UNIVERSITY OF PIRAEUS

DEPARTMENT OF MARITIME STUDIES

PROGRAM OF POSTGRADUATE STUDIES
IN
SHIPPING
MANAGEMENT

THESIS

THE IMPLICATIONS OF THE FUELEU MARITIME REGULATION ON THE MARITIME SECTOR

Stamatina Angeli

Diploma Thesis
submitted to the Department of Maritime Studies
of the University of Piraeus as part of the
requirements for the acquisition of Master's degree

PIRAEUS NOVEMBER 2024

Declaration of authenticity

The person conducting the Diploma Thesis bears the entire responsibility for determining the fair use of the material, which is defined on the basis of the following factors: the purpose and nature of the use (commercial, non-profit or educational), the nature of the used material (part of the text, tables, figures, images or maps), of the proportion and importance of the part, which is used in relation to the whole copyrighted text, and the possible consequences of such use on the market or the general value of the copyrighted text.

Three-member committee

This Diploma Thesis was unanimously approved by the Three-member Examination Committee appointed by the SGA of the Department of Maritime Studies of the University of Piraeus in accordance with the Operating Regulations of the Postgraduate Program in Shipping Management.

The members of the Committee were:

- Assistant Prof. Anastasia Christodoulou (Supervisor)

- Assistant Prof. Stefanos Chatzinikolaou

- Assistant Prof. Evangelos Tsioumas

The approval of the Thesis by the Department of Maritime Studies of the University of Piraeus does not imply acceptance of the author's opinions.

Table of Contents

Abstract

The purpose of this diploma thesis is to provide a comprehensive overview of the new environmental policies that are regulated by international and regional bodies in an effort to support decarbonization. More precisely, a reference is made to the IMO's Annex VI of MARPOL for the Prevention of Pollution from Ships and the EU's efforts through the Fit for 55 package to reduce the carbon footprint across Europe by introducing tools in order to monitor, tax and trade emissions. However, the current research is mainly focused on the analysis of the FuelEU Maritime Regulation that sets carbon intensity limits on the vessels operating inside the European Economic Area. The research outlines the regulation's structure, its objectives and the actions needed for achieving compliance. In addition, the strategies a shipowner can pursue are presented, since it remains unclear which approach—whether operational measures, retrofitting the existing fleet, or investing in new fuel-efficient vessels—will be the most effective for complying with the regulation. Moreover, the employment of alternative fuels, such us low carbon intensity fossil fuels, e-fuels, methanol, biofuels, ammonia, hydrogen are evaluated, along with the potential role of renewable energy sources that will possibly be used in the upcoming years. Lastly, a case study in a shipping company is conducted, outlining the implications of the FuelEU Maritime Regulation on the maritime sector, while considering all the stakeholders of the shipping industry.

Key words: FuelEU Maritime Regulation, Alternative fuels, Alternative energy sources, Retrofit, Implications

1. Introduction

Shipping is the driving force of the global trade as roughly 80% of the supply chain relies on it. Maritime industry is one of the cleaner sectors, accounting for roughly 2% to 3% of the global greenhouse gas emissions. However, the flourishing trade market will lead to an annual cargo increase by 3.2% by 2050, which will consequently lead to a rise in global emissions. Supposing that the current amount of greenhouse gas emissions persists until 2050, the shipping industry could be responsible for the 17% of total emissions unless additional measures are implemented (Stopford 2020; Zhang, Bao and Ge, 2021). If the aforementioned increase in trade was also taken into consideration, then the estimated increase in carbon dioxide emissions by 3000 million tons pers year would place the shipping industry in the first place of air pollution among all the other sectors (Zhang, Bao and Ge, 2021).

For many years, the maritime sector had been excluded from the regulations affecting other industrial sectors due to the international nature of the industry, which makes it difficult to attribute emissions to any one state. Many discussions have taken place throughout the years for the inclusion of the shipping in the environmental efforts for emissions reduction, but to no avail (Zamboni et al., 2024).

One of the most prominent measures to be implemented in shipping by its prime regulator, namely the International Maritime Organization (IMO), was aiming to significantly cut down on sulphur oxides, and as a result, a sulphur limit that restricts the sulphur content of fuel used by ships was set to 0.5%, effective from the beginning of 2020. This limit was even stricter for the so-called Emission Control Areas (ECAs), such as the North America coasts, the North Sea, the Baltic and US Caribbean, where ships are required to use fuel with a sulphur content of 0.1% or less. In addition, IMO has also established limits to the nitrogen oxide emissions for vessels operating not only inside ECAs, but outside as well. The limits are expressed in fuel consumption of the engine (g/kWh) and there are three levels related to the construction date of the vessel (Zannis et al., 2022). However, many harmful emissions, such as carbon oxides, continued to be released in the environment, since no relevant regulation existed, unlike other industries where measures had been in place for years.

The European Union (EU), in an effort to reach climate neutrality by 2050, introduced the Fit for 55 package that aims at the decarbonization of Europe, including among others measures that the shipping industry has to comply to. One of the regulations is the FuelEU Maritime Regulation, coming into effect from 2025, which establishes progressively stringent GHG intensity limits for the energy consumed, with limit adjustments every five years. The regulation promotes the use of alternative and renewable fuels, along with the development of new technologies (Council of the European Union, 2021). As a result, the FuelEU Maritime Regulation will have a significant impact on all stakeholders of the maritime sector. Both the uncertainty over the future fuel choices and the implementation of the most effective plan in order to not only comply with the regulation, but also be ahead of the competition, burdens the ship owners. Furthermore, intriguing questions have arisen concerning the way the FuelEU Maritime Regulation will influence investment decisions and technology adoption in the maritime sector, particularly in terms of retrofitting existing vessels or investing in new fuel-efficient ships.

The current research aims to answer the aforementioned questions in the chapters below. Chapter 2 describes the methodology used for the conduction of the research. Chapter 3 carries out an analysis of the existing regulatory framework regarding decarbonization, while in Chapter 4 the FuelEU Maritime Regulation is introduced. The possible strategies that a shipping company can adopt for the reduction of carbon emissions, including operational measures, retrofitting the existing fleet and / or investing in new fuel-efficient vessels are presented in Chapter 5. In Chapter 6 a comprehensive analysis is conducted on all the available alternative fuels and energy sources that could ensure compliance with the FuelEU Maritime Regulation limits. Chapter 7 illustrates the implications of the regulation to all the aspects of the maritime sector by conducting an assessment on the macro-environment of the industry. Chapter 8 presents a case study conducted on Starbