2.3. Storage

Methanol has lower energy density than traditional marine fuels and it is considered as the main drawback. If compared to MGO which has energy density of 36.6 GJ/m^3, while methanol's is 15.8GJ/m^3. If this is translated storage space, a methanol tank would require to be 2.4 times bigger than the space required for MGO and in general traditional fuels. Methanol and LNG can be considered similar in terms of energy density. However, this challenge can be relatively mitigated due to the fact that methanol can be stored in liquid state and doesn't require cryogenic conditions. Traditional fuel storage tanks and ballast tanks could be deployed for methanol. (Methanol Institute, 2023)

3.2.4. Logistics & Infrastructure

Methanol is similar to the marine fuels which are currently used due to is liquid state. Due to this fact, the existing fuel storage and fuel bunkering infrastructure would only require minor modifications for the handling of methanol. The infrastructure investment costs are relatively modest if compared with the considerable investments needed for the construction of LNG terminals.

It is necessary for fuel to be considered as an attractive option for shipping, that there is adequate infrastructure that covers a large number of ports. Bunkering of ships can be carried out by bunkering vessels or from land. Both solutions require terminals for bunkering. The infrastructure for methanol available today is based on the worldwide distribution of methanol in the chemical industry, ensuring widespread availability.

However, additional terminals for ship bunkering may be needed. Within the SECAs, numerous terminals serve the chemical industry, including some ports in Europe where methanol is one of the leading chemicals in terms of volume handled.

Technology and safety precautions are based on the broad experience of handling methanol deliveries for other applications. The technology for handling low-flashpoint chemicals is broadly developed enabling the safe handling of methanol. There is vast experience in handling methanol as a chemical in loading, transporting, and unloading methanol by road transport. This experience is already utilized in methanol bunkering. Methanol can be bunkered either by truck, barge, or a terminal. In the case of the ropax-ferry Stena Germanica, the bunkering of the vessels has been done by truck since 2015. Bunkering using a barge enables the vessels to be refueled while being at anchor. In 2021 an exercise of methanol bunkering was successfully completed, demonstrating the safe bunkering operations from a large-scale barge to a methanol tanker at port of Rotterdam (Fastwater, 2021).

Terminal bunkering could be utilized by vessels operating in fixed routes. As methanol grows in popularity as a marine fuel, ports are taking into consideration in investing in terminal infrastructure for methanol bunkering. Ports that are participating in the Green Corridors initiative are more likely to become hubs in the future for methanol bunkering, transport, and production.

3.2.5. Safety and Regulations

Adaptation to handling new fuels onboard can pose several challenges. The main difference between diesel fuel and methanol is that the latter is a low-flashpoint fuel. A low-flashpoint fuel can be vaporized and mixed with air causing ignition at a lower temperature. This is an important characteristic that has to be taken into consideration in a safety assessment and is a commonality between Methanol and LNG. Methanol has a low flashpoint of 12 degrees on the Celsius scale. Methanol’s flammability range in dry air is between 6% - 36.5%, this characteristic can impose threat of creating an explosive or flammable environment. Another characteristic is methanol could burn in low temperatures and during daytime its flame is not recognizable by the human eye (ABS, 2021). Additionally, as the molecular weight of methanol is higher than the airs (32 g/mole – 28 g/mole), its vapor is accumulating closer to the ground. Methanol is not spreading in enclosed and not ventilated spaces. All the above-mentioned characteristics, require certain safety precautions to avoid methanol vapors. The risks can be mitigated by installing ventilation and leak detection systems. Methanol is toxic for humans if ingested, absorbed by the skin or inhaled in high concentrations. High exposure can lead to blindness, kidney failure or even death. The bunkering infrastructure, the on-board fuel supply systems and the engine systems are specially designed preventing the direct exposure of humans with methanol. It is necessary for the crew members to receive adequate training of how to handle methanol and being able to respond in methanol leakage or spill. The IGF code, which was adopted in November 2020 by IMO, included guidelines and obligatory criteria to decrease safety risks for the crew members on methanol-fueled vessels (Methanol Institute, 2023). It is a relatively safe fuel from an environmental pollution perspective as it is fully miscible in water and biodegradable. It is toxic to aquatic organisms at concentrations above 1000 mg/l and especially 10,000 mg/l and above. However, other fuels are even more lethal to fish than methanol. Methanol bunkering at sea is possible due to its low risk of environmental damage from spills compared to other fuels. the consequences of short-term methanol spill in marine environment are temporary and reversible. Methanol combustion reduces emissions of particulate matter or black carbon by 95 percent, making it ideal for sailing in sensitive environments such as the Arctic (Methanol Institute, 2023).

From a regulatory perspective, methanol as a marine fuel complies with the strictest regulations imposed by the IMO, on SO_x, NO_x and PM emissions. When the carbon e-methanol and bio-methanol become widely available for shipping, marine methanol will be setting a clear step towards reducing carbon emissions. However, the cost of e-methanol and bio-methanol still is way higher than traditional marine fuels, this factor highlights the need for regulatory measures to incentivize the shipowner and operators the uptake of low carbon marine fuels. Safety regulations on-board haven already been developed for methanol as a marine fuel.

3.2.6. Methanol as a Marine Fuel

Methanol is now considered as a safe alternative marine fuel. The IMO in December 2020 released approved guidelines for methanol to be used as marine fuel. As methanol is non-cryogenic, and due to its liquid state at normal ambient conditions, it can be stored in traditional tanks and transported using the existing infrastructures as for diesel oil. However, a vessel's conversion requires around the double fuel tank capacity than the ones needed for HFO for a given trading distance (DNV GL, 2022). Globally, methanol is one of the top 5 chemical commodities transported. There are many existing production facilities which supply big volumes for use in industrial applications. Also, bunkering processes are available from vessel-to-vessel or shore-to-vessel basis and as a marine fuel can be found in about 122 ports and is already being used by 22 ships. The Ro-Pax vessel Stena Germanica was the first ship in the world using methanol as a marine fuel, which was retrofitted with fuel flexible Wärtsilä 4-stroke engine (Wärtsilä, 2023).

Low conversion cost for methanol operation is Approx. 1/4 – 1/3 of the Corresponding Cost for LNG Retrofit

Methanol internal combustion engines have a relatively progressed level of technological maturity and are already commercially available by engine manufacturers. Engine technology has been developed both for low-pressure and high-pressure systems. Marine methanol engines are dual fuel engines and require no modification in their design in order to run on methanol. Modifications are already in place in the fuel injectors, the cylinder heads and the fuel supply system. It is of great importance that both two-stroke and four-stroke methanol engines become fully commercially available in order for methanol to be used widely in shipping industry.

Engine efficiency when using methanol as a fuel is improved in comparison with traditional fuels (Haraldson, 2015) (Buitendijk, 2020). Methanol could be a good replacement of gas oil and can be used in fuel blends achieving good levels of performance in diesel engines. It would require an ignition enhancer such as diesel oil.

Methanol also has a lower adiabatic flame temperature than traditional fuels such as diesel. This characteristic results in lower peak temperatures within the cylinders, consequently less NOx emissions. However, still this emission reduction may not be enough to comply with IMO Tier III requirements on NO_x if methanol is used on its own at may still require a catalyst system for treatment. If Methanol is mixed with water in a high-pressure injection system, it is possible to meet Tier III standards without the need for selective catalytic reduction (SCR) or exhaust gas recirculation (EGR).

Methanol is corrosive to aluminum and titanium alloys, which are broadly used in engine systems. Manufactures would be required to apply corrosion-inhibiting additives or coatings.

The adoption of methanol as a marine fuel is likely to have significant impacts on its supply, demand, and pricing. As the maritime industry shifts towards cleaner fuels to meet environmental regulations, the demand for methanol is expected to rise. This increase will be driven by its potential to reduce greenhouse gas emissions and its compatibility with existing marine engines.

1. Production Expansion: To meet the growing demand, methanol production will need to expand. This could involve scaling up existing production facilities and investing in new plants, particularly those that produce green methanol from renewable sources.
2. Diversification of Supply Sources: The increased demand may also encourage diversification of supply sources, including the development of new feedstocks like biomass and waste CO2, which can be converted into methanol.

The increased demand for methanol as a marine fuel could lead to price volatility, especially if supply does not keep pace with demand. This volatility could be influenced by fluctuations in the prices of natural gas, the primary feedstock for methanol production. As with other fuels, regional differences in production capacity, feedstock availability, and regulatory environments will likely result in varying methanol prices across different markets. The push for sustainable and renewable methanol could drive up prices initially, as green methanol production is currently more expensive than conventional methods. However, as technology advances and economies of scale are achieved, the cost of green methanol is expected to decrease over time.

In summary, the adoption of methanol as a marine fuel is poised to increase its demand significantly, which will, in turn, impact its supply dynamics and pricing structure. While there may be initial price volatility and higher costs associated with green methanol, the long-term outlook suggests a more stable and potentially lower-cost scenario as production technologies evolve and scale up.

The current pricing of methanol as a marine fuel varies by region. As of the latest data, methanol prices are approximately:

- Europe: Around €580 per metric ton.
- North America: Approximately $570 per metric ton.
- Asia: Roughly 2,350 CNY per metric ton.

These prices can fluctuate based on factors such as feedstock costs, regional demand, and transportation expenses.

Picture 11: Methanol Price Trend (source: Methanex.com)

3.2.7. Lifecycle assessment / Environmental performance

Methanol have been produced traditionally by dry distillation of wood, known as wood alcohol. In 1913 the industrial synthesis of methanol was developed as it was one of the by products of a catalytic process, utilizing carbon monoxide and hydrogen. The industrial production of methanol is divided in three main stages:

1. Production of synthesis gas
2. Synthesis of methanol

3. Processing of crude methanol

The first stage is deriving from fossil or renewable raw materials. Nowadays, methanol is produced by natural gas, coal or HFO. Alternatively, all kinds of bio-mass can be used for the first stage.

3.3. Hydrogen

Hydrogen is the simplest, lightest and one of the most abundant elements on earth. It has been identified as one of the potential future fuels for marine industry. Hydrogen when deployed as a fuel, creates only water and minor volume of NO_x as by-products. Hydrogen can be generated by a variety of renewable feedstocks, such as biomass, nuclear power, wind, and solar power.

Hydrogen in ambient conditions is a gas of diatomic molecules with the formula H_2. It consists of two hydrogen atoms bonded together (H-H). It is colorless, odorless, tasteless, non-toxic, and highly combustible. Hydrogen's boiling point is -253 °C at atmospheric pressure. Hydrogen is characterized by a very low volumetric energy density. On a lower heating value (LHV) basis, liquid hydrogen (LH_2) has an energy density of 8.5 megajoules per litre (MJ/litre), while in its compressed state (CH_2) has 4,7 Mj/litre at a pressure rate of 690 bar and 25°C temperature.

3.3.1. Production

As hydrogen exists in compound form, it needs to be taken out from different sources, ie. fossil fuels, biomass, water etc. There are different existing technologies and methods to produce hydrogen including reforming, gasification, pyrolysis, and water electrolysis (Wang Y, 2021). Based on the method and energy resources used for productions, hydrogen is classified into different categories. Green hydrogen, also known as clean hydrogen, is produced from water electrolysis, which utilizes electricity generated from renewable energy sources, such as biomass, solar and wind. The use of renewable energy indicates that no CO_2 emissions are occurring for the hydrogen production. A low-carbon hydrogen is the so-called blue hydrogen, its production is based on fossil fuels, like natural gas, while deploying a carbon capture, utilization, and storage (CCUS) system, making it more cost-viable than green hydrogen. Blue hydrogen could be characterized as carbon-neutral because there are no CO_2 emissions and is considered a potential solution for the energy transition. Moving along the hydrogen's color spectrum, purple, pink, or red hydrogen is also produced by water electrolysis with the exception that the electricity used, comes from nuclear power plants. Electrolysis is also used to produce yellow hydrogen, however, in this case the electricity is provided from the energy grid and depending on the country, the energy power mix differs. Grey hydrogen is generated from steam methane reforming, autothermal reforming and partial oxidation. About 40% of grey hydrogen is a byproduct of chemical processes. Brown or black hydrogen is the least environmentally sustainable method of production, considering that the production comes from coal (Arcos & Santos, 2023). Currently grey hydrogen is covering most demand through steam methane reforming (SMR) using natural gas as a resource. The amount of clean hydrogen produced worldwide accounts only of the 4% of total production (IEA, 2022).

	Terminology	Technology	Feedstock/ Electricity source	GHG footprint*
PRODUCTION VIA ELECTRICITY	Green Hydrogen	Electrolysis	Wind | Solar | Hydro Geothermal | Tidal	Minimal
	Purple/Pink Hydrogen		Nuclear	
	Yellow Hydrogen		Mixed-origin grid energy	Medium
PRODUCTION VIA FOSSIL FUELS	Blue Hydrogen	Natural gas reforming + CCUS Gasification + CCUS	Natural gas | coal	Low
	Turquoise Hydrogen	Pyrolysis	Natural gas	Solid carbon (by-product)
	Grey Hydrogen	Natural gas reforming		Medium
	Brown Hydrogen	Gasification	Brown coal (lignite)	High
	Black Hydrogen		Black coal	

*GHG footprint given as a general guide but it is accepted that each category can be higher in some cases.

Picture 12: The hydrogen color spectrum and indications for carbon emissions (Cheng & Lee, 2022)

3.3.2. Emissions

Hydrogen can be used as fuel in fuel cells or currently as a blend in existing combustion engines, and does not release any CO_2, PM or SO_x emissions. It has been reported, that utilized as a drop in fuel in marine diesel engines up to 25% blending, it does not risk the engine in any significant level (Wärtsilä Corporation, 2023).

3.3.3. Storage

Hydrogen in ambient conditions has low volumetric energy density, thus requires additional infrastructure and storage systems to be developed. Hydrogen in liquid state requires deep cryogenics in order to be stored, higher than nitrogen or LNG.

There are four possible storage methods that can be applicable for shipping industry (Hoecke, et al., 2021):

- Applying high pressured to compress the hydrogen
- Very low temperature for its liquid state
- Utilizing chemical storage
- Metal hybrids

The compressed hydrogen is currently more widely acceptable as storage method for the shipping industry. On the other hand, hydrogen in liquid form has much higher density than compressed hydrogen. The process of liquefaction involves cooling hydrogen gas to -253°C and then storing it in an insulated tank, thus its storage and supply system in terms of insulation requirements would be high-energy intensive.

Hydrogen also requires a considerable amount of space compared to marine gas oil, even if it is condensed. From an energy content perspective, hydrogen requires tank volumes that are almost eight times more than the ones for marine gas oil, considering the equivalent energy. However, land-based storage solutions for both liquid and compressed hydrogen have already been developed, which could potentially be applicable for shipping industry. Moreover, due to its low weight relative to diesel, hydrogen may be a more viable option for weight-limited vessels.

Hydrogen to be stored on board of a marine vessel would require substantially larger fuel storage tanks in comparing with other fuels for the same voyage distance. Liquid hydrogen would require about four times when compared to traditional oil fuels and two and a half time than LNG. In condensed state, it would require double space storage. It is most probable that hydrogen would be considered for short-sea shipping, because the storage requirements in case of deep-sea shipping will pose limitations to the vessel's cargo capacity.

3.3.4. Logistics & Infrastructure

Hydrogen can be transported with pipelines or by road transport. Natural gas pipelines are capable of transporting hydrogen in 5-20% without major modifications. Worldwide there are about 4,500km hydrogen pipelines primarily in Europe and North America, while there are over a million km of natural gas pipelines. Road transport for small volumes of hydrogen is already widespread in both liquid and compressed state. Infrastructure for liquid hydrogen requires more development. In matter of energy density and space efficiency (tank to hull shape), liquid hydrogen is preferred to compressed hydrogen. However, there are higher cost implications from pressurized to deep cryogenic conditions. The liquefaction of hydrogen is a highly energy intensive process and requires consumption of the equivalent of about 30% hydrogen. In comparison to LNG, which requires 8-15% of natural gas (SGMF, 2023).

3.3.5. Safety and Regulations

Due to its cryogenic state could result to release of oxygen from the air condensing through piping, creating risks of explosion. Same as LNG there are risks of boil-off leakages, which would require additionally energy intensive reliquification technologies onboard (Mallouppas & Yfantis, 2021). Moreover, hydrogen is highly volatile and challenging to contain, equipment materials are subject to embrittlement and need to be specifically considered as for LNG. For example, it is necessary the use of specific types of steel and welded connections rather than fittings. When hydrogen gas combines with air or oxygen and ignites, it leads to a form of explosion known as hydrogen deflagration. Due to its unique characteristics, managing hydrogen can be challenging and requires safety measures. The explosive nature of concentrated hydrogen is necessary to be assessed for the development of the infrastructure for the shipping industry. To elaborate, tanks must be appropriately insulated to prevent evaporation, which may occur if heat is transferred to the stored substance via conduction. Hydrogen has a higher likelihood of fire and/or explosion compared to other substances because of its broad range of flammability and low ignition energy. (Crowl & Jo, 2007)

From a regulatory perspective, there are currently underway efforts at the IMO to incorporate hydrogen into the IGF code. The IGF Code offers guidelines for using low-flashpoint fuels such as hydrogen in maritime settings. However, the code has primarily been utilized in installations related to LNG, and the inclusion of hydrogen is still in its early stages.

3.4. Ammonia

Ammonia is a liquefied gaseous fuel. It is an inorganic chemical composed of nitrogen and hydrogen with the formula NH_3. At ambient temperatures, ammonia is a colorless gas with an irritating odor. When in gaseous state, it can be liquefied either by applying a moderate pressure (e.g. about 7.5 bar(g) at 20°C (ambient temperature), or by cooling it down to approximately -33°C at atmospheric pressure. Gaseous ammonia has a notable degree of solubility in water. This solubility tends to rise as the temperature decreases. Approximately 500 or more volumes of ammonia gas can be dissolved by one volume of water. The solubility of ammonia in seawater varies based on factors such as temperature, pH, and the concentration of salts present. When dissolved in water, ammonia reacts to form ammonium hydroxide (NH_4OH), often referred to as aqueous ammonia or ammonia solution. which is a 'base' in nature (i.e., an alkali, not an acid) and toxic to aquatic life and humans. This dissolution process releases substantial amounts of heat (exothermic).

3.4.1. Production

Ammonia has been produced safely on large-scale production for more than a century and has been shipped in bulk worldwide for over six decades. It currently ranks among the most widely produced inorganic chemicals globally, with established infrastructure for storage and transportation. Presently, approximately 80% of the produced ammonia serves agricultural purposes as a fertilizer, while the residual portion finds application in various industrial applications. The most commercially used method of ammonia synthesis is the Haber-Bosch process, developed at the end of the 19th century combining hydrogen and nitrogen with the use of high temperatures and the presence of a catalyst (ITF, 2018). The

hydrogen derived from the steam reformation of methane, a process that emits CO_2. The ammonia produced with this method is classified as grey or brown ammonia and accounts for about 180 million tons of world's annual production. Following the usual color scheme, blue ammonia is produced like gray, but the CO_2 which is generated as by-product has been captured and stored, reducing its GHG impact. Green ammonia is produced with the use of hydrogen which is deriving form water electrolysis, powered with electricity from deploying renewable energy sources (Machaj, et al., 2022).
The production of green ammonia has not been widely scaled, thus is not yet cost-efficient if compared to the conventional ammonia, which is 90% dependable on natural gas. The energy costs to produce green ammonia are still high and could be potentially reduced if alternative methods are adopted. (Wang Y, 2021)

The conventional production process of ammonia is characterized as carbon intensive. The emissions deriving from the process contain approximately 450 million tonnes (Mt) of CO2 annually, which is comparable to the collective energy system emissions of South Africa (SGMF, 2023).

3.4.2. Emissions

Since ammonia is a carbon-free molecule, there is no CO_2 emissions during its combustion. According to its chemical composition, each nitrogen atom is bonded with three other hydrogen atoms, ammonia can be considered as an effective hydrogen carrier: 10.7kg of hydrogen can be found in 100 liters of liquid ammonia (SGMF, 2023). Ammonia is being considered as a potential clean fuel for maritime industry due to the absence of carbon and sulfur in its emissions, given the fact that NO_x and N_2O emissions from fuel combustion are treated properly.

3.4.3. Storage

Ammonia if compared to LNG and Hydrogen, requires less effort for handling it in liquid form as it requires around -33°C temperature, indicating that as a marine fuel, storage and delivery systems could be less complex and less capital cost intensive. Storage requirements of ammonia are comparable with the ones for propane, in usual ambient temperatures needs to be pressurized to 8.6 bar vapor pressure to maintain its liquid form

(Wang Y, 2021) (Zamfirescu & Dincer, 2009). Ammonia could be a potential chemical carrier for hydrogen, as the investment costs for storing it are less expensive (ITF, 2018).

On a volumetric basis, its energy density is approximately half that of LNG and one-third that of traditional oil fuels. This has directly an impact on the volume of ammonia fuel required, which is approximately three times the amount of MGO, and almost double that of LNG to cover the same distance voyage. If compared to hydrogen, it has low volumetric efficiency and is about 50% more energy-dense per unit volume (around 3kWh/litre), making it simpler for storage and distribution, however, still would requisite bigger storage capacity infrastructure on board (DNV GL, 2019). It is recommended to store NH_3 in iron or steel containers due to its corrosive nature towards metals. Storing NH_3 as a liquefied gas can result in a potential risk of flash fire (Inamuddin, et al., 2020).

3.4.4. Infrastructure & Logistics

Infrastructure such as terminals and storage facilities can be found among 100 ports worldwide. China is the largest producer of ammonia followed by Russia, the US, the Middle East, the European Union, and India. The accessibility to low-cost renewable energy will play a significant role to the production of green hydrogen, and hence green ammonia. It is projected that new production and bunkering facilities will be developed in areas with abundant renewable energy resources such as Australia, Europe, parts of south America, Africa, and the Middle East.

Due to its liquefaction point of approximately -33°C under standard atmospheric pressure, ammonia can be transported in bulk using vessels designed to handle liquefied gases, either in completely refrigerated or pressurized storage conditions. The prevailing vessel type for ammonia transportation is medium-sized, fully refrigerated vessels (approximately 20,000-50,000m3). However, there is a significant number of vessels transporting using pressurized tanks at ambient temperatures.

In comparison to other hydrocarbon gases that might be transported by vessels, ammonia has a higher density (680 kg/m³ in comparison to propane and butane's 583-600 kg/m³), necessitating appropriately designed tank structures. Ships carrying ammonia typically utilize tanks made from steel alloys suitable for the cargo's temperature and incorporate specialized equipment and fittings to ensure adequate corrosion protection.

In certain scenarios, containerized pressure vessels adhering to the criteria set by the International Maritime Dangerous Goods (IMDG) Code may be utilized for ammonia transport. This applies particularly when they conform to the limitations established by the International Organization for Standardization (ISO) for tank containers.

3.4.5. Safety and Regulatory Framework

The flammability range of ammonia is low and generally is perceived as non-flammable. The toxic nature of ammonia is posing an important challenge and creates a new dimension on how to control a gas leakage as it cannot be just released to its surroundings. Even though ammonia gas leakage could be detected quickly due to its strong odor characteristic, exposure in high concentration could cause serious health issues and death to humans, posing serious threats for the onboard personnel. If ammonia could be used as a marine fuel, the industry must examine thorough its implications, taking into consideration that its toxicity threats have already been addressed and mitigated in other industrial sectors. (Wang Y, 2021) Ammonia's toxic risks are widely acknowledged and understood. The well-established expertise and knowledge across the industry will facilitate to form safety and handling regulations for its bunkering and use as a fuel aboard vessels. The IMO initiated the regulatory procedures for ammonia in 2022, and interim guidance is expected in 2023-2024 (SGMF, 2023).

The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) incorporates specific requirements for bulk transportation of ammonia by seagoing vessels, due its toxic nature. These requirements include distinct mandates for materials, tank gauging systems, and personal protective equipment (PPE). Currently the utilization of ammonia as fuel for gas carriers is prohibited under the IGC Code. On the other hand, even though the IGF code does not yet include guidelines for ammonia, the IMO has initiated in 2022 the work to add the necessary provisions for ammonia.

In the same manner, the STCW Code (Standards of Training, Certification & Watchkeeping for Seafarers) will be required to be updated alongside the IGF Code to provide additional guidelines and rules for training protocols.

Classification societies have established regulations for the utilization of ammonia as a refrigerant on board vessels like fishing ships. These regulations outline the criteria for permissible leakage thresholds, measured in ppm, within specific zones. Additionally, there are extensive regulations onshore around the world covering a range of matters related to ammonia's usage. These regulations could be used as a reference basis to expedite the regulatory framework for the ammonia as a marine fuel.

3.4.6. Environmental impact

Grey ammonia, which is ammonia produced from fossil fuels without carbon capture and storage, is generally considered to have higher well-to-tank GHG emissions compared to oil-based marine fuels and LNG. This is due to the carbon-intensive nature of the ammonia production process from fossil fuels. The carbon footprint from the ammonia productions account about 1.2% of the global anthropogenic CO_2 emissions (Al-Aboosi, et al., 21). The environmental impact analysis of ammonia as a marine fuel relies on the life cycle assessment for the carbon footprint over two bases: well-to-tank and tank-to-propeller (TtP). Since ammonia is a carbon-free molecule, the tank-to-propeller carbon footprint is ignored in comparison to the well-to-tank footprint.

The formula to calculate the overall CO_2 equivalent emissions is:

$$gCO_2eq = gCO_2 + 25 \times gCH_4 + 298 \times gN_2O$$

According to analyses, the WtT emission values vary widely between 9.7 and 277.6 g CO_2 eq/ MJ fuel, The variability depends on the use of technology, feedstocks, and conventional or renewable energy sources (Al-Aboosi, et al., 21).

Grey ammonia has higher well-to-tank GHG emissions than fossil marine fuels.

Since the full commercialization of production of blue and green ammonia has not still been initiated, there are several assumptions that cannot be verified. Blue and green ammonia will have substantially reduced GHG footprint in comparison to grey ammonia.

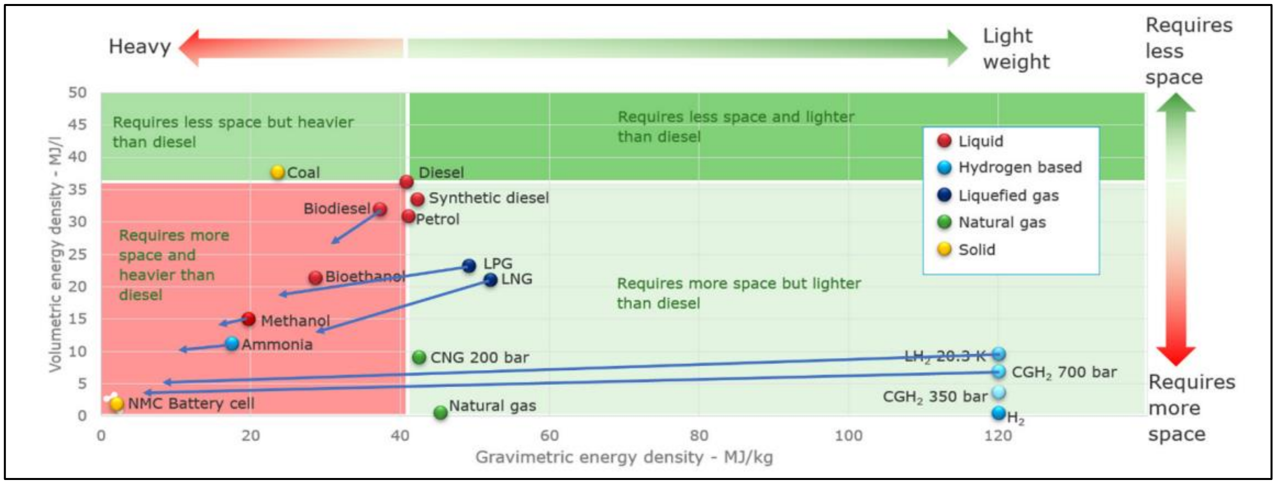
From a tank-to-wake perspective, the use of ammonia as an alternative marine fuel has close to zero carbon emissions, regardless its production method. However, as it has low flammability compared to other fuels, there would still be need for pilot fuel to start the combustion. When ammonia is burned, nitrogen by-products are released, and their treatment have to be considered. These by products are NO_x, a toxic air pollutant and N_2O is a potent GHG with a global warming potential (GWP) 273 times that of CO_2 over 100 years (SGMF, 2023).

3.4.7. Ammonia as a marine fuel

Ammonia could be utilized as primary fuel for fuel cells technology and act as drop-in fuel ammonia in internal combustion engines and gas turbines (Mallouppas & Yfantis, 2021). Ammonia does not contain any carbon in its molecular formula; thus, its combustion produces zero CO_2 emissions. However, the incomplete combustion could cause an increase of NO_x emissions and potentially N_2O emissions that would need special handling and treatment. The slow ignition and narrow flammability limits could prompt incomplete combustion in the engine system (Wang Y, 2021). Ammonia as a fuel in combustion engines had several downsides, like very high auto-ignition temperature, low flame speed, high heat of vaporization, narrow flammability limits, and toxicity, moreover ammonia's reported corrosiveness to metals and plastics would need to be taken into account for the design of an ammonia-fueled engines (DNV GL, 2019).

Global demand for ammonia is expected to grow in the coming years. Especially when new applications including ammonia as a marine fuel, for power generation or a hydrogen carrier will mature, the demand is projected to increase.

The adoption of ammonia as a maritime fuel relies on various factors, including the resolution of regulatory, production, and technical challenges, with the main concerns revolving around its toxicity, availability, and upstream environmental performance.



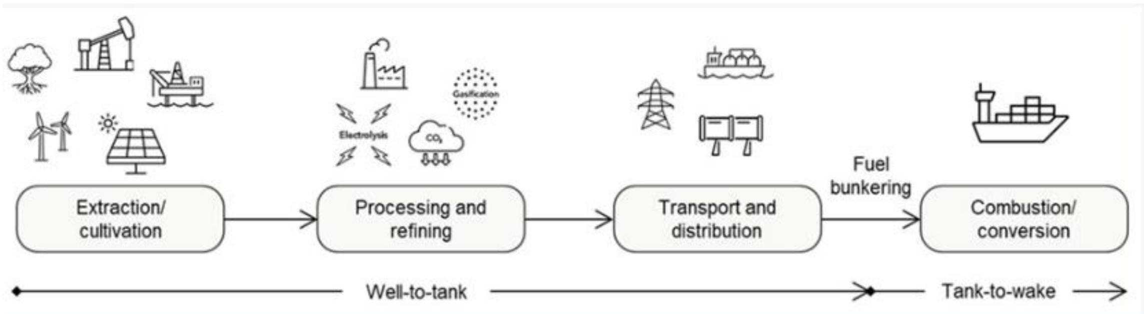
Picture 13: Energy densities for different energy carriers, Source: (DNV GL, 2019)

3.5. Alternative fuels – Life Cycle Assessment

The Revised IMO Strategy on Reduction of GHG Emissions from Ships underscores the necessity for new zero or near-zero greenhouse gas (GHG) emission fuels in the shipping industry. Key objectives include a 40% reduction in the carbon intensity of international shipping by 2030 and a subsequent significant decrease to attain net-zero GHG emissions by approximately 2050. To guide this transition, indicative checkpoints are outlined, targeting a 20% to 30% reduction by 2030 and 70% to 80% by 2040, compared to 2008 emission levels. The strategy emphasizes considering the well-to-wake GHG emissions of marine fuels, aligning with lifecycle GHG intensity guidelines to prevent emissions from shifting to other sectors. Projections from the Fourth IMO GHG Study 2020 anticipate that approximately 64% of the total CO2 reduction in shipping by 2050 will come from alternative low/zero-carbon fuels.

The life cycle assessment (LCA) is a term that refers to the assessment of GHG emissions coming from the fuel production until the end-use by a ship know as Well-to-Wake (WtW).

Well-to-wake refers to the end-to-end process of fuel production, delivery and use onboard ships, and all emissions produced therein. Well-to-wake analysis is similar to well-to-wheel analysis for road vehicles. This analysis assesses the emissions during the complete life cycle of a fuel.



Picture 14: Generic well-to-wake supply chain Source: IMO 2023

The WtW is the combination of a "Well-to-Tank" part and "Tank-to-Wake". Well-to-Tank (WtT) are the emissions from the primary production up to the transportation of the fuel into a ship's tank, also known as upstream emissions Tank-to-wake (also called "Tank-to Propeller"): this analysis considers only the emissions coming from burned fuel when it is already in the tank, known as downstream emissions Fuel's production and transportation and bunkering on to the vessel are excluded.

A well-to-wake approach and a LCA are enabling a more solid evaluation of marine fuel performance in relation to their emissions of GHGs, beyond carbon emissions, including methane and nitrous oxides. (Methanol Institute, 2021)
The candidate low-carbon and zero-carbon fuels considered for shipping have different production pathways, such as various generations of biofuels and hydrogen-based fuels, resulting in notable variations in their overall environmental impact. The transition to alternative low- and zero-emission fuels necessitates the establishment of a comprehensive international framework for scientifically and holistically assessing the GHG intensity and sustainability of these fuels.

The MEPC 80 adopted in 2024 the Guidelines on life cycle GHG intensity of marine fuels (LCA guidelines) RESOLUTION MEPC.376(80) (IMO, 2023). The LCA guidelines enable a Well-to-Wake calculation, including Well-to-Tank and Tank-to-Wake emission factors, of total GHG emissions related to the production and use of marine fuels.

This is a first version of the LCA guidelines, and the work will continue until all details are finalized. The calculation of the WtW GHG intensity is expressed. Methane (CH_4) and nitrous oxide (N_2O) will be included using 100-year global warming potential (GWP100).

4. An Overview of Ship Engine Technology

4.1. Internal Combustion Engines

Internal combustion engines (ICE) have been the most widely used source of energy both for ship propulsion and electricity production onboard. The marine engines based on the power they serve are classified as main or auxiliary engines. Main engines (ME) are converting thermal energy into kinetic energy which is used to drive the ship's propeller and move the ship into the water. The auxiliary engines (AE) are deployed to generate uninterrupted electrical power flow to the ship. Internal combustion engines have the highest efficiency of transforming thermal energy into mechanical work and are installed on about 98% of the global merchant fleet. In relation with the cost of energy (fossil fuels), ICE is a cost-effective option for shipping. Internal combustion engines exist for more than 100 years. Environmental performance of ICE is continuously improved, while they are transitioning to gas and gas-diesel applications. Their technology is mature and there is vast knowledge and expertise in the field. New technologies like electronic control systems, have solved issues in terms of their operation, provided simplicity and have advanced their life expectancy to be equivalent to ship's lifetime. The ship engine-manufacturing sector is an advanced sector that constantly fulfills the demands from shipping industry while meeting the regulatory requirements posed from the governing bodies. Engine manufacturers have been developing different approaches in handling problems related to fuel efficiency, environmental compliance, reliability, and operational costs (Bilousov, et al., 2020). The technology of ICE is continuously improved to meet emissions regulations, and it is designed to be flexible and fuel-ready for future alternative marine fuels.

The internal combustion engines produce mechanical energy which is the energy converted by the controlled fuel burning in an enclosed space (cylinder). In a reciprocating engine, also known as piston engine, the explosion (fuel burning) is driving the rotation of the engines parts and regulates the piston movement into the cylinder. This kinetic energy is then transferred to the crankshaft through the connecting rod.

4.1.1. Classification of Marine Internal Combustion Engines

Two-Stroke and Four-Stroke Marine Engines

There are two basic types of marine engines. These are the two-stroke and the four-stroke engines. A two-stroke (or two-cycle) engine an internal combustion engine that completes a power cycle with two strokes (up and down movements) of the piston during only one crankshaft revolution. While in the four-stroke engine the piston completes four separate strokes while turning the crankshaft. A stroke refers to the full movement of the piston within the cylinder, in either direction (Wärtsilä, 2015).

The four-stroke engines are usually installed on vessels to generate electrical power and for smaller sized applications are used also for ship-propulsion. In the four-stroke engines, a complete cycle consists of the following events: suction, compression, explosion, and exhaust. In simple terms, the events are taking places as described below:

- Suction stroke: fresh air intake into the combustion chamber (downward movement of the piston)
- Compression stroke: air-fuel mix is compressed (upward movement of the piston)
- Power stroke: explosion happens and moves the piston downwards
- Exhaust stroke: the gases released are moving the piston upwards

These four events, a complete engine cycle, is accomplished within four strokes of piston or two revolutions of the crankshaft. Inlet and exhaust valves are placed on the top of the cylinder head to intake fresh air and exhaust the released gases.

In two stroke engines the complete cycle of these events is taking place in a single revolution of the crankshaft or in two strokes of the piston.

The complete sequence of the events is accomplished in two cycles as described below:

- Suction and compression stroke: the piston is moving upwards for the admission of fresh air inside the cylinder and to compress the air-fuel mixture
- Power and exhaust stroke: the piston is moving downwards because of the explosion inside the chamber followed by removal of exhaust gases through the exhaust valve

However, there is another classification for the engines according to the process of combustion: explosion or constant-volume combustion engines and constant-pressure combustion. When the set of processes which cause the explosion happens with a constant volume process then the engine is an Otto-cycle. The Otto engine works according to the Otto cycle with spark ignition. As spark ignited engine is an internal combustion engine that commonly runs on gasoline or natural gas. While the engines which compress the fuel to increase the temperature and cause ignition are known as Diesel Engines. The diesel cycle explosion takes place with a constant pressure process.

Four-stroke engines if compared to two-stroke are of smaller size and weight, they can achieve higher RPM or speed, there is more ease of maneuvering and less cost of construction, thus less investment cost. However, they have more complexity in their design. Four-stroke engines have been improved and become more environmentally friendly through developments in the fuel injections systems and optimization in the air-fuel mix. They could be a suitable choice for vessels operating in areas with restrictions applied on ships emissions (ECA, SECA) (Bilousov, et al., 2020).

Two-stroke engines on the other hand if compared with four-stroke are capable to increase output power without increasing the working volume. Two-stroke engines have been the prime mover in the shipping industry for many decades. Low-speed, two-stroke, crosshead type, reversible, uniflow-scavenged, turbocharged, electronic design. They are more thermally efficient and reliable due to the less moving parts.

Low-speed two-stroke engines. Two approaches for air-fuel mixture (Bilousov, et al., 2020):

- The fuel (in gas state) is admitted to the combustion cylinder, after the exhaust valves are closed, in the initial phase of the compression stroke with low pressure. This system is known as low compression supply.
- The fuel (also in gas state) along with the ignition fuel are admitted to the combustion cylinder at the end phase of the compression stroke with high pressure. This system is known as high-pressure supply or direct gas injection (GD)

The two-stroke advantages as main propulsion method are:

- Fuel selection: lower quality of fuel, reduce operating costs
- Higher thermal efficiency
- Higher power output- Higher power to weight ratio
- More cargo - Higher power to weight ratio
- More reliable in operation
- Less maintenance requirements
- Direct start and reverse
- Defined as low-speed engines, no need for reduction gear as for high-speed four stroke

Spark Ignited and Compression Ignited Engines

Another classification of marine ICE is done according to the method of ignition, spark ignited (SI) and compression ignited (CI) engines. In spark ignition engines, the fuel-air mixture is drawn into a cylinder and ignited by a spark during compression, while in compression ignited engines the heat of compression is used to initiate ignition to burn the fuel, which is injected into the combustion chamber during the final stage of compression.

Low, Medium and High-Speed Engines

Marine reciprocating diesel engines, based on their revolution per minute (rpm) are grouped into the three types: slow, medium, and high speed. Each type has different properties that according to the ship type, size and applications are being more suitable.

Low speed engines are common choice for seagoing vessels, such as tankers, bulk carriers, and containerships, while medium speed engines are preferred for smaller vessels, like ferries, cruise ships, Ro-Ro and other vessels. However, there seem to be overlapping between the solution, where new high-powered large bore engines of medium speed are compared with low-speed engines (Molland, 2008).

Gas and Gas Diesel (Dual Fuel) Engines

There is another classification of internal combustion engines based on the type of fuel that can burn. Marine ICE can also run on gas fuels. The most common marine gas fuels are methane, propane, and butane. Methane in its liquid form (LNG) is stored in cryogenic tanks on board, while liquid mixtures of propane and butane (LPG) are stored in high pressure tanks in ambient conditions. The biggest advantage of gas fuels is the significant reduction in emissions if compared with heavy fuel oil, as SO_x emissions are almost eliminated, NO_x emissions are decreased by 90% and CO_2 reduced up to 30%.

There are three different technologies for gas fueled engines which can be both deployed in two and four-stroke engines.

(1) One solution is to convert the diesel engine to run based on the Otto cycle, meaning to mix the air-fuel before the combustion cylinder and ignite the mixture with a spark plug.
(2) Another variation is to mix the air-fuel before it reached the combustion cylinder while deploying electric spark ignition in combination with liquid fuel oil injection into the cylinder, dual fuel (DF) engine
(3) Another type of DF engine is utilizing the same combination of electric spark ignition with liquid fuel injection, but the mix of air-fuel is completed into the combustion chamber.

This approach is deployed in two-stroke low-speed engines while the first two options are used in four-stroke engines. The second option is most common in medium and high-speed four-stroke engines. The DF four-stroke engines are capable of operating in gas fuel, liquid fuel or a combination of the two. DF engines have better fuel-efficiency in medium to high loads, their performance is dependent on the operating profile and their control configuration. DF engines are the as the best candidate solution in the energy transition (Mallouppas & Yfantis, 2021). However, there are technical challenges with the DF engines, with the most ordinary ones the high knocking and the methane slip.

4.2. Alternative Fuel Combustion in Internal Combustion Engines

4.2.1. LNG in ICE

LNG as a marine fuel is burned in dual-fuel engines, either in high (diesel) or low-pressure (Otto) systems. Methane slip occurrence is higher in low-pressure engine than in high-pressure. On the other hand, NO_x emissions are lower in the low-pressure compared to high-pressure engines, in which case SCR is required on board for the emissions treatment. Release of unburned methane is much higher in Otto dual fuel engines. Methane slip is increased significantly when Otto DF engines are loaded in less than 50%, while in higher power the methane slip is lower. Methane slip released to the atmosphere has about 28–34 times higher GHG impact per gram emitted than CO_2 from a 100-year perspective. In a short-term timeline methane's warming impact is 85 times higher per gram compared to CO_2. (Lindstad, et al., 2020)

Knocking is one of the most important problems of the LNG dual-fuel engines and it is a factor of the engine's power decrease (Arefin, et al., 2020). The knocking phenomenon is caused by spontaneous ignition (due to its high flammability) by a gas mixture which occurs in the combustion chamber before the propagating flame. Pure methane (CH_4) has a methane number (MN) of 100, meaning when combusted, knocking is not occurring. The higher the MN in LNG fuel, specifies its quality. The minimum required MN is defined from the engine manufacturer, i.e. some engine manufactures require LNG with a methane number at least of 80 (Kuczyński, et al., 2020). The indicated thermal efficiency of an engine burning LNG is equivalent to that of diesel and gases emitted are less when using LNG.

Diesel DF engines emit about 15% less GHG from a well-to-wake perspective, while 2-stroke Otto DF engines emit about equivalent GHG emissions with MGO, or even higher. When considering EEDI compliance for a newbuild vessel, IMO has set the maximum grams of CO_2 per ton-mile that can be emitted based on vessel type and size. However, methane emissions are not taken into consideration in the EEDI formula, nor well-to-tank emissions. Well-to-tank emissions are not in scope as the index calculates vessel specific fuel values. The formula includes only CO_2 and not CO_2 equivalents, thus IMO could revise and add including methane as a CO_2 equivalent in the EEDI. Either if the engine is diesel or Otto, based on the EEDI 30% reduction requirement from the baseline for phase 3, the LNG engine will be compliant. Even if complying with the phase 3 requirements, an Otto DF reduces total GHG by 4%, while a diesel DF provides a 15% GHG reduction of Well-to-wake emissions, still less than the 30% reduction in tank-to-wake perspective.

LNG can be considered as a transitional fuel, if it is combined with the best engine technology, i.e., diesel dual fuel engines. Additionally, an advantage of a diesel dual fuel engine is that it can be retrofitted in the long term to switch to alternative fuels with very low or zero GHG emissions, produced renewable energy resources, like ammonia. (Lindstad, et al., 2020)

4.2.2. Methanol in ICE

Methanol could be used as fuel in internal combustion engines, both in marine SI and CI dual fuel engines. Methanol when combusted produces zero PM & sulfur emissions and significantly reduced NO_x emissions, taking into consideration that EGR system or water emulsion is applied in DF engines. If compared to LNG, a methanol conversion is less costly about 25% to 35% of the corresponding investment needed for LNG retrofit for 10–25 MW engines. (Mallouppas & Yfantis, 2021)

Methanol is characterized by a low cetane number, same as LNG. The dual-fuel engines need a certain amount of cetane for ignition, thus diesel oil is used a pilot fuel. Wärtsilä a Finnish ship engine manufacturer has used its existing developed technology for dual fuel engines to run on methanol. The concept of using methanol as a fuel requires that the natural gas compressors would be substituted by high-pressure methanol pumps to increase the fuel’s pressure. A common rail system is required to be deployed to inject methanol and all piping needs to be designed as double-walled installations. The exhaust valves need to be designed with higher resistance to wear for exhaust gas and less lubricating substance than the commonly used for diesel oil. (Andersson & Salazar, 2015) This concept has been tested since 2015 on the ferry Stena Germanica which is equipped with the methanol converted Wärtsilä-Sulzer eight-cylinder Z40S engines. The converted engines have been performing at efficient levels and future engines are projected to have increased efficiency.

Also, another ship engine manufacturer MAN Diesel & Turbo has developed and tested two-stroke methanol engine technology for new-build tankers.

However, methanol would still require a pilot fuel as an ignition enhancer. From safety perspective, methanol has the same properties as diesel oil. The only exception is the low flashpoint, its risks have been considered with the same way as LNG regulations, and IMO has released guidelines for the safety on ships using methanol as marine fuel (IMO, 2020). Bunkering and supply terminals would not require additional cost investments, as methanol is available worldwide and already carried as cargo from the shipping industry. Considering future developments, methanol fueled engine technology will become mature and would be plausible to expect that the capex of constructing a new methanol-powered vessel could be comparable to the cost of a standard vessel that uses HFO as fuel, given the fact that methanol eliminates the need for fuel heating and oil separators, as it is clean and can be pumped at ambient temperatures (Andersson & Salazar, 2015).

4.2.3. Hydrogen in ICE

Hydrogen deriving from renewable energy sources is a candidate marine fuel for shipping to reach decarbonization. However, there are several challenges that need to be addressed. Hydrogen has a very low ignition temperature, which may cause unrestricted pre-ignition incidents and very high combustion temperatures by burning hydrogen-air mixtures. Hydrogen would be more suitable as marine fuel for a spark-ignited engine comparing to a compression ignition engine, because of its high auto-ignition temperature. Hydrogen has a lower heating value of about 120Mj/kg, significantly larger if compared to diesel and gasoline which is around 43Mj/kg, and when used in combustion engines both CI and SI, it reduces their volumetric efficiency. (Shadidi, et al., 2021) Currently, most marine engines are compression-ignition engines and hydrogen could be utilized as a secondary fuel in a blend without compromising engine performance, while reducing carbon emissions (Mallouppas & Yfantis, 2021).

The physical, chemical, and thermal properties of hydrogen make it superior to conventional fuels, but also pose challenges for practical applications. Despite this, hydrogen could be a potential marine fuel for ICE as it does not emit any carbon during combustion. Additionally, the high flammability range of H_2 allows for ultra-lean operation, resulting in low NO_x emissions. Compared to gasoline, hydrogen has a higher flame speed, auto-ignition temperature, and octane number, which reduces the risk of knocking and enables increased engine compression ratio for better thermal efficiency. However, hydrogen has lower volumetric energy density than conventional fuels, meaning that a larger volume of hydrogen is required to reach a high load on the engines. The power output of an engine running on hydrogen if compared to an equivalent volumetric size of convention fuel power output, will be significant lower. Development is needed in design to achieve a higher compression ratio. One more challenge is to prevent knocking, the engine compression ratio should be optimized, proper mixture formation should be achieved. Another threat is the risk of explosion. For spark ignited engines, the spark plug's hot electrode surface is a primary source of backfire in hydrogen-fueled engines. Another challenge that needs to be addressed in the NO_x emissions from hydrogens combustion, which could be solved by after-treatment systems, like SCR (Onorati , et al., 2022).

4.2.4. Ammonia in ICE

Ammonia is one of the most common chemicals used for fertilizers production, representing about 80% of its the global demand. Annual production levels of ammonia are about 180million tons globally. Ammonia in its liquid state at ambient conditions can be stored and transported without limitation on vessels, hence it requires about 4,1 time more volumetric space for storage than conventional fuels. It contains one nitrogen atom and three hydrogen atoms, and its combustion does not emit any carbon, sulfur, or PMs. The by-products of its combustion are mainly water and nitrogen (Zincir, 2020). The absence of PMs, sulfur and carbon emissions make ammonia a potential marine fuel. The important challenge when combusting ammonia is the NH_3 slip, NO_x and N_2O emissions. Since ammonia is toxic, a high concentration slip could result in health risks. Additionally, N_2O is a GHG emission, affecting about 300times more global warming than CO_2, thus these emissions are necessary to be mitigated with correct combustion process.

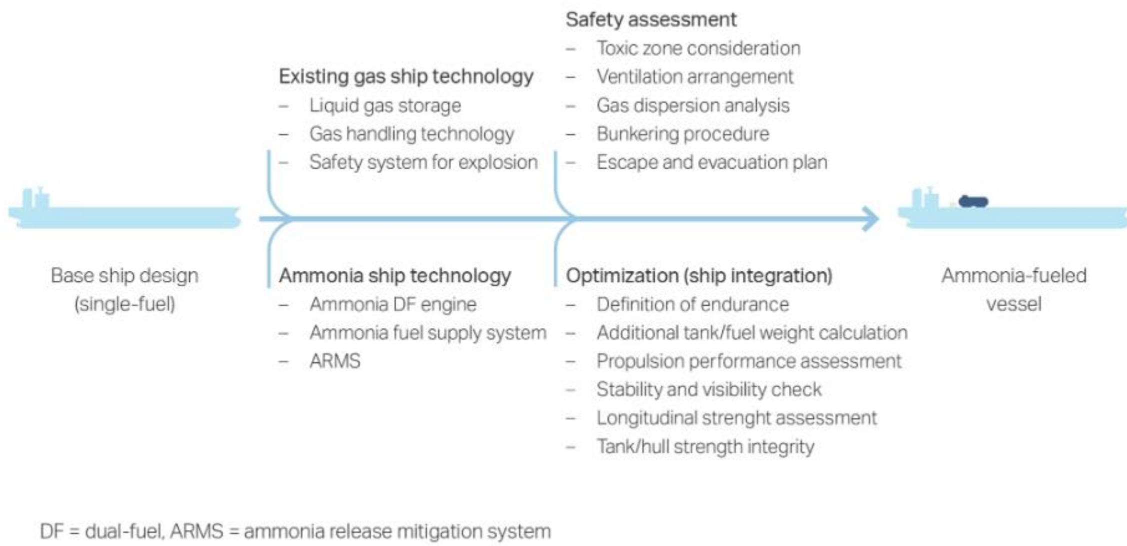
If compared to gasoline, ammonia same as hydrogen has a high-octane rating 110, thus could run at a higher compression ratio, facilitating its usage in diesel engines. Ammonia has high-autoignition temperature of 924K, making possible to be fueled in dual fuel diesel engines. However, ammonia has a lower energy content than the typical hydrocarbon fuels and requires more amount to be combusted in the same amount of air (air-fuel ratio). Flammability ration is between 16-25% volume in air, low flame temperature and low burning velocity. These combustion characteristics can result to instable combustion at very low or very high engine loads. The thermal efficiency of ammonia combustion is expected to be higher than conventional fuels, as ammonia has lower heating value than diesel and can reduce combustion temperature and heat loss.

Ammonia due to its high auto-ignition resistance needs a pilot fuel to initiate combustions so as to be used in conventional diesel engines. The partially premixed combustion (PPC) concept could be utilized for ammonia combustion, same as for methanol which also contains high octane fuel and resulted in high engine efficiency and low NO_x emissions from low to medium loads. Exhaust gas recirculation (EGR) system or selective catalytic reduction (SCR) system would be required as an after-treatment system to mitigate NO_x emissions. Ammonia slip due to its toxic substance would be necessary to be prevented. Additionally, ammonia's corrosive properties can seriously affect the fuel supply system and engine parts. Production materials must be compatible with ammonia and avoid the use of copper, nickel, and plastics.

The interest in ammonia as a marine fuel has increased significantly since 2010. Experimental studies conducted with ammonia in the fuel mixture, have concluded that specific fuel consumption (SFC) was higher for ammonia when ammonia energy content was higher in the total fuel mix (Zincir, 2020).

However, the following properties need to be examined thoroughly, before ammonia could be commercially available as marine fuel (Mallouppas & Yfantis, 2021):

- Low ignition level and slow flame propagation speed if compared to other fuels
- Toxicity and corrosiveness, requiring after-treatment or ensuring complete combustion process.
- Regulations, policies, and safety guidelines are important to be adopted



Picture 15: Design flow for ammonia-fueled vessels Source: Zero Carbon Shipping

4.3. Alternative Technologies for Ship Propulsion

The mechanical propulsion system is rather simple and is comprised of an internal combustion engine which is directly connected to a propeller shaft which drive the propeller. Alternative propulsion systems include electrical generators which supply electrical power to an electric motor which drives the propeller. The selection of the propulsion system depends on the vessel size, trade and operation profile.

4.3.1. Electric Propulsion

The primary equipment used in electric ship propulsion are steam turbines or diesel engines, which provide power to an alternating current or direct current generator. The generator is supplying electricity an alternating current or direct current motor mounted on the propeller shafts (Indragandhi, et al., 2022).

An electric propulsion system, in general, is comprised of a Diesel Generator Set which is providing and distributing the electrical power to an Alternative Current (AC) network. The system usually contains a Transformer which regulates the voltage before it reaches the Frequency Converter and the Electric Propulsion Motor or the Auxiliary Equipment. Electric propulsion is a viable solution both efficiently and economically for vessels with different operating profiles. Moreover, NO_x emissions are less than mechanical propulsion systems. The utilization of a Power Management System (PMS) along with electric propulsion enables the optimization of the running profile of the generator set meeting their design performance. In electric propulsion, the demand load from main propulsion and ancillary equipment is shared and the generator set are turned off when not used which results to less maintenance costs. Electric propulsion enables higher power availability, reliability, and optimization. Electric propulsion networks are also equipped with advance safety and automation systems which monitor, protect, and control the generator set and the propulsion system. It can be considered that electric propulsion systems require increased investment costs. They are used broadly in passenger ships where they can provide high power and stability in different operating profiles (Hoang, et al., 2020). Nowadays, electric propulsion has been deployed to commercial cargo vessels and LNG carriers, while it is most popular type of propulsion for cruise vessels and passenger/car ferries.

The propulsion system design for commercial ships is considering emissions levels and fuel consumption. The different operation profiles per vessel type and several performance factors affect the decision for the selection of a propulsion system. There is an increasing trend towards electric propulsion systems due to the ability to utilize renewable energy sources, decrease CO_2 emissions and increased energy efficiency.

4.3.2. Hybrid Propulsion

A hybrid propulsion system is a combination of internal combustion engines with electric motors which deploy renewable energy sources and battery power. In simple terms a hybrid propelled ship is using two differed power sources to provide propulsion to the propeller. A usual combination is a battery-electric motor integrated with diesel engines (Hoang, et al., 2020).

Hybrid power systems apart from power and machinery, include also waste heat recovery systems, energy saving devices and renewable energy sources like wind and solar. Hybrid power systems allow the effective utilization of different energy sources and the combination of battery energy storage systems with combustion engines taking advantage of the best characteristics of each technology. Batteries have the capability to cover peak power demand and reduce the low loads of the combustion engines (Bouman, et al., 2017).

For more than a decade, there is an increasing swift towards ships electrification by deploying hybrid models. The technology is advancing with different integration solutions between various energy storage systems (ESSs) and renewable energy sources (RES) (Anwar, et al., 2020).

An electric motor provides starting capability for the diesel engines. The batteries in such system can be charged from the diesel engines. In hybrid solutions, the battery systems can be charged from the diesel engines during voyage or by connecting to the grid when the vessel is at port. A hybrid propulsion system can be suitable for ships with low-speed operation profile. The advantages of both mechanical and electrical propulsion systems can be utilized in hybrid solutions. Yet, hybrid power supply in not widely deployed in cargo shipping, but it has been widely used in offshore installations, naval ship, tugs, and yachts.

A hybrid power supply system is combining two or more different power sources like internal combustion engines, generators, and power storage systems. Integrated battery solutions and DC technologies on vessels can reduce fuel consumption and emissions 10-35%.

The most important element in hybrid-electric solutions for ships is the energy storage system. Battery operations can be categorized into two concepts. A fully electric ship is utilizing a big volume of battery racks to drive an electric motor for its propulsion. The batteries are charged from the shore-grid during port stays. However, in case of emergency, it is usual that a small generator is installed on-board to be deployed for immediate charging. Battery systems when used continuously requisite a cooling system to maintain performance and battery life. A hybrid ship contains traditional fuel engines and battery systems. This concept enables longer voyages. Usually, the battery systems are used during port-stays or under lower speeds.

The specifications of the battery system, including its capacity, dimensions, weight, duration, charging speed, lifetime, cooling system, recycling needs, and investment cost are playing significant role in the vessel’s electrification. The Li-On batteries are broadly used in energy storage systems for electric or hybrid vessels. While Li-On batteries are cost efficient and high energy productive, their expected lifetime is a barrier due to the degradation caused from charging and discharging cycles. The lifetime of an energy storage system is determined by the number of charging/discharging cycle and when a system reaches a 70-80% performance reduction from the nameplate capacity, is at the end of lifetime. Based on its charging/discharging cycles, cooling method and physical degradation, the lifetime of Li-On battery system is 7-10 years. Temperature is affecting battery's state-of-health and lifetime. The three common cooling methods are air cooling, liquid cooling, and fin cooling. Each methods have its advantages and disadvantages depending on cost and complexity. Apart from battery performance, it is important to avoid overheating around the energy storage system from a safety perspective. Safety is a key factor for electric ship power systems. Proper insulation and firefighting systems are required (Anwar, et al., 2020).

There are certain challenges that need to be addressed when considering ship electrification, both from technical and operational perspective. In case of fully electric ships, the most important technical barrier is the voyage distance, such cases have been examined for short-sea ferry voyages. Additionally, the charging of the battery systems requires specific electrical installations both on-board and at ports and short port stay could be a challenge related to charging procedures. Furthermore, battery systems solution for ships is important to be manufactured with light-weighted materials to avoid extra burden on the vessel. The weight of the vessel is directly related with its energy efficiency (Anwar, et al., 2020).

4.3.3. Renewable Energy Sources

Renewable Energy Ssources (RES) could be utilized for production of green fuels or for direct ship propulsion. Since internal combustion engines are proven to be the most efficient technology for ship propulsion, in relation with the over-supply and fuel prices globally, the development of renewable energy solutions for ships has been impeded. The lack of commercial viability and limited financial incentives have been the main barriers for impeded the development and adoption of renewable ship propulsion (IRENA, 2015).

However, as the need for decarbonization is increasing, ship owners, operators and charters are now exploring the alternatives in a broader manner. There are several applications that could be applicable as solutions for shipping, such as wind power, solar power, and batteries, given that the last is charged with renewable energy. Renewable energy solutions can be investigated for shipping industry in form of retrofits for the existing vessels or new designs for the newbuilds ships. Up to now, renewable energy is designed to provide power for the auxiliary and ancillary applications of the ship. On the contrary, there are also concepts explored that ship propulsion which will be powered 100% by renewable energy or zero-emissions (IRENA, 2015).

Wind Propulsion

There are ongoing efforts to incorporate various renewable energy technologies into ships of different sizes, from small vessels to large cargo carriers. These technologies can be utilized as primary or auxiliary propulsion. Among the options available, there are soft-sail, fixed-sail, rotor, kite, and turbine technologies that fall under the category of wind propulsion.

Soft-Sails are traditionally attached to yards and masts and they have been proven to be a reliable and well-established technology that can effectively utilize wind as a source of propulsive power. With recent advancements in technology, the innovations developed for the super-yacht and yacht-racing sectors can now be integrated into sea-cargo vessels. These sails can serve as either primary or auxiliary propulsion and can be retrofitted onto existing vessels or integrated into the design of new-build vessels.

Fixed-Sails: Fixed-sails are rigid sails mounted on a rotating mast. There are various designs installed on ships, some of them with the capability to fold down.

Recent research efforts have been conducted towards exploring alternative ship propulsion systems. Wind-assisted propulsion, which involves the utilization of Flettner rotors is such an alternative. Although the integration of wind-assisted propulsion in the shipping industry presents some challenges & uncertainties, the potential cost savings could make it a viable solution both environmentally and economically (Tillig & Ringsberg, 2020).

Flettner Rotors are utilizing the magnus effect which generates propulsion as wind moves across a rotating cylinder. These rotors have been successfully installed onto the E-Ship 1 and Viking Grace. Retrofitting Flettner rotors onto the decks of various types of ships, including bulkers and tankers up to the VLCC class, is currently considered as a viable option for shipping (Blenkey, 2021).

Picture 16: Viking Grace Rotor Sail, Source (VIKING LINE, 2021)

Rotor sails have been identified as the most efficient type of Wind-Assisted Propulsion System (WAPS) based on force generation per square meter of projected sail area. In light of a high-level assessment, the findings reveal that rotor sails perform better than other WAPS in downwind and broad reach headings for the selected sailing conditions (Reche-Vilanova, et al., 2021).

Kite Sails are mounted to the bow of the ship and operate at high altitudes to capitalize on maximum wind speeds. The kite sails can reduce annual fuel costs by 10-35% (Mallouppas & Yfantis, 2021). This technology has been deployed in 2008 on vessel MS Beluga Skysail, which became the first commercial container cargo vessel to be partly powered by a 160-square-meter kite.

In general, the wind propulsion technologies have low levels of maturity. The decision for the installation of wind rotors and the similar technologies is dependent on the vessel's trading area and if there is available room for installation on deck.

Solar Photovoltaic Systems

Solar photovoltaic (PV) applications utilize PV cells to produce electricity generated directly by sunlight. The continuous improvement of this technology could be an opportunity for the shipping industry. Nevertheless, the primary constraints are the luck of space onboard for the deployment of PV panels and their energy storage needs. Although there have been significant developments in energy storage technology that offers greater potential and more favorable prospects for solar PV-powered propulsion systems in the near future, the advancement of technology required for full ship propulsion using solar PV will necessitate further research and is likely to be limited to relatively small vessels (IRENA, 2015). Other constraints for applications on vessels are the intermittency of solar energy and the maintenance of the PV cells. Moreover, there are studies examining how much solar energy can reduce fuel consumption, reporting in a range 0.2-12% (Bouman, et al., 2017). PV systems could be a promising renewable energy application for ships, given their advancements in efficiency. Nevertheless, for PV systems to be implemented on ships, further research and development are needed concerning materials due to the corrosive effects of seawater. Consequently, the efficiency of PV systems on ships is expected to be lower than the land-based applications.

Solar energy efficiency is subject to environmental and weather conditions. A key parameter that needs to be taken into consideration is the region that the candidate ship will be operating, as the performance of the solar power system is highly dependent on environmental factors. Another important challenge for solar PV deployment on ships is the lack of available space onboard for their installation. From a techno-economic perspective, small-scaled PV solutions on ships have been proven to have short payback time and fuel savings for small and short-sea vessels. Hybrid power generation on ships has become more popular, however, PV technology for ships is on early stage and there are still technical challenges that need to be addressed, like such as energy storage, infrastructure for electric charging and demands on high power capacity to propel ships (Park, et al., 2022).

Picture 17: MV Auriga Leader with solar power array, NYK Lines (IMO, DNV, 2023)

According to Clarkson's database (2024 data) there are about 55 vessels globally that have installed applied solar panels, mostly deployed on Pure Car Carriers, Ro-Ro vessels and Ferries. The estimated reduction potential for solar panels is 0.5% to 2% on the auxiliary engines fuel consumption (IMO, DNV, 2023). The solar panels technology on board ships is not yet mature and its deployment is highly dependent on ship's trading area and the sufficient free deck-surface.

5. Analysis of Alternative Fuel Uptake in the Global Fleet Orderbook

5.1. Introduction

The purpose of this analysis is to examine the uptake of alternative fuels within the Global Fleet Orderbook from 2019 to 2024, utilizing data sourced from Clarkson's Research licensed to University of Piraeus. As the shipping industry embarks on a significant transition towards achieving net-zero emissions, this analysis aims to explore the evolution of alternative fuel adoption in response to regulatory changes. Additionally, it seeks to identify key trends across different Fleet Groups and understand how these trends influence alternative fuel decisions. The period from 2019 to 2024 has been marked by substantial regulatory shifts aimed at reducing the carbon footprint of the shipping industry. These regulations have spurred the adoption of alternative fuels, with a noticeable increase in the number of vessels opting for cleaner energy sources. The analysis will highlight the industry's approach to fuel choices, emphasizing the correlation between fleet groups and fuel adoption rates. The uptake of alternative fuels varies significantly across different Fleet Groups. This section will categorize the fleet into distinct groups and analyze the adoption patterns within each category. By examining the data, we can identify which Fleet Groups are leading in alternative fuel adoption and which are lagging. Factors influencing these trends, such as fleet type, operational routes, and economic considerations, will be discussed in detail. Understanding the factors that drive alternative fuel decisions is crucial for predicting future trends. This section will explore the various elements that influence shipowners' choices, including technological advancements, fuel availability, and cost implications. By dissecting these factors, the analysis aims to provide an overview of the alternative fuel adoption. In conclusion, the analysis of alternative fuel uptake in the Global Fleet Orderbook reveals a dynamic interplay between regulatory changes and industry adaptation.

5.2. Data Collection and Preparation

The data utilized for this analysis were retrieved from the Clarkson's Research Database in October 2024. Specifically, the data were sourced from the World Fleet Register Report, which offers comprehensive information on the global shipping fleet. This includes details on fleet composition, shipbuilding activity, technological specifications, regulatory compliance, market trends, environmental data, and profiles of owning companies. Furthermore, the report provides in-depth insights into the future state of the global shipping fleet, encompassing information on new ship orders, delivery schedules, and technological specifications, with a particular focus on trends in alternative fuels and green technologies. The data also analyze investment patterns in new shipbuilding, identifying the most active sectors and regions. Additionally, the report examines the impact of the orderbook on fleet composition, including shifts in vessel types and sizes, and provides information on regulatory compliance, especially concerning emissions and sustainability.

For this study, the dataset utilized contains all the orderbook records with Contract Year ranging from January, 2019, to October, 2024. The primary objective is to identify patterns in the alternative fuel uptake in general and across different fleet groups. Accordingly, the data include records pertaining to merchant vessels, cruise and ferries. During data cleaning process, the fleet types such as Non-Cargo, Special Tankers, Tugs, Offshore and, Dredgers were excluded from the study’s scope. Additionally, the record items with Status: Idle, Storage, Damaged and Laid Up have been also excluded. The final dataset comprises of 11,162 record items.

The method of analysis employed in this study is variable analysis, which involves examining the relationships and patterns among different variables within the dataset. This approach is particularly suited for identifying trends and correlations in the uptake of alternative fuels across various fleet groups. The type of analysis conducted is descriptive, providing a detailed summary of the data and highlighting key characteristics and distributions. This approach allows for a comprehensive understanding of the factors influencing alternative fuel adoption in the global shipping fleet.

5.3. Descriptive Analysis

5.3.1. Global Shipping Orderbook (2019-2024)

According to the collected data, there have been 11,162 orders, and the Fleet Group types are: Bulkers, Chemical Tankers, Containerships, Crude Tankers, Cruise ships, Ferries, General Cargo, LNG Carriers, LPG Tankers, Multi-Purpose vessels, Pure Car Carriers, Product Tankers, and, Ro-Ro vessels.

Fleet Type	Number of Orders	Proportion	Gross Tonnage (Millions)	Proportion
Bulkers	3040	27,24%	126,6043	27,6%
Chemical Tankers	758	6,79%	8,046844	1,8%
Containerships	1750	15,68%	133,1027	29,1%
Crude Tankers	454	4,07%	48,09394	10,5%
Cruise	92	0,82%	5,503768	1,2%
Ferries	755	6,76%	2,738687	0,6%
General Cargo	1329	11,91%	5,269365	1,2%
LNG Carriers	497	4,45%	53,27207	11,6%
LPG Tankers	538	4,82%	18,30339	4,0%
Multi-Purpose	336	3,01%	4,447391	1,0%
Pure Car Carriers	270	2,42%	17,23447	3,8%
Product Tankers	1278	11,45%	33,80892	7,4%
Ro-Ro	65	0,58%	1,54834	0,3%
Grand Total	**11162**	100,00%	457,9742	100,0%

Table 8: Orderbook categorized per fleet type

The period from 2019 to 2024 has witnessed significant developments in the global shipping orderbook, as reported by Clarksons Research. This overview highlights the key trends and fluctuations observed during these years.

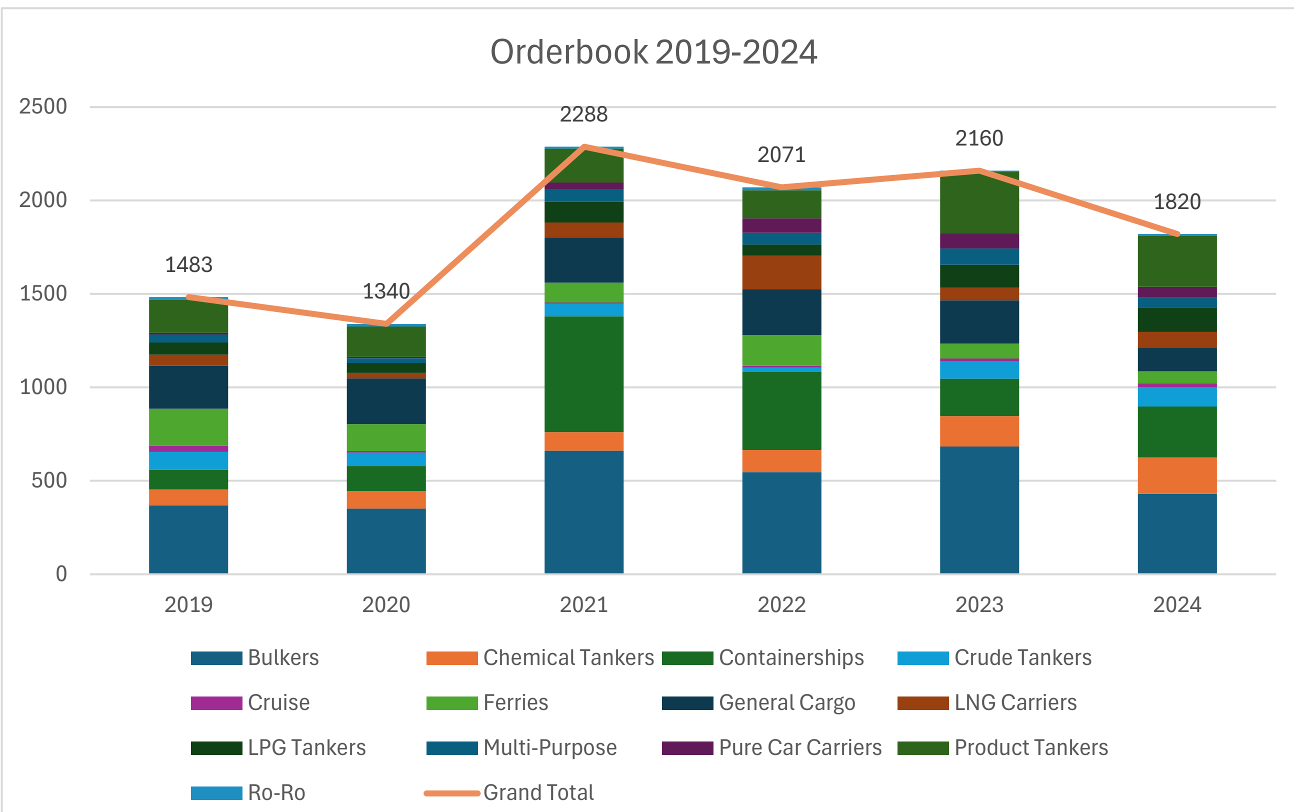


Chart 1: Shipping Orderbook categorized according to the vessel type per year

The shipping orderbook during 2019-2020 was relatively low, reflecting a cautious market sentiment amidst economic uncertainties. The industry focused on fleet renewal and compliance with new environmental regulations, leading to a conservative approach towards new orders. Additionally, the COVID-19 pandemic caused a substantial decrease in new ship orders, bringing the orderbook to its lowest level in 17 years (Liang, 2020).

In 2020, several key environmental regulations significantly impacted the global shipping orderbook, primarily driven by the International Maritime Organization's (IMO) initiatives. The most notable regulation was the IMO 2020 Sulphur Cap, which mandated a drastic reduction in the allowable sulfur content of marine fuels from 3.5% to 0.5%. This regulation aimed to mitigate air pollution and improve public health by reducing sulfur oxide emissions from ships. Additionally, the IMO introduced strategies to address greenhouse gas emissions, including the Energy Efficiency Existing Ship Index (EEXI) and enhanced Ship Energy Efficiency Management Plan (SEEMP), which sought to improve the energy efficiency of existing vessels. Furthermore, the European Green Deal proposed integrating shipping into the European Emission Trading System (ETS), adding another layer of regulatory complexity for shipowners operating in European waters. Collectively, these regulations not only increased compliance costs but also influenced ship design and construction decisions, thereby reshaping the global shipping orderbook in response to the urgent need for decarbonization and sustainable practices in the maritime industry.

In 2021, the global shipping orderbook experienced several significant trends, reflecting the industry's response to increased demand and ongoing supply chain challenges. Firstly, the orderbook reached a seven-year high, driven by a surge in new orders, particularly for container ships and gas carriers, as shipping companies sought to capitalize on elevated freight rates and address capacity shortages. The container shipping sector saw a significant increase in orders, with container ships accounting for a substantial portion of the orderbook, representing about 27% of the orders in year 2021. Additionally, the orderbook for Bulkers experienced a notable increase, driven by a surge in demand amid market conditions favoring investment in new vessels. As freight rates rose and operational efficiencies became more critical, many companies sought to expand their fleets. For the rest segments, there was a cautious approach to new builds due to market uncertainties and environmental regulations. Overall, 2021 was characterized by a robust recovery in new ship orders, particularly in the Container and Bulker segment.

In 2022, the global shipping orderbook continued an upward trend in comparison to recent years. The continued trend was the orderbook for container ships, fueled by strong demand and a rebound from disruptions caused by the pandemic. This trend was paralleled by a rising interest in LNG carriers, reflecting shifts in global energy dynamics and a growing focus on cleaner fuel alternatives. In 2022, the order book for Pure Car Carriers (PCCs) experienced notable growth, reflecting a robust recovery in demand within the maritime transport sector. Approximately 77 PCCs were ordered, representing a significant increase compared to the 39 orders recorded in 2021. This increase in orders was primarily driven by a rise in Chinese car exports and an increasing demand for car carriers, particularly to European and American markets. This trend was further supported by a recovery in global vehicle demand following the COVID-19 pandemic. In contrast, the orderbook for bulk carriers and tankers remained relatively stagnant, as shipowners took a cautious stance amid uncertainties stemming from geopolitical tensions and fluctuating market demand. The shipping sector faced various challenges, including capacity constraints, escalating shipping costs, and persistent supply chain disruptions, particularly influenced by the geopolitical situation surrounding the Russia-Ukraine conflict. Furthermore, environmental considerations became increasingly important, with shipping companies prioritizing sustainability and emissions reduction, which significantly impacted their investment strategies and fleet development. Overall, 2022 was characterized by a complex interaction of strong demand for specific vessel types, cautious investment in others, and an enhanced awareness of environmental issues, all of which shaped the future direction of the global shipping orderbook.

In year 2023 there was a notable increase in the Bulkers orderbook, reflecting a strong demand for new tonnage amid an aging fleet. This upward trend in newbuild orders is attributed to favorable market conditions and a growing recognition of the necessity for more efficient and environmentally compliant ships. The Container ship newbuild orders declined in comparison to the previous year, this shift occurred as the market began to stabilize. This decline reflects a more cautious approach by shipowners amid fluctuating demand and concerns about overcapacity in the market. Overall, while the orderbook remains substantial, the trend indicates a more measured pace in new orders for container vessels as the industry adjusts to changing economic conditions.

In 2023, there was a substantial growth in newbuild orders for both Chemical Tankers and Product Tankers. According to BIMCO, the contracting of product tankers surged dramatically, with a 337% year-over-year increase in orders during the first half of the year. This spike was driven by heightened demand resulting from geopolitical factors, including the EU's ban on Russian oil products, which has led to longer shipping distances and increased freight rates. This rise in orders reflects a broader trend of fleet renewal as older vessels are phased out in favor of more efficient and environmentally compliant designs. The increase in newbuild orders for chemical tankers also aligns with these market dynamics, as operators seek to modernize their fleets to meet evolving regulatory standards and market demands. A positive trend was noticed in the number of newbuild orders for LPG carriers with 122 orders compared to 58 the previous year. On the other hand, there was a significant decrease in the number of new orders for LNG carriers compared to the previous year. The results indicate that 68 LNG carriers were ordered, a sharp decline from over 170 orders recorded in 2022. This reduction is mainly due to the limited availability of shipyard capacity, which has resulted from the record number of orders placed in 2022, creating a backlog in production. Consequently, shipowners are adopting a more cautious strategy, prioritizing the optimization of their existing fleets over significant expansion in new orders, as they navigate the evolving market landscape. Regarding PCCs, there was a continued increase in newbuild orders, reflecting strong demand in the market. The growth in orders is largely attributed to rising car exports, particularly from China, and the need for shipowners to replace aging fleets, highlighting a robust outlook for the pure car carrier segment in the shipping industry.

In year 2024, in the year to date (October 2024) analysis, there has been a noticeable decrease in the Bulkers sector, which could be justified by rising investment costs and market uncertainties. The Containership orderbook remains in below the record levels of year 2021. The orders for LNG carriers has been firm with 82 records, while the LPG

Tankers are on record levers with 132 newbuild orders. Meanwhile, in general for Tankers the trend is strong and steady. Additionally, in 2024, there has been a remarkable growth in orders for cruise ships, driven by a resurgence in demand and the expansion of cruise lines. According to the results, there are 60 new cruise ships expected to enter service by 2033, with significant orders from major cruise brands contributing to this growth. This trend reflects a broader recovery in the cruise industry as it adapts to post-pandemic conditions and seeks to enhance capacity to meet rising passenger demand. Overall, the past five years have been characterized by a rebound in cruise ship orders, signaling a positive outlook for the industry as it adapts to changing market conditions and consumer preferences.

Throughout these years, the shipping industry has navigated many challenges and changes resulting in a diverse and evolving orderbook landscape. The newbuild vessel orderbook has been shaped by several key trends, disruptions, regulatory changes, and market dynamics. A significant trend has been the increasing focus on sustainability and environmental regulations, which have prompted shipowners to invest in more energy-efficient and compliant vessels. The International Maritime Organization's (IMO) regulations, such as the IMO 2020 Sulphur Cap and the EEDI, and CII indexes, have driven demand for greener technologies in shipbuilding. Disruptions from the COVID-19 pandemic and geopolitical tensions, particularly the Russia-Ukraine conflict, have also impacted supply chains and shipping demand, leading to fluctuations in order volumes. Additionally, the rise in freight rates during the pandemic created a temporary surge in orders for certain vessel types, particularly container ships and LNG carriers, while other segments, like bulkers and tankers, faced more cautious investment.

5.3.2. Alternative Fuels Uptake

The field of "Alternative Fuel Type" has been divided into 9 categories (Conventional Fuels, LNG, LPG, Methanol, Hydrogen, Ammonia, Ethane, Biofuels and Battery Propulsion). The orderbook was examined per each year and per fleet type. The dataset has been filtered according to the field "Alternative Fuel Type" thus, it does not contain records of the vessels which are characterized as "Alternative Fuel Type Ready". Battery Propulsion is considered as a "Fuel Type" in order to highlight the proportion of vessels running entirely on electrical power. The record items where the type of fuel of the main engines was unknown (empty) were removed from the analysis (1700 item lines).

Fuel Type	Number of Orders	Proportion	Gross Tonnage (Millions)	Proportion
Conventional Fuels	7246	76,58%	265,436	59%
Ammonia	29	0,31%	1,541	0%
Battery Propulsion	74	0,78%	0,121	0%
Biofuel	26	0,27%	0,436	0%
Ethane	82	0,87%	4,464	1%
Hydrogen	18	0,19%	0,713	0%
LNG	1463	15,46%	140,726	31%
LPG	240	2,54%	10,333	2%
Methanol	284	3,00%	26,050	6%
Total	9462	100%	449,821	100%

Table 9: Number of order and Proportion of Gross Tonnage per Fuel Type

According to the findings, LNG is still the most attractive alternative fuel as a number of newbuild orders (15,46%), followed by Methanol, where methanol-fueled vessel orders have increased significantly since 2022, consisting of 3% of the total orderbook in the examined period. The alternative fuels have progressed in development, with methanol prevailing as an option.

The following chart visualizes the alternative fuels uptake as a proportion of gross tonnage. It is important to highlight that in 2023, the share of methanol-capable contracts nearly matched that of LNG-capable orderbook. However, in 2024, the trend has shifted back in favor of LNG.

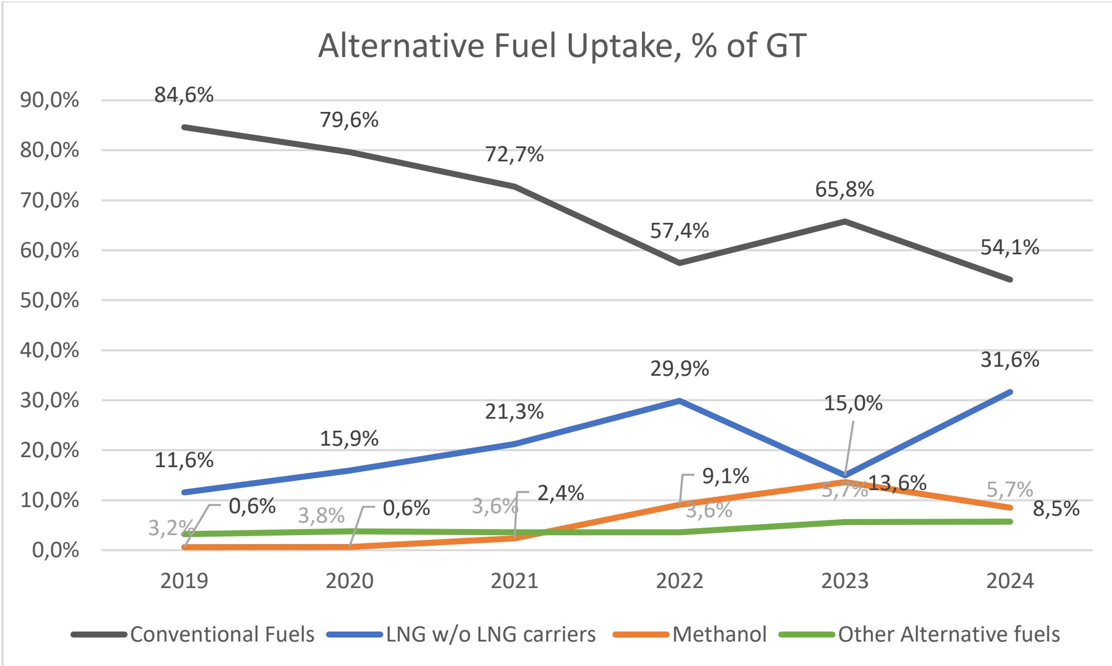


Chart 2: Alternative Fuel Uptake as a percentage of Gross Tonnage

In year 2024, alternative fueled vessels have reached a 45% of the ordered tonnage (excluding the LNG Carriers.)

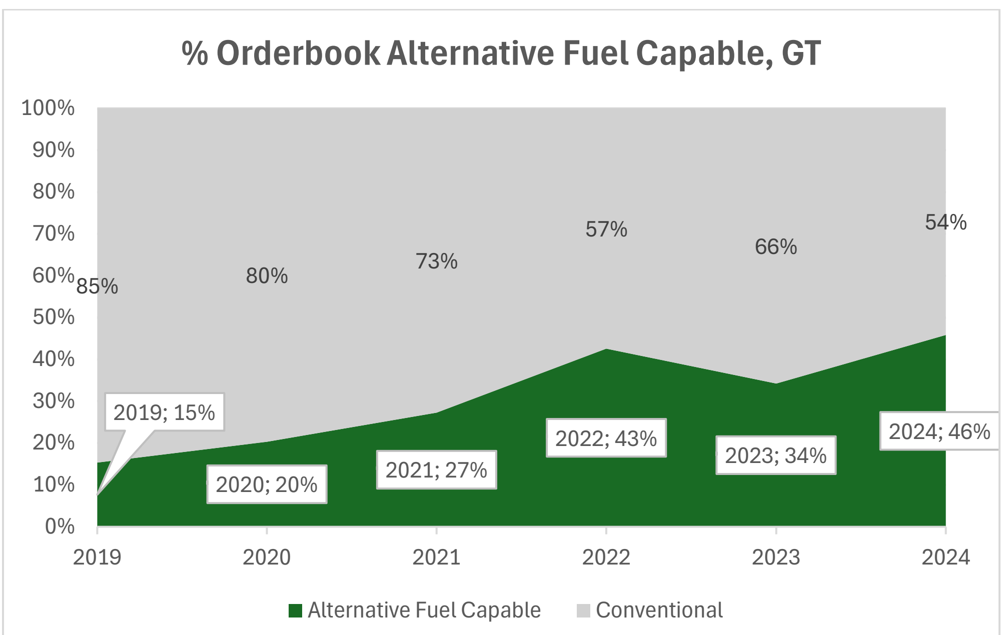


Chart 3: Percentage of Orderbook Alternative Fuel Capable in Gross Tonnage

The following chart visualizes the proportion of Alternative Fuel Capable Vessels and the LNG Carriers in millions of gross tonnages and the trends over the years. The year 2022 has reached a peak 57% of alternative fuel capability in proportion of ordered GT.

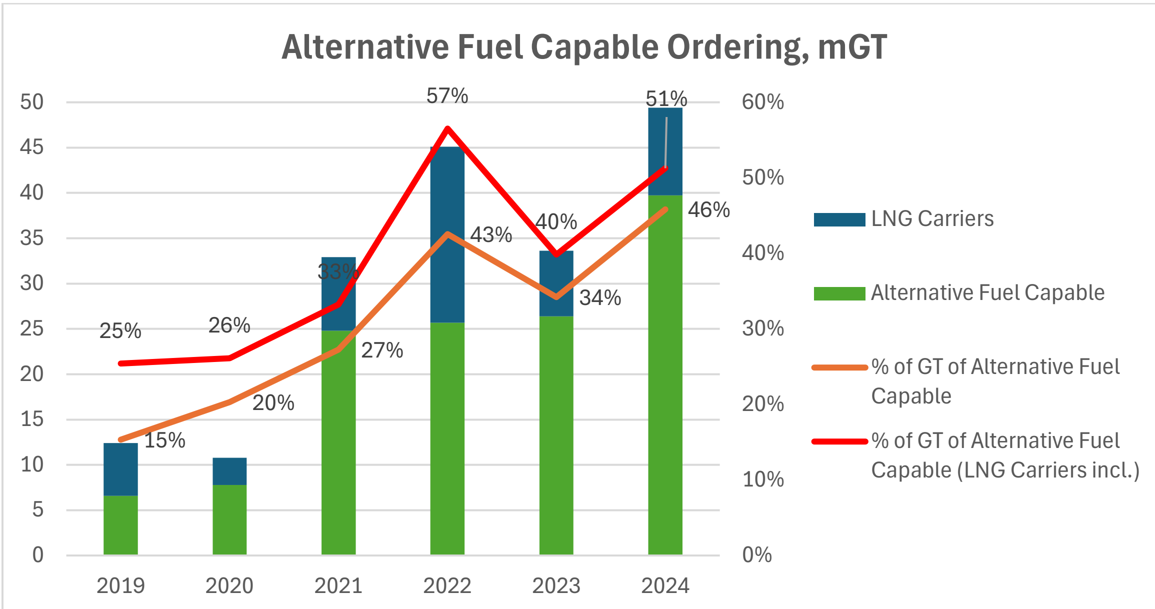


Chart 4: Alternative Fuel Capable Ordering, mGT

Continuing with the analysis, the data set was filtered with only the "On-Order" records, considering all the vessel which are yet to be delivered. It is apparent LNG most popular fuel type but methanol now gaining share in the current orderbook.

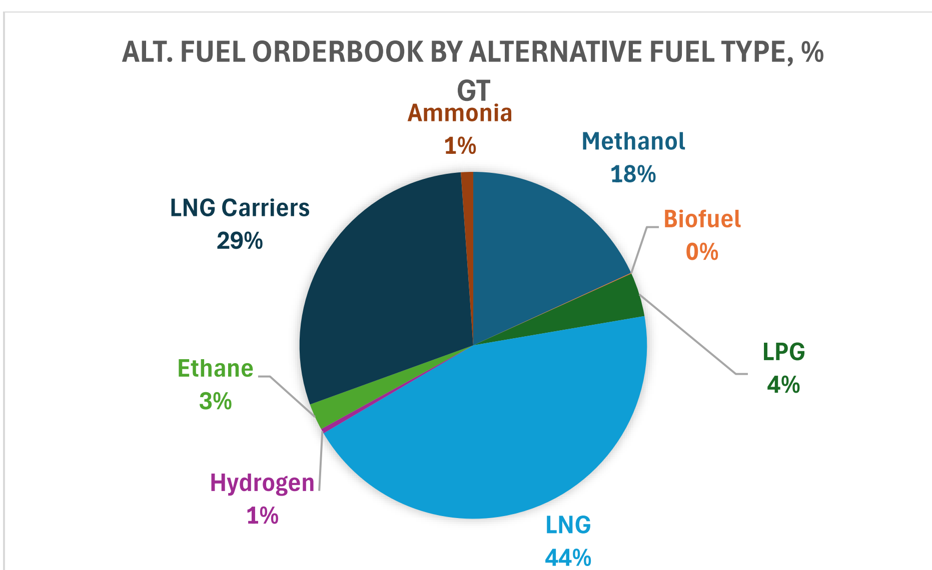


Chart 5: Alternative Fueled Orderbook by Alternative Fuel type, % of GT

Liquified Natural Gas

It is evident that LNG is the most popular alternative fuel option in the recent years. LNG reduces greenhouse gas emissions and air pollutants compared to conventional fuels and is considered as a viable alternative for shipping companies that are aiming to meet the IMO targets. The following graph demonstrates that LNG has been widely adopted by Containerships and Pure Car Carriers, followed with smaller growth by other fleet groups (excluding LNG Carriers).

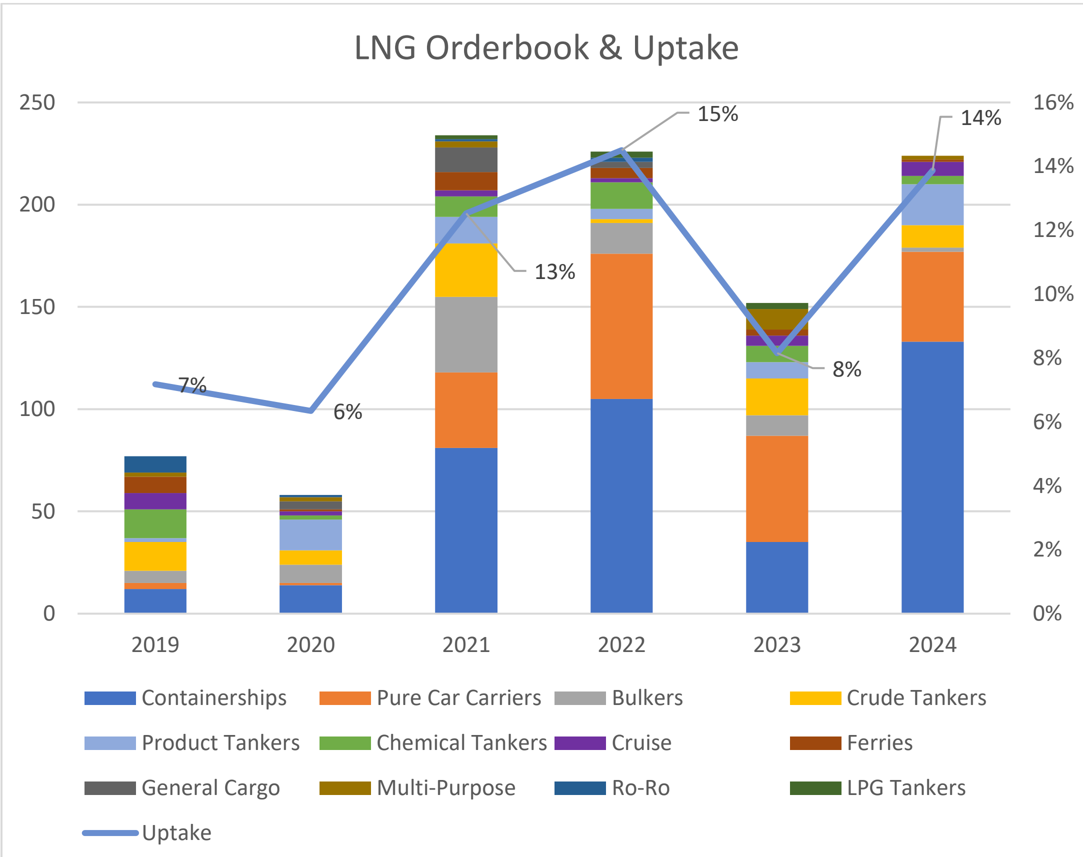


Chart 6: LNG Orderbook & Uptake

Prior 2019, LNG adoption was a regional phenomenon, especially in the US and it has expanded globally, with various companies diversifying their fleets to include LNG alongside other solutions. Especially after 2017, more containership companies started to order LNG fueled container vessels in order to meet the IMO low sulfur regulations. A common practice in the industry was to maintain a diverse fleet that incorporates various solutions, which limited the proportion of LNG-powered vessels. Many major container shipping lines had adopted a wait-and-see approach, remaining receptive to a range of emission-reducing strategies. For instance, Maersk has been exploring alternative fuels such as ammonia and methanol, while ONE (formed from the merger of Japanese K-Line, MOL, and NYK) and Evergreen have been also considering similar options. Meanwhile, MSC has opted for scrubbers, and companies like COSCO continued to rely on low-sulfur fuel oil (LSFO) as their primary strategy (Casey, 2023).

The uptake LNG as a fuel in the Pure Car Carrier (PCC) sector has been gaining momentum, driven by environmental regulations and the industry's commitment to sustainability. Major players like NYK have recently launched LNG-fueled pure car and truck carriers, with plans to incorporate a total of 20 such vessels by 2028 as part of their strategy to reduce greenhouse gas emissions and transition to greener operations. Similarly, United European Car Carriers (UECC) has embraced bio-LNG, facilitating its use in their fleet to significantly cut emissions and enhance sustainability in logistics. Notably, a report indicates that approximately 93% of new car carrier orders are now LNG-capable, reflecting a strong industry shift towards this cleaner fuel option. This trend not only aligns with regulatory compliance but also positions LNG as a viable interim solution in the maritime industry's broader decarbonization efforts (Mandra, 2022).

Despite facing criticism regarding emissions and sustainability, LNG remains a favored choice for shipping companies seeking compliance with environmental regulations and aiming to enhance their operational efficiency and reputation.

Methanol

In the recent years, Methanol has emerged as an alternative marine fuel, reflecting the shipping industry's efforts towards decarbonization. It is evident that methanol has been gaining traction. As of 2023, approximately over one hundred ten (110) new methanol dual-fuel vessels were ordered, following a notable increase from years 2022 and 2021. The following chart shows that Methanol uptake reached about 6% compared to the total new build orders, indicating a steady increase.

Methanol has been adopted by different fleet groups within the shipping industry, with the Containership industry leading the way. Containerships are at the forefront of the transition towards methanol, with a significant number of orders. This growth will also drive the development of the required bunkering infrastructure across the world which will enable other fleet groups to follow this transition. It is noteworthy that methanol uptake is considerably growing by Bulkers and Pure Car Carriers.

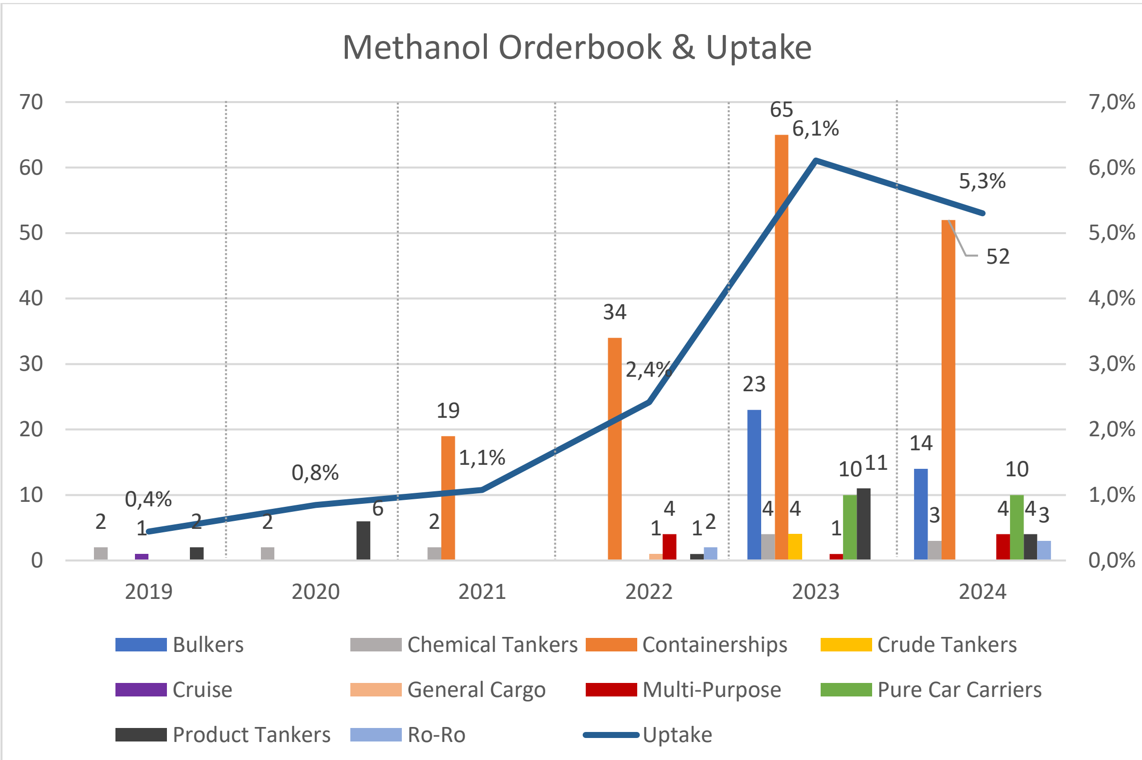


Chart 7: Methanol Orderbook & Uptake

Methanol as an alternative marine fuel has been supported from IMO, who has introduced guidelines that facilitate its deployment and encouraged shipowners to invest in methanol-fueled vessels. Major shipping companies (Maersk, CMA CGM, ONE, COSCO and Evergreen) have been leading the way by ordering methanol dual-fuel vessels and demonstrating the fuels viability. From a technology perspective, the development of efficient engine and bunkering systems is progressing, improving the fuel's attractiveness as alternative.

LNG and Methanol

It is important to mention that if we exclude the LNG Carriers from the analysis, LNG is still the most attractive alternative fuel, followed by Methanol and the rest alternatives. The following chart illustrates LNG and Methanol uptake as number of orders compared to the total orderbook excluding the LNG Carriers. The conventional fuels are still the main option, whereas there has been a noticeable fluctuation in LNG-fueled vessels and a steady flow in Methanol-fueled vessel orders.

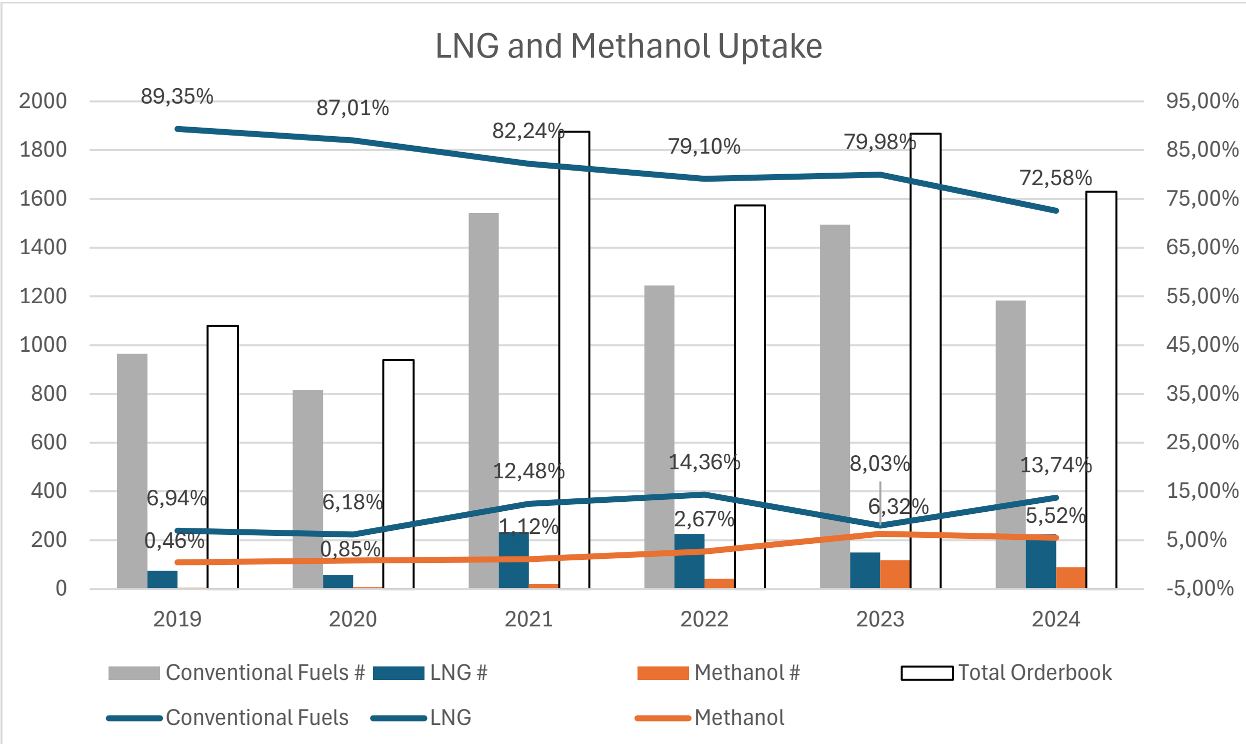


Chart 8: LNG and Methanol Uptake (excluding LNG Carriers)

Hydrogen

It is important to mention that the vessels using Hydrogen as primary or alternative fuel are equipped with Fuel Cell technology, given that internal combustion engines with hydrogen capability are not yet commercially available for the shipping industry. Fuel Cell technology is particularly prevalent in the cruise sector, where 66% of the new ordered vessels with Power Type recorded with Fuel Cells are Cruise ships.

Fuel cell technology is emerging as a transformative solution for maritime applications, particularly in the quest for zero-emission vessels. Fuel Cells operate by converting the chemical energy of hydrogen into electrical energy through an electrochemical process, producing only water vapor and heat as byproducts. This technology is particularly advantageous for ships, as it allows for longer operational ranges and faster refueling compared to traditional battery systems. The modular design of fuel cells enables easy integration into existing marine architectures, providing reliable power for both propulsion and auxiliary systems.

There are different types of Fuel Cells being explored for their potential to provide clean and efficient power. The most prominent types include (Hui, et al., 2021) (Spectra Fuels, 2024) (Ballard, 2021):

1. Proton Exchange Membrane Fuel Cells (PEMFCs): These are widely regarded for their high efficiency and quick start-up times, making them suitable for various marine applications, including auxiliary power and hybrid propulsion systems. PEMFCs operate at relatively low temperatures and are known for their compact size and lightweight design.
2. Solid Oxide Fuel Cells (SOFCs): are characterized by their high efficiency and ability to utilize a variety of fuels, including hydrogen and natural gas. They operate at high temperatures, which allows for greater efficiency in converting fuel to electricity. This type of fuel cell is particularly promising for larger vessels requiring substantial power output.
3. Direct Methanol Fuel Cells (DMFCs): use methanol directly as fuel, simplifying the fuel supply chain. They are less common in marine applications but offer advantages in terms of fuel storage and handling, making them a potential option for specific vessel types.
4. Molten Carbonate Fuel Cells (MCFCs): These cells operate at high temperatures and can utilize a range of fuels, including hydrogen and natural gas. MCFCs are noted for their high efficiency and are being researched for larger marine applications, particularly in scenarios where waste heat recovery is beneficial.

The adoption of Fuel Cell technology in the shipping industry encounters several critical challenges that impede its widespread implementation. One of the foremost issues is the insufficient hydrogen fueling infrastructure at ports, which is vital for supporting fuel cell operations. Additionally, the high costs associated with hydrogen production, especially green hydrogen sourced from renewable energy, create economic hurdles that deter shipping companies from making the switch. Furthermore, while advancements in fuel cell technology have been made, further improvements are necessary to enhance efficiency, reduce costs, and increase durability, particularly given the sensitivity of these systems to varying environmental conditions. Space limitations on vessels also pose a challenge, as many ships, particularly smaller ones, lack the capacity to accommodate fuel cell systems and hydrogen storage. Lastly, the regulatory framework surrounding hydrogen use in maritime applications is still developing, leading to uncertainties that can slow down the adoption process. Overcoming these diverse challenges will require collaborative efforts among various stakeholders, including shipbuilders, fuel suppliers, and regulatory authorities, to pave the way for the successful integration of fuel cells in the maritime sector. (Melnyk, et al., 2023)

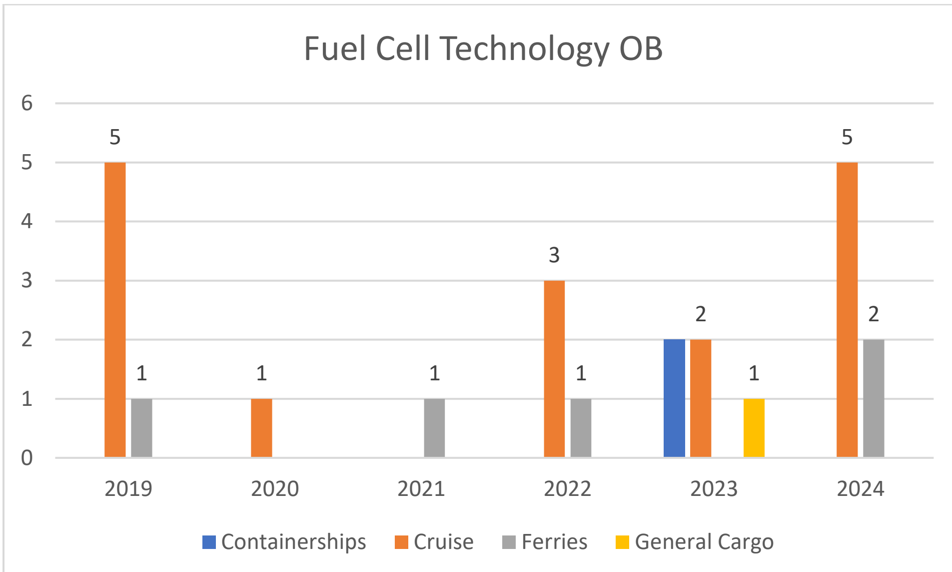


Chart 9: Fuel Cell Technology Orderbook

The chart visualizes the vessel orderbook equipped with Fuel Cell technologies from 2019 to 2024. These vessels are powered by a combination of fuel cell systems and traditional diesel engines, while some of them are also equipped with battery systems. The Fuel Cell systems from this data set are recorded either to be using Hydrogen or LNG.

Ammonia

The adoption of ammonia as a marine fuel is progressing slowly, with a noticeable trend emerging among Bulkers and LPG Tankers. Currently, these vessels are still under construction, which means that there have been no practical applications of ammonia fuel tests in real-world scenarios. The ships being developed are mostly equipped with two-stroke dual-fuel technology engines, allowing them to operate on both ammonia and conventional fuels. This dual-fuel capability is crucial for facilitating the transition to ammonia as a viable marine fuel, as it provides flexibility during the early stages of adoption. As these vessels enter service, they will play a pivotal role in assessing the performance and feasibility of ammonia propulsion in maritime operations.

Innovative dual-fuel engine technology has been developed for ammonia propulsion. This technology enables vessels to operate on either ammonia or conventional diesel fuel, offering flexibility during the transition to more sustainable marine fuels. These engines feature a two-stroke design and utilize high-pressure injection systems, which are consistent with the operational principles existing diesel engines. The design ensures that performance remains comparable in both ammonia and diesel modes while adhering to stringent NOx emissions regulations through the integration of Selective Catalytic Reduction (SCR) systems (WinGD, 2023).

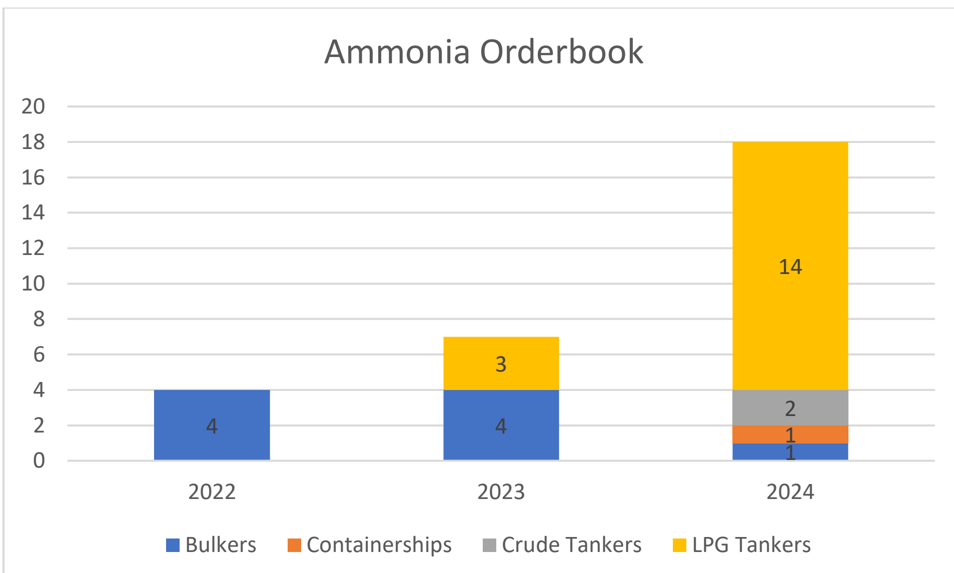


Chart 10: Ammonia-fueled vessels Orderbook

Ammonia-fueled LPG Tankers are gaining attention as the maritime industry explores sustainable fuel alternatives. Notably, Exmar LPG has placed orders for four new vessels designed to operate on ammonia, marking a significant step in this direction (S&P Global, 2023).

Liquified Petroleum Gas (LPG) and Ethane

Liquefied Petroleum Gas (LPG) and ethane are gaining traction as alternative marine fuels, particularly utilized from LPG Tankers. According to the results of this analysis Ethane and LPG represent about 1 and 2% of the alternative fuel uptake, respectively along the years 2019 to 2024. While both fuels are recognized as alternatives, their current adoption levels are relatively low compared to other alternative fuels and adopted only from the vessels that are carrying these fuels. It highlights the challenges these fuels face in gaining wider acceptance and usage within other industries.

LPG, primarily composed of propane and butane, offers significant environmental benefits, including reduced sulfur oxides (SOx) and particulate matter emissions compared to traditional marine fuels. Its combustion results in lower carbon dioxide emissions, making it an attractive option for shipping companies aiming to comply with stringent regulations like IMO 2020. (The Nautical Institute, 2021)

Ethane, which can also be derived from LPG, presents additional versatility as a fuel source. The ability to use a mixture of LPG and ethane allows for greater flexibility in fuel management, particularly for gas carriers equipped with engines capable of burning multiple gas types. This adaptability not only enhances operational efficiency but also supports the industry's transition towards more sustainable practices.

The infrastructure for LPG bunkering is already well-established, with numerous terminals worldwide, facilitating the adoption of LPG and ethane as marine fuels. As the shipping industry continues to seek immediate and practical solutions for reducing emissions, LPG and ethane stand out as promising alternatives that can help meet both regulatory requirements and environmental goals.

Ethane is emerging as a promising alternative marine fuel, particularly for vessels that transport liquefied ethane gas (LEG). It can be used in dual-fuel engines, which are capable of running on both ethane and traditional marine fuels, providing flexibility to switch between fuels based on availability and cost. Ethane combustion produces fewer (SOx) and nitrogen oxides (NOx) compared to conventional fuels, resulting in lower emissions and aiding in meeting stringent environmental regulations. Additionally, ethane has a higher energy density compared to methane, the primary component of LNG, making it an efficient fuel option for long voyages. Technological advancements have also played a significant role, where engine manufacturers are developing engines optimized for ethane use, ensuring efficient and safe operation. Furthermore, ethane-powered vessels can utilize boil-off gas from their cargo as fuel, reducing the need for separate bunkering operations and enhancing operational efficiency. Ethane is purely utilized as an alternative fuel on LPG carriers. LPG carriers are designed to transport various liquefied gases, including ethane, making it convenient to use the cargo itself as fuel. This reduces the need for separate bunkering operations and enhances operational efficiency. Secondly, ethane has a higher energy density compared to methane, which means it can provide more energy per unit volume, making a more efficient fuel option for long voyages. Additionally, the economic viability of ethane is boosted by its favorable pricing, particularly due to the increase in shale gas production in the United States.

Biofuels

Biofuels could be a viable alternative marine fuel, offering a sustainable option for the shipping industry. According to this analysis, biofuels as alternative fuel is representing less than 1% as a number of newbuild orders.

Derived from renewable sources such as plant oils, algae, and waste materials, biofuels can significantly reduce greenhouse gas emissions compared to traditional fossil fuels. They are categorized into three generations (European Maritime Safety Agency , 2023):

1. First-generation biofuels, produced from food crops, raise concerns regarding food security and land use.
2. Second-generation biofuels utilize non-food biomass, such as agricultural residues and forestry waste, thereby minimizing competition with food production.
3. Third-generation biofuels are derived from algae and microbes, which have high yields and do not compete for arable land.

Unlike conventional diesel fuels, biodiesel does not contain sulfur and has a higher oxygen content, which facilitates complete combustion and reduces total emissions of carbon monoxide, particulate matter, smoke, and hydrocarbons during combustion. In addition to these benefits, biodiesel has a higher flashpoint, is biodegradable, non-toxic, and inherent lubricity, making it a direct substitute for marine fuel. Moreover, biodiesel is compatible with most existing diesel-based engine systems, requiring little or no modification (Wang Y, 2021).

Biofuels can be blended with conventional marine fuels, facilitating a smoother transition to greener alternatives without necessitating significant modifications to existing vessels. This adaptability positions them as a practical choice for ship operators aiming to comply with increasingly stringent emissions regulations. However, challenges persist, including the need for sustainable production pathways and ensuring adequate supply to meet maritime demand (Kesieme, et al., 2019). Overall, biofuels represent a promising transitional solution in the maritime sector’s efforts to decarbonize and enhance environmental sustainability.

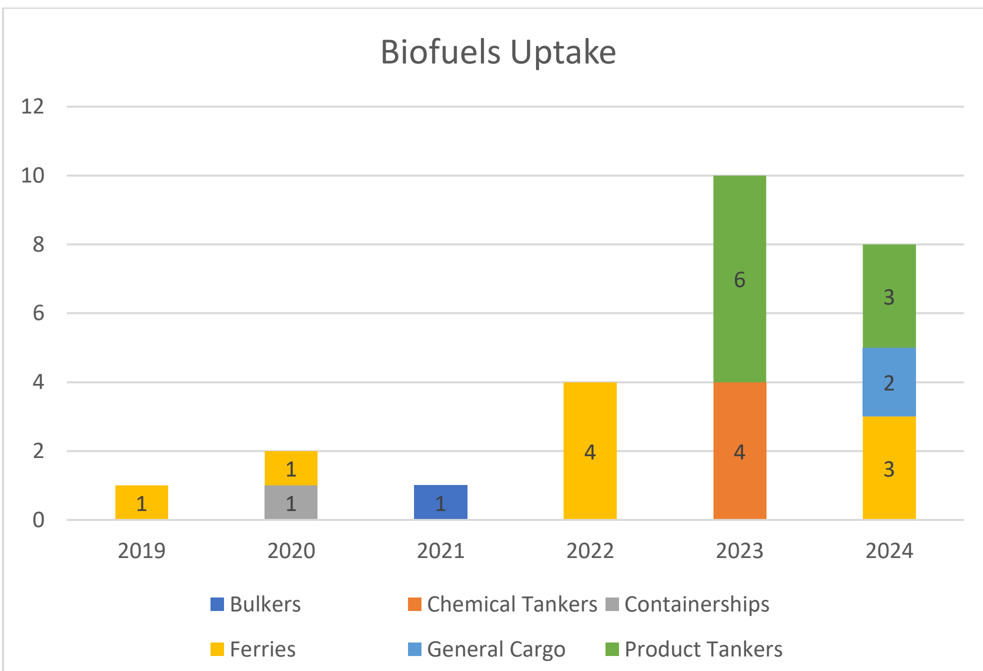


Chart 11: Biofuels Uptake in Newbuild Orderbook

Taking a closer look over the yearly orderbook, there are very few newbuild orders recorded with Biofuels as fuel option, from which 90% are ranging between 4.500 – 7.000 gross tonnage. However, a conclusion on the uptake of biofuels should not be taken into consideration only by the above results. The technology readiness for the deployment of biofuels is more progressed than any other alternative fuel. FAME and HVO are performing in the same way with the conventional fuels, and they are compatible with existing engine technology and vessel infrastructure. Biofuels are supported already by major OEMs, which have provided fuel specifications for their engines (Lloyd's Register , 2024). The main challenges that prohibit a wider uptake of biofuels in shipping are availability of the fuel and the scalability of their production. Shipping industry requires significant fuel quantities if conventional fuels are to be replaced. Currently, feedstock availability is limited, and the pricing of biofuels is very sensitive to the availability and demand of other fuels.

Furthermore, it is important to take into consideration the lifecycle analysis of biofuels in order to highlight their GHG reduction potential. The IMO has adopted guidelines for biofuels at MEPC 81, which contain initial default emission factors for FAME and HVO.

Fuel Type	**Fuel Pathway**	**WtT GHG intensity (gCO_2eq/ MJ)**	**LCV (MJ/g)**
Diesel (FAME)	Transesterification from second-generation feedstocks using grid mix electricity	20.8	0.0372
Renewable Diesel (HVO)	Hydrogenation of first-generation feedstocks using grid mix electricity	14.9	0.044

Table 10: IMO initial default emission factors by fuel

Battery Propulsion

Battery-propelled ships are part of a growing trend towards zero-emission maritime transportation mostly in cruise and ferries industries. These vessels use large battery systems, often lithium-ion, to store and provide electrical energy for propulsion and onboard systems. These vessels rely entirely on battery power, eliminating the need for internal combustion engines and significantly reducing greenhouse gas emissions.

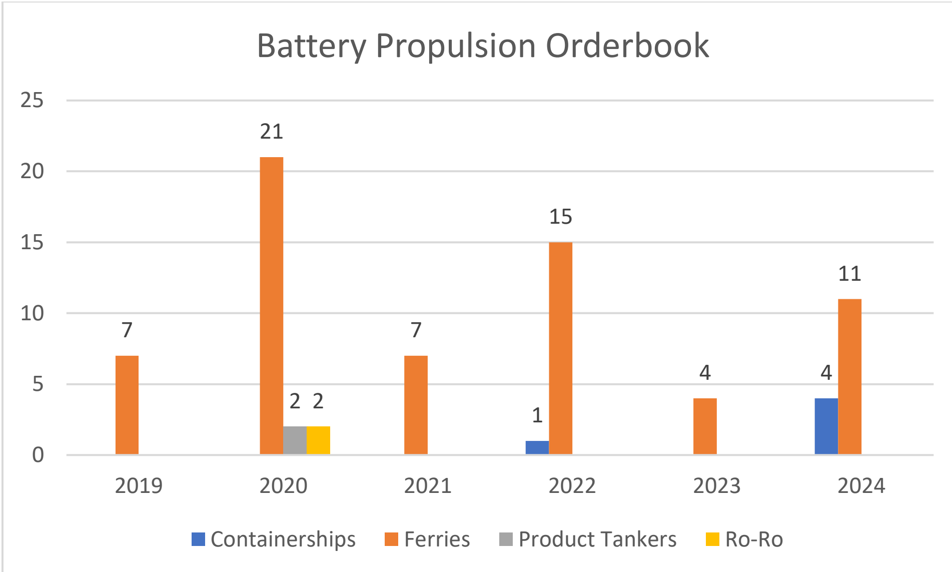


Chart 12: Battery-propelled vessels orderbook

It is apparent that battery propelled vessels are generally less attractive options, however they are more viable for short-sea shipping, particularly for coastal ferries.

When considering hybrid systems, there is a notable shift towards diversification of the power systems on board. The data set was filtered according to if the vessel is fitted with batteries, with options: Pure Battery or Hybrid Battery (the auxiliary battery systems have been excluded). The new-build vessels orders which are recorded as battery-fitted have different Power Types. These are:

Power Type
Batteries & Diesel
Fuel Cell & Battery
Batteries, Diesel & Fuel Cell
Combined
Battery Propulsion

Table 11: Battery-fitted vessels Power Type

The following chart shows that hybrid systems are becoming more popular, with Ferries being in the forefront, followed by Pure Car Carriers.

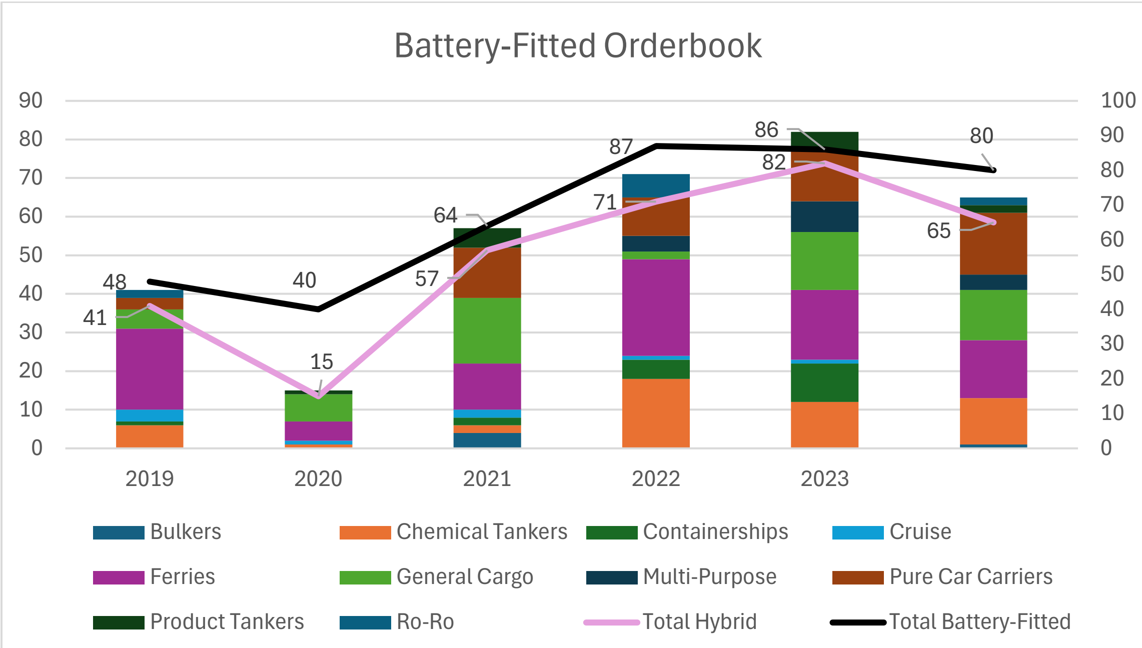


Chart 13: Battery-Fitted Newbuild Orderbook

5.3.3. Vessel Type Analysis

Conventional Fuels are still the main choice of fuel for all vessel types, except LNG Carriers. Bulkers and General Cargo vessels reach over 95% of the orders are with conventional fuels, as shipowners are not willing to invest in alternative fuel technologies. On the other hand, Containerships have the highest share of Methanol fuel orders (10%) and a significant proportion of LNG as fuel (22,5%). Containership market is characterized by stable returns on investment and fixed routes, which accommodate the adaption of alternative fuels. Chemical, Product and Crude Tankers are continuing to be fueled with conventional fuels, where about 17% of Crude Tankers are equipped with dual fuel technology and can run on LNG. There is a small proportion of tanker vessels which are LNG Capable and LNG Ready. In the Cruise sector, there is a shift towards LNG fuel. Cruise vessels is under pressure to minimize its environmental impact, in particular because they often operate in environmentally sensitive areas. The growing infrastructure for LNG bunkering and availability has enabled the adoption by the cruise industry. LPG Carriers are mainly powered by LPG, followed by Conventional fuels and Ethane. Additionally, it is noticeable that there is a trend towards LNG fuel by the Pure Car Carriers sector. This sector has recovered by post-covid car trade increase which has uplifted the pure car carrier's capacity demand and charter rates. There has been a significant increase in the newbuild orders for car carriers and a substantial portion which are LNG Capable (77,6%) and Methanol capable (7,5%) in addition with the vessels which are Ammonia and Methanol Ready. Similarly, there is a clear transition towards LNG (23,1%) and Methanol (9,6%) for Ro-Ro / Passenger vessels.

Fleet Type	Conventional Fuels	Ammonia	Biofuel	Ethane	Hydrogen	LNG	LPG	Methanol	Battery Propulsion	Total Orders
Bulkers	95,7%	0,3%	0,0%	0,0%	0,0%	2,7%	0,0%	1,3%	0,0%	2905
Chemical Tankers	89,6%	0,0%	0,6%	0,0%	0,0%	7,8%	0,0%	2,0%	0,0%	656
Containerships	67,0%	0,1%	0,1%	0,0%	0,1%	22,5%	0,0%	10,0%	0,3%	1692
Crude Tankers	81,5%	0,4%	0,0%	0,0%	0,0%	17,2%	0,0%	0,9%	0,0%	454
Cruise	42,2%	0,0%	0,0%	0,0%	20,3%	35,9%	0,0%	1,6%	0,0%	64
Ferries	65,7%	0,0%	3,0%	0,0%	0,7%	9,0%	0,0%	0,0%	21,7%	300
General Cargo	96,7%	0,0%	0,3%	0,0%	0,1%	2,7%	0,0%	0,1%	0,0%	706
LNG Carriers	0,0%	0,0%	0,0%	0,0%	0,0%	100,0%	0,0%	0,0%	0,0%	496
LPG Tankers	33,8%	3,2%	0,0%	15,6%	0,0%	1,5%	45,8%	0,0%	0,0%	524
Multi-Purpose	89,1%	0,0%	0,0%	0,0%	0,0%	7,4%	0,0%	3,5%	0,0%	256
Pure Car Carriers	14,9%	0,0%	0,0%	0,0%	0,0%	77,6%	0,0%	7,5%	0,0%	268
Product Tankers	91,0%	0,0%	0,8%	0,0%	0,0%	5,8%	0,0%	2,2%	0,2%	1089
Ro-Ro	63,5%	0,0%	0,0%	0,0%	0,0%	23,1%	0,0%	9,6%	3,8%	52

Table 12: Proportion of Fuel Type per Fleet Group Orders

The following pie chart demonstrates the current orderbook with 1502 orders for alternative fuel capable vessels as a percentage of gross tonnage. Container ship industry is leading the way on the transition, followed by the LPG industry and the Pure Car Carrier sector.

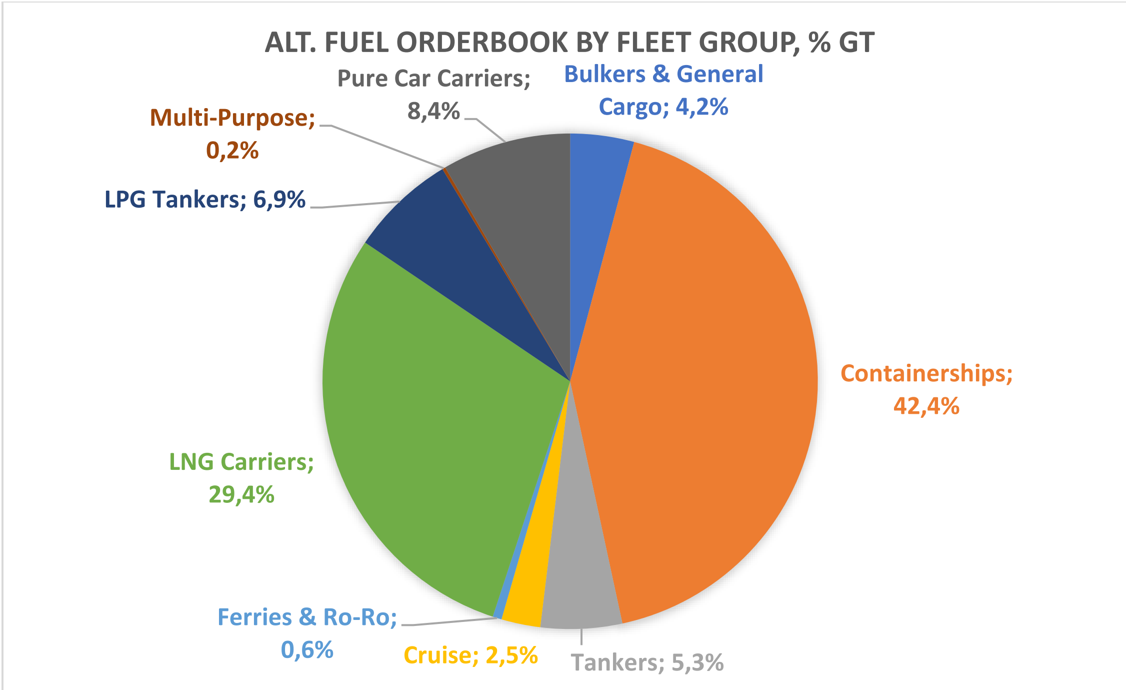


Chart 14: Alternative Fuel Orderbook by Fleet Group, % GT

Further for this analysis, there was a deep dive on each year's orderbook. The dataset was examined according to the Alternative Fuel Type orders per Fleet Group. The entries which were empty in the "Alternative Fuel Type have been considered as "Conventional Fuels", while taking into consideration the entries with Power Type: "Battery Propulsion". In the selected dataset there have been 1700 entries without any record in the field either on "Alternative Fuel Type or "Main Engine Fuel Type", which have been removed from the below results.

5.3.4. Annual Order Trends by Fleet Group and Fuel Type

The purpose of this section is to provide a clear visual representation of the trends in vessel orders over time, highlighting the preferences for different fuel types across various fleet groups. By analyzing the graphs, the target is to identify how fuel type choices vary among different vessel categories.

Newbuild Orderbook Year 2019

In 2019, the marine industry saw a notable shift towards alternative fuels, driven by increasing environmental regulations and the need to reduce greenhouse gas emissions. According to data from the shipping orderbook, there was a significant rise in orders for vessels capable of using alternative fuels, while LNG has gained interest as an important "steppingstone" to the IMO carbon targets, there was also progress in the number newbuild orders with other alternatives such as Methanol (5), Ethane (8), LPG (14) Hydrogen (5) and Battery Propulsion (7). LNG, emerged as a popular choice with (11,8%) due to its relatively lower emissions compared to traditional marine fuels, indicating a growing interest in diversifying fuel options to meet future regulatory requirements. Methanol was preferred choice by Product Tankers and Chemical Tankers, while there was a shift towards LNG in almost all fleets. Hydrogen was optioned by Cruise and Ferries equipped with fuel cell systems. These trends were part of a broader movement within the maritime sector to explore and invest in sustainable fuel technologies, reflecting a commitment to achieving long-term environmental goals.

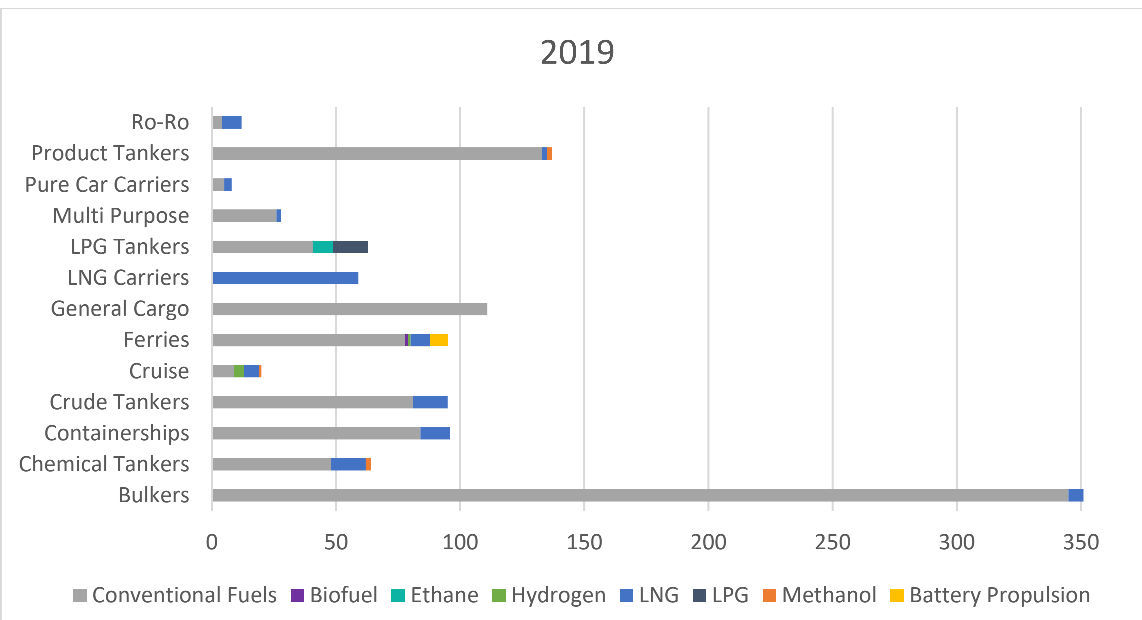


Chart 15: Orderbook by Fleet Type 2019

Newbuild Orderbook Year 2020

In 2020, the global vessel order book saw a dramatic decline, with orders plummeting by nearly 50% compared to the previous year, marking the lowest level in 17 years due to the economic fallout from the COVID-19 pandemic. While the pandemic's impact dominated the global economy and the shipping industry's agenda, several notable trends emerged in the energy transition. LNG remained the primary alternative fuel choice, consistent with previous years, followed by methanol and battery propulsion, particularly in smaller ferry vessels. LNG uptake accounted for 22% of the total ordered gross tonnage, with a significant number of newbuilds across various sectors, including Cruise ships (14), Product Tankers (15), Crude Tankers (7) and Bulkers (9). Methanol also followed the previous year's trend, with methanol-capable vessels primarily recorded in the tanker sector, including Chemical Tankers (2) and Product Tankers (6). Additionally, there were Ethane-capable (6) and LPG-capable (23) newbuilds in the LPG segment, reflecting a continuation of earlier trends. A significant development was the rise in battery propulsion, with (21) orders for Ferries, (2) for Product tankers, and (2) for Ro-Ro vessels. This shift highlights the industry's growing commitment to sustainable energy solutions, even amid challenging economic conditions.

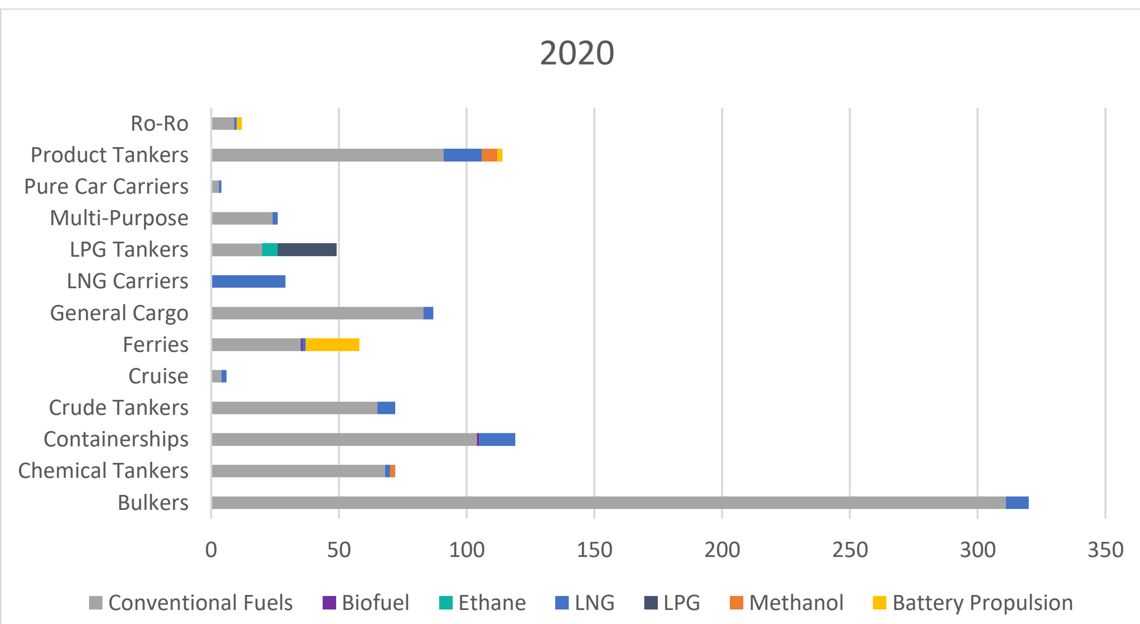


Chart 16: Orderbook by Fleet Type 2020

Newbuild Orderbook Year 2021

The uptake of alternative fuels continued to progress steadily accounting for about 33% of the newbuild orderbook tonnage. LNG remained the primary alternative fuel of choice, representing 21% of the tonnage when excluding the LNG Carriers. The uptake of LNG grew across various sectors with significant orders recorded for Containerships (81), Bulkers (37), Pure Car Carriers (37), Crude Tankers (26), Product Tankers (13) and General Cargo vessels (12). Methanol capable vessels constituted for 2,2% of the year's orderbook tonnage, with notable orders in Container sector (21) and Chemical Tankers (2), with notable orders from major shipping companies like Maersk, which ordered the world's first methanol-enabled container vessel.

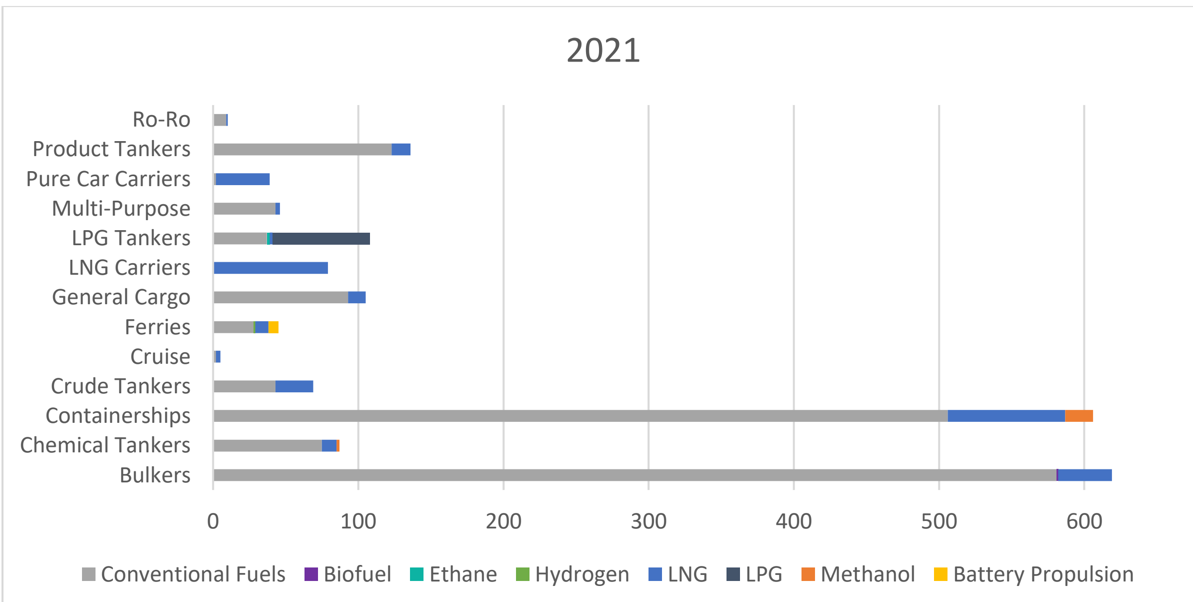


Chart 17: Orderbook by Fleet Type 2021

Newbuild Orderbook Year 2022

In 2022, 29% of newbuild orders were capable of using alternative fuels, with 21% when excluding LNG Carriers. Among these, LNG dual-fueled vessels (LNG carriers excluded) accounted for 14% of the total orders. The adoption of LNG was primarily seen in Containerships orderbook (105), followed closely by Pure Car Carriers (71), and other segments Bulkers (15) and Chemical Tankers (13). Notably, there were forty-two (42) Methanol-fueled vessels ordered, representing approximately 7% of the total orderbook gross tonnage, with the Containership sector driving this uptake with thirty-four (34) orders followed by Multipurpose (4) and Ro-Ro (2). Additionally, there was a significant shift towards Ethane among LPG tankers, which constituted about 1% of GT. The year also saw fifteen (15) orders for Ferries equipped with battery propulsion. According to Clarksons. battery and hybrid propulsion systems gained traction in smaller vessels, making up 1.1% of the total order book in 2022. This trend underscores a growing preference for battery propulsion in smaller ships, such as coastal vessels and ferries, due to their operational profiles and the suitability of battery technology for shorter, frequent routes. Despite these advancements, 70% of the newbuild fleet is still expected to operate on Conventional Fuels. As illustrated in the accompanying graph, the sectors with the slowest transition to alternative fuels include Bulkers, General Cargo, and Product Tankers. This highlights the ongoing challenges in shifting towards more sustainable fuel options across the industry.

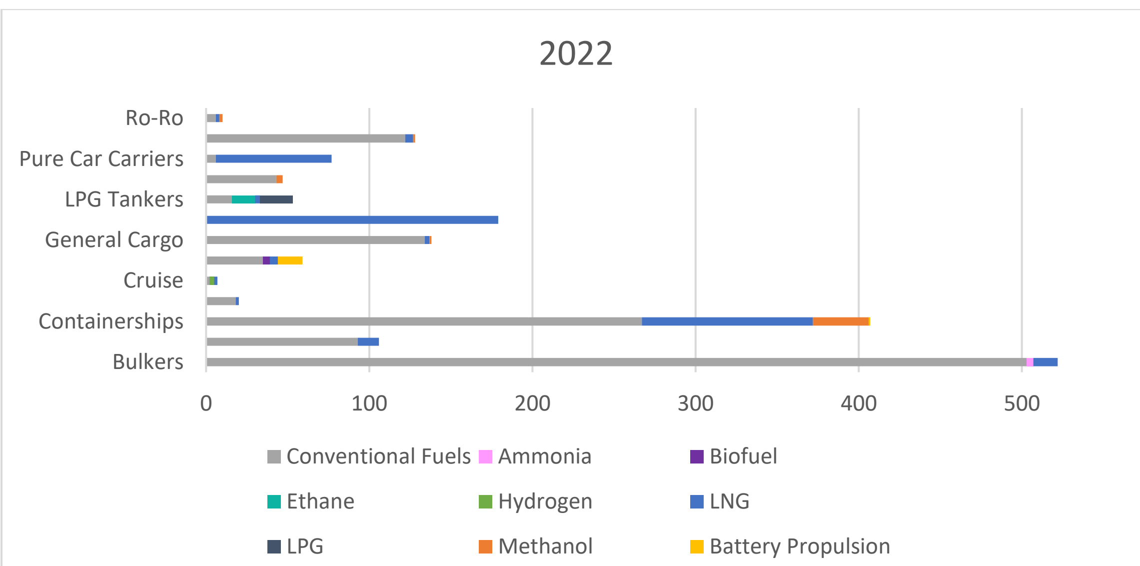


Chart 18: Orderbook by Fleet Type 2022

Newbuild Orderbook Year 2023

In 2023, the maritime industry experienced a steady influx of newbuild contracts, with 23% of vessels reported to have alternative fuel capabilities. While the adoption of alternative fuels remained moderate compared to the previous year, 77% of the total order book was still dominated by conventional fuels. Among the alternatives, Methanol emerged as the preferred option after LNG, accounting for 27% of alternative fuel-capable orders and representing 6% of total orders and 12% in GT. Containerships led the way in methanol adoption, with 65 newbuild orders. Additionally, there was a notable shift in the Bulk Carrier sector, where twenty-three (23) orders—representing 3.4% of Bulk Carrier orders—were recorded as methanol-fueled. Methanol orders also gained traction in other sectors, including Product Tankers (11), Pure Car Carriers (10), and Chemical Tankers (4). Approximately 150 vessels (or 8%) were LNG-capable, excluding LNG carriers. However, LNG adoption faced a downward trend, primarily due to a decrease in orders for LNG carriers and a more cautious approach from the industry. This reflects a steady commitment to LNG as a transitional fuel while other alternatives are still being developed. Notably, the most significant transition to LNG was observed among Pure Car Carriers, which represented over 60% of PCC orders. This shift underscores the industry's evolving landscape as it navigates the transition to more sustainable fuel options.

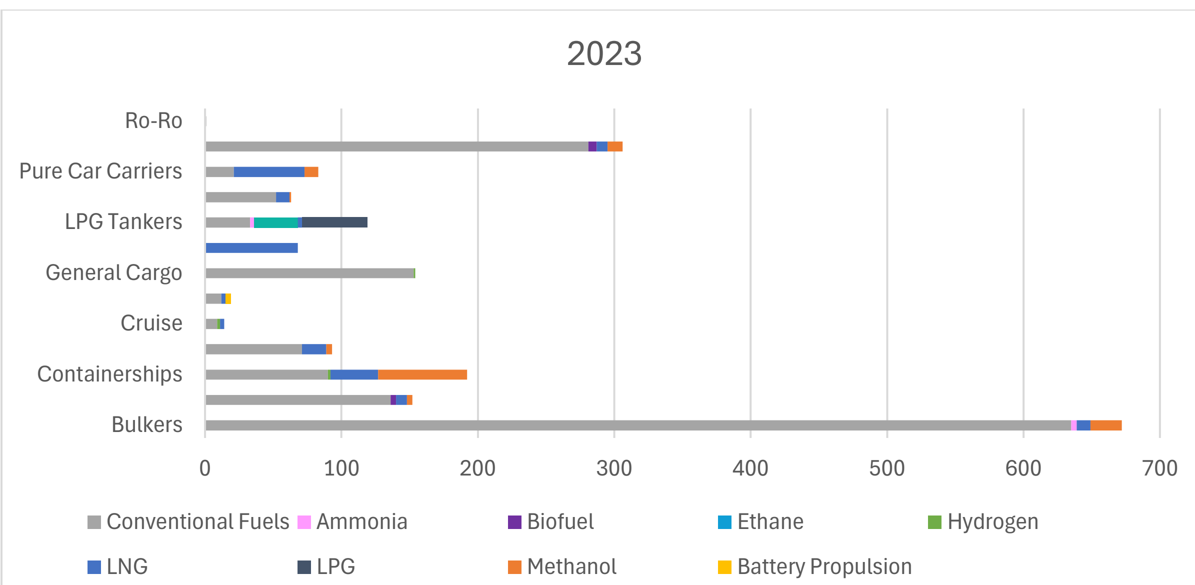


Chart 19: Orderbook by Fleet Type 2023

Newbuild Orderbook Year 2024

As of 2024, approximately 31% of the order book is capable of using alternative fuels, which corresponds to about 50% of the total contracted tonnage. This follows a record year in 2022, where 57% of gross tonnage (GT) was ordered with alternative fuel capabilities. So far this year, the contracted alternative fuel vessels include 306 LNG-capable ships, 90 methanol-fueled vessels, 68 LPG-capable ships, and 15 battery-propelled vessels. Excluding LNG carriers, LNG-fueled ships account for 28% of the contracted tonnage, while methanol follows with 8% of GT. Methanol remains particularly popular in the container shipping sector with 52 newbuild orders, with interest also growing in other industries: Bulkers (14), PCC (10), Product Tankers (4), Multipurpose (4), Chemical Tankers (3) and Ro-Ro vessels (3). Additionally, there has been a steady approach to LPG and ethane adoption within the LPG sector. Notably, there is a significant shift towards Ammonia with a total of eighteen (18) orders classified as Ammonia-ready, mainly in the LPG carrier sector (14) and other segments: Crude Tankers (2), Bulkers (1) and Containerships (1).

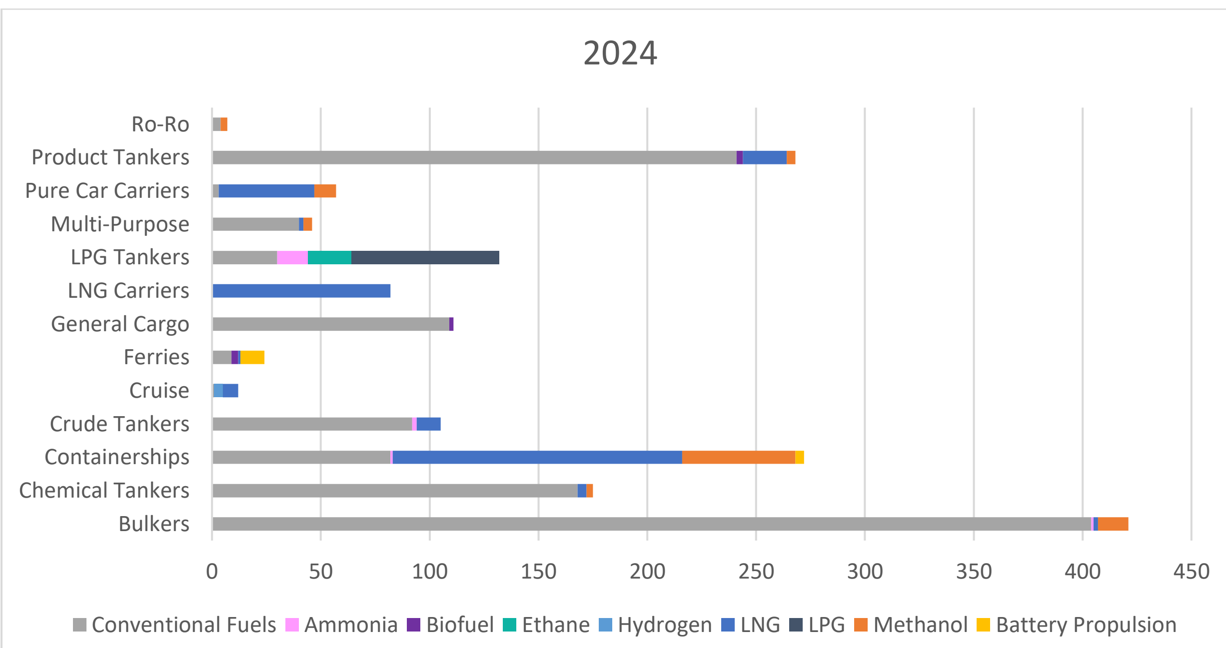


Chart 20: Orderbook by Fleet Type 2024

5.3.5. Alternative Fuel Readiness

Additionally, there is a significant increase in "optionality", involving vessels orders which have status "ready" in alternative fuels (Ammonia, Hydrogen, LNG and Methanol). Particularly, the "optionality" represents a 13,6% in 2022, following with 15,7% in 2023 and 20% in 2024 year-to-date in the respective year's orderbook. In the examined period (2019-2024) the "optionality" stands for about 12,5% of total orders.

The following graph illustrates the trend of the increasing optionality for alternatives fuels compared to the total orders per year.

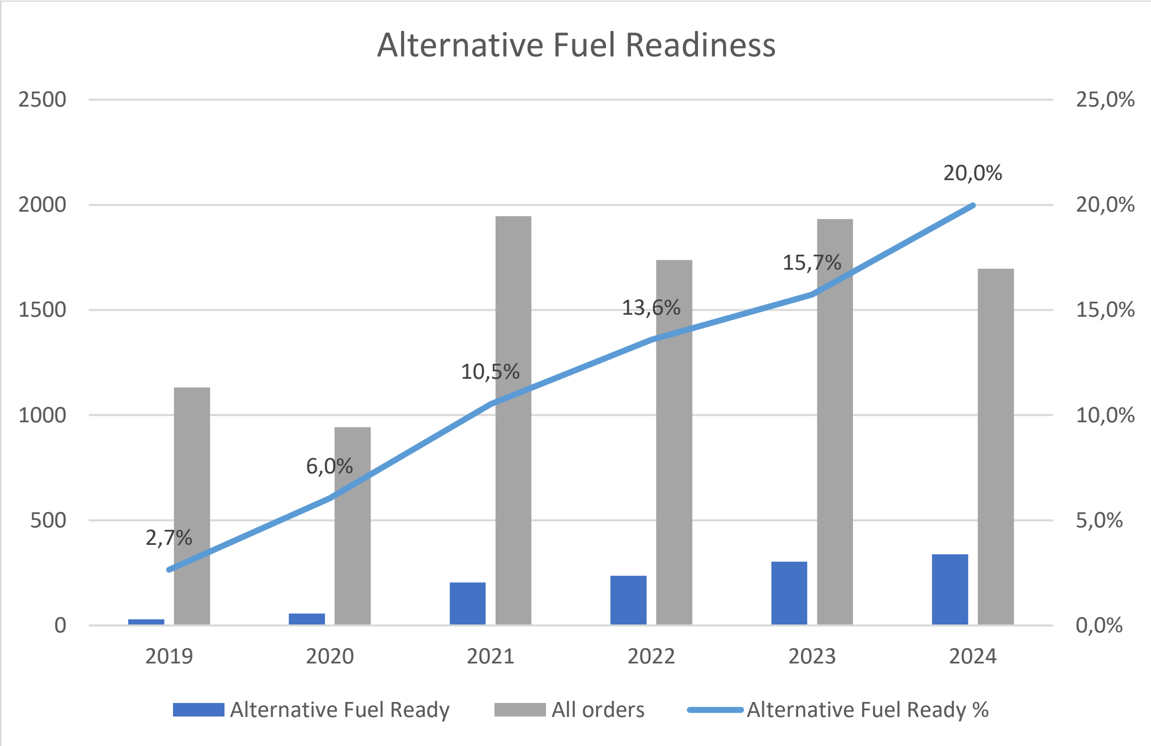


Chart 21: Alternative Fuel Readiness Annual Trends

The alternative fuel readiness could be either for the main or the auxiliary engine systems. The categories found in the data set are the following:

A/A	**Alternative Fuel Ready**
1	Ammonia Ready
2	Ammonia Ready, LNG Ready
3	Ammonia Ready, LNG Ready, Methanol Ready
4	Ammonia Ready, LPG Ready
5	Ammonia Ready, Methanol Ready

6	Hydrogen Ready
7	LNG Ready
8	LNG Ready, Methanol Ready
9	LPG Ready
10	Methanol Ready

Table 13: Alternative Fuel Ready Record Types

It is notable that the 82% of these vessels' orders are registered with main engine fuel as conventional fuel, which clearly highlights the need for the shipping companies to demonstrate efforts towards energy transition and only 13% of the ships which are already capable to run on LNG are registered to be ready for either ammonia or methanol.

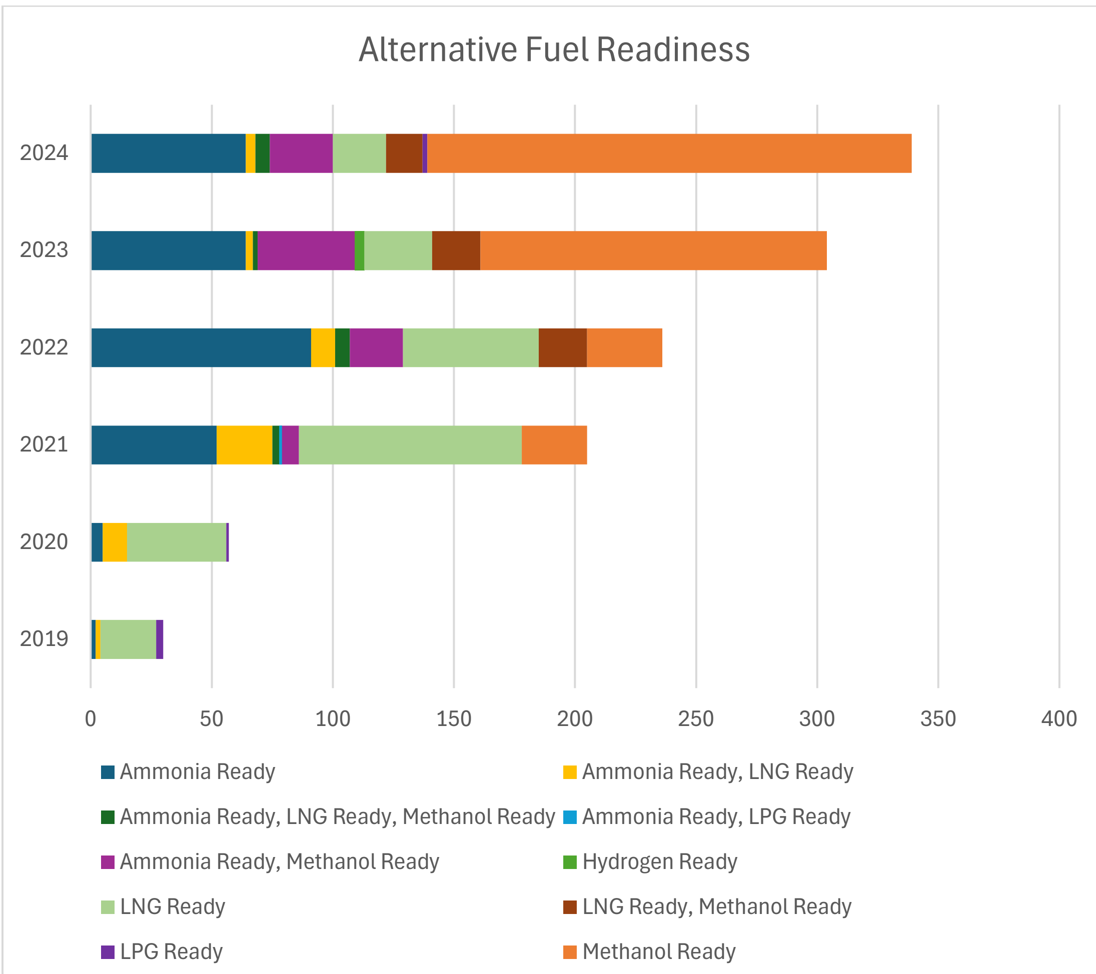


Chart 22: Alternative Fuel Readiness - Fuel Type Trends

The above chart demonstrates that Methanol is the most preferred option when it comes to fleet readiness, followed by Ammonia and LNG.

In technical terms, an Alternative Fuel Ready ship is defined as a vessel designed to facilitate future conversion to various alternative fuels, such as LNG, methanol, or hydrogen. This designation indicates that the ship has been constructed or modified with specific features that allow for the safe storage, handling, and use of these fuels, which are considered more environmentally friendly compared to traditional marine fuels.

For example, DNV classification society introduced a "Fuel Ready" notation, which allows shipowners to prepare for later conversions to multiple alternative fuel options. This notation provides flexibility in design and operational capabilities, ensuring that vessels can adapt to evolving fuel technologies and regulatory requirements in the maritime industry. This notation is applicable for Ammonia, Methanol, LNG and LPG as marine fuel, either individually or with more than one fuel options. It provides insights into the technical and operational considerations for adopting these fuels. (DNV, 2021)

An LNG Ready ship is defined as a vessel specifically designed and constructed to utilize LNG as fuel. This designation signifies that the ship incorporates particular features and safety measures to facilitate the safe storage, handling, and use of LNG, which is recognized as a cleaner alternative to conventional marine fuels. Typically, an LNG Ready ship includes design modifications that enhance its structural integrity to support LNG fuel systems, as well as established safety protocols to address the unique risks associated with LNG. Furthermore, this readiness allows for flexibility in future upgrades, enabling the vessel to be retrofitted or adapted for LNG use with minimal extensive modifications. As the shipping industry increasingly shifts towards sustainable fuel options to comply with environmental regulations and reduce greenhouse gas emissions, the concept of LNG Ready ships becomes crucial in promoting an eco-friendlier maritime sector.

A Methanol Ready ship is generally defined by class societies as a vessel which is designed to accommodate methanol as a future fuel. This includes elements related to its design and safety protocols ensuring safe storage, handling and use of methanol. For instance, Bureau Veritas provides a "Methanol-fueled Prepared" notation, indicating that a ship has been built or modified to be compatible with methanol fuel. This notation ensures adherence to design and operational standards that comply with regulatory requirements. (BV , n.d.)

The Gas Fueled Ammonia Notation has been introduced by DNV as ammonia is emerging as an alternative fuel option in the shipping industry. It sets out the requirements for the vessel's fuel systems and bunkering connections for the owners which are interested to order vessels as Ammonia Ready. (DNV, 2021)

The following table offers a high-level overview of the progress and challenges in the sustainable fuel pathway development. The fuels featured on the table have been selected based on expectations of scalability, sustainability, technological development, and commercial viability. Although other alternative energy solutions for maritime use exist, they are currently considered less likely to significantly contribute to decarbonizing the maritime sector by 2050. The maturity levels indicated on this table represent a technological assessment of readiness for maritime application and should not be interpreted as recommendations.

	Feedstock availability	Fuel production	Fuel storage, logistics & bunkering	Onboard energy storage & fuel conversion	Onboard safety & fuel management	Vessel emissions	Regulation & certification
e-ammonia							
Blue ammonia							
e-methanol							
Bio-methanol							
e-methane							
Bio-methane							
e-diesel							
bio-oils							

Mature	**Solutions Identified**	**Major Challenges**
Solutions are available, none or marginal barriers identified	Solutions exist, but some challenges on e.g., maturity and availability	Solutions are not developed or lack specification

Table 14: Fuel Pathway Maturity Map Source: (Mærsk Mc-Kinney Møller, 2022)

6. Conclusions

This master thesis outlines the global issue of the greenhouse effect and the international initiatives addressing global warming and its associated challenges. The Paris Agreement stands as a landmark accord, setting ambitious targets to limit global warming to well below 2 degrees Celsius, with efforts to restrict it to 1.5 degrees Celsius. Despite being a relatively small contributor to global emissions, international shipping has been making efforts to establish measures to enhance the energy efficiency and reduce its carbon footprint. In 2018, the IMO had adopted its initial strategy on reduction of greenhouse gas emissions from shipping. This strategy has set ambitious targets to reduce carbon intensity by at least 40% by 2030 and pursue efforts toward a 70% reduction by 2050, compared to 2008 levels. The IMO has developed policies, regulations and implemented measures for seagoing vessels with the aim to improve the energy efficiency, reduce emissions and foster a culture of continuous improvement. The inclusion of alternative fuels in the IMO's strategy has sparked debate, with some stakeholders advocating for greater emphasis on zero-emission solutions, such as hydrogen or ammonia, while others raise questions about the feasibility and scalability of these alternatives within the maritime industry.

The maritime industry has been exploring alternative fuels as a means to reduce emissions and transition towards more sustainable shipping practices. Among these alternative fuels are LNG, methanol, hydrogen, and ammonia, each with distinct properties, production methods, feasibility as marine fuels, scalability, and environmental impacts. Despite the advancements, the majority of the global fleet is still relying on conventional fuels.

Among the most feasible alternatives is LNG, for which significant development has occurred over the past decades in deploying it as a marine fuel. LNG requires LNG-capable engines and specialized fuel handling and storage systems. Dual fuel engines have matured, and global bunkering and storage infrastructure have been developed. LNG is considered a transition fuel for the marine industry because it emits significantly lower CO2 emissions (~30% less than HFO); however, the release of unburned methane is not neglected and poses a significant concern. Currently, LNG is the cleanest and most available alternative marine fuel, supplied in large volumes globally. Dual-fuel engines provide fuel flexibility, meaning that vessels that are able to run on LNG will be easier to switch to another alternative fuel in the future. Despite some benefits, LNG attracts controversy as it is still a fossil fuel and currently faces challenges as for example lack of bunkering infrastructure. There are efforts by several countries to minimize investments in LNG infrastructure and as of today, there is no consensus on whether technologies utilizing natural gas should be recognized as sustainable, even for a transitional period.

Methanol presents an alternative to traditional marine fuels, offering advantages aligning with environmental and economic goals. Its widespread availability and the projected increase in production capacity ensure that it can meet the growing demand for sustainable marine fuel. Methanol can be deployed in dual fuel oil/methanol engines. It's ease of handling and existing infrastructure compatibility makes it practical for ship operators transitioning to alternative fuels without prohibitive costs. Methanol fuel handling and risk management is simpler compared to LNG. For the existing fleet, retrofit potential is easier and less costly. Switching from conventional fuels to methanol significantly reduces harmful emissions, including SOX, PM, and NOX, and the potential for e-methanol and bio-methanol to produce minimal CO2 emissions enhances its appeal as a sustainable option. Absence of methane slip further strengthens methanol's environmental credentials. Important to highlight is that non-renewable methanol can have higher GHG emission impact than HFO. The transition to methanol as a marine fuel is not without challenges. One of the disadvantages is its lower energy density, which will require larger fuel storage capacity on board, and it is likely to be costlier in the short-term.

While methanol is cost-effective on a total cost of ownership basis, the initial investment and the higher price of low-carbon fuels compared to fossil fuels necessitate supportive policy measures. Implementing a carbon pricing mechanism could incentivize the adoption of methanol and other low-carbon fuels, ensuring that the maritime industry can achieve its sustainability targets. Overall, methanol's competitive advantages make it a promising candidate for the future of marine fuel, balancing economic feasibility with significant environmental benefits. It is important to mention that there are several ongoing research efforts aimed at improving methanol production and usage. One significant area of focus is the development of renewable methanol. Organizations like the International Renewable

Energy Agency (IRENA) and the Methanol Institute are working on innovative methods to produce methanol from renewable sources such as biomass and carbon dioxide. These efforts aim to make methanol production more sustainable and cost-effective, potentially reducing the reliance on fossil fuels. Overall, these research efforts are crucial for advancing methanol as a sustainable marine fuel and other applications.

Hydrogen is another candidate alternative fuel for shipping. However, readiness concerns exist regarding technologies that utilize hydrogen fuel cells and combustion engines. Hydrogen fuel cell systems are more advanced are generally considered more advanced than hydrogen engine applications, particularly in terms of efficiency and maturity in various applications. Current fuel cell technologies involve pressurized tanks which can accommodate hydrogen in gas form, however their volume efficiency is low. As a result of the low volume efficiency and the high costs, hydrogen could be a more attractive marine fuel option for short-sea shipping instead of long routes, due to the fact that in short sea shipping vessels can have more frequent port calls for bunkering. On the other hand, storage of hydrogen in liquid state is technically an option, but it would require additional reliquefication systems due to the high boil-off gas, generating more negative impact on operating costs (OPEX) and investment costs (CAPEX). From a life cycle GHG emissions perspective, only green hydrogen could be recognized as a candidate marine fuel for shipping's decarbonization. Currently the global production is mainly grey hydrogen which is energy and cost intensive and can have bigger CO2 intensity than conventional fuels. The production of green hydrogen is expected to increase when the global renewable electricity production would grow enough to fulfill the additional for green energy from the maritime industry. Regarding safety, there are still major concerns for deploying hydrogen as marine fuel and they are related to its flammability range, leakage potential, flame speed and deflagration issues. There is a need to further studies to comprehend the risks and also the additional safety measures that would need to be taken to mitigate the possible hazards. In a nutshell, the major challenges are the cost for development hydrogen infrastructure for vessels. Due to its low volumetric energy density and high explosive limit requires large tank systems and additional safety requirements in order to store hydrogen onboard. Another challenge is the limited availability of green hydrogen globally and the lack of bunkering infrastructure.

Ammonia as a marine fuel presents a pathway towards achieving a sustainable and carbon-neutral maritime industry. One significant advantage of ammonia is its potential to be a zero-carbon fuel when produced using renewable energy sources. As ammonia is a widely traded commodity with an established global distribution network, the existing infrastructure for storage and transportation of ammonia can be leveraged, facilitating its adoption as a marine fuel. Although ammonia has a lower energy density compared to conventional fuels, it is still higher than that of hydrogen, making it a practical option for long voyages, as it can be stored and transported more easily. Technological advancements in using ammonia in internal combustion engines and fuel cells bring the maritime industry closer to large-scale implementation. However, ammonia is highly toxic and poses health risks to crew members and marine life, requiring stringent safety measures to prevent leaks and exposure. Despite its advantages mentioned above, ammonia's lower energy density compared to conventional fuels means that larger volumes are needed, which can reduce cargo space and increase storage requirements. While ammonia combustion does not produce CO2, it can emit nitrous oxide (N2O), a potent greenhouse gas. Effective measures must be implemented to mitigate these emissions. On a global level, the current supply of green ammonia is limited, and its production is costly. Competition from other sectors could drive up prices, making it a less economically viable option in the short term. In conclusion, while ammonia offers a promising route towards decarbonizing the maritime industry, its adoption comes with significant challenges. Addressing the safety, environmental, and economic concerns will be crucial for its successful integration as a marine fuel. Continued research and development, along with robust regulatory frameworks, will be essential to unlock the full potential of ammonia in achieving a sustainable future for maritime transportation.

LPG as an alternative marine fuel, requires LPG capable engines with additional fuel handling systems required on board. On the positive side, it has significant less NOx, Sox, PM and approximately 10-20% less CO2 emissions than conventional fuels. It has been only adopted by LPG carriers which can utilize their cargo as fuel and plus there is existent terminal infrastructure globally. On the negative side, LPG uptake is very limited (insert %) outside of LPG carriers and it's not a green fuel.

Biofuels are in general commercially available and gaining more traction over the year. They are often used as drop-in fuels as they are already compatible with existing engine technology. Biofuels could be considered as a transition fuel option mainly because their widespread availability and lower lifecycle GHG emissions.

Battery propulsion is an option for short-sea shipping and for areas where High Voltage Shore Connection (HVSC) is available. There are no emissions generated from the vessels itself and could fee zero emission from lifecycle perspective if the in-land power is coming from renewable sources. Battery propulsion has been mainly deployed for small ferries and will continue to grow as port infrastructure expands. On the other hand, batteries are not practical for large vessels and long voyages due to the battery size which can affect the cargo space/capacity. However, batteries can be utilized for hybrid vessels in order to reduce the vessel's CO2 intensity, but important is not to neglect the upstream emissions deriving from the production of the battery systems. In conclusion, the adoption of pure battery power is primarily concentrated on smaller vessels operating short-sea routes, including ferries, Ro-Ros. In contrast, larger vessels are more likely to be equipped with hybrid or auxiliary battery systems.

International shipping has taken serious efforts to adopt alternative fuels, and deployment will continue as technologies are emerging; however, uncertainties remain in terms of timing and technological maturity. LNG remains the most widely adopted alternative fuel option and leads the transition, though it shall not be considered as a long-term solution. Methanol has gained traction over the past few years, but its market share remains stagnant. Other options include ammonia, LPG, ethane, hydrogen, biofuels, and battery propulsion (particularly for coastal vessels). According to the analysis conducted, there is significant emphasis on optionality and fleet flexibility for alternative fuels. Currently as of year to date, almost 51% of the ordered GT consists of vessels capable to run on alternative fuels (28% LNG excluding LNG Carriers and 9% Methanol), with an increasing optionality of 20% (e.g., ammonia-ready and methanol-ready), gaining back from 2022 record high at 25%.

Several trends are evident within the existing fleet, focusing on energy-saving technologies such as air lubrication systems and other advancements that enhance energy efficiency.

Retrofits will play a crucial role in this transition increasing the fuel flexibility and adaptability of the in-service fleet. Alternative fuel conversions present various challenges depending on the fuel type. For LNG, initial projects often face delays and cost overruns, with an estimated retrofit time of at least 4 months. The process is more expensive and complex than methanol conversions due to the need for cryogenic tanks. Methanol retrofits are generally less costly and quicker, as they do not require cryogenic tanks, but fewer conventional 2-stroke engines can be converted to methanol than LNG. Ammonia conversions face uncertainty regarding suitable engine types and the development of fuel supply systems, with issues related to toxicity and corrosiveness. It is expected in regard to ammonia conversions that owners would have a wait and see approach until after the first ammonia-capable vessels are operational (2026-2027) before taking any decisions.

This analysis has considered the yearly orderbook from 2019 to 2024 (year-to-date), focusing on alternative fuel types and fleet groups, with an emphasis on the number of orders and the proportion of gross tonnage. For future research, it would be valuable to analyze alternative fuel trends by fleet group and vessel size to identify the main considerations and any relationships between vessel size, deadweight capacity, and alternative fuel choice. Additionally, examining the trends in the adoption of Energy Saving Devices (ESDs) and their popularity across different fleet groups would provide further insights. This study has focused on the recent orderbook to understand how international shipping is aligning with the IMO 2050 GHG reduction target and the significance of adopting alternative fuels. However, to gain a comprehensive understanding of the uptake of alternative fuels, an analysis of the existing fleet's conversion status should also be considered.

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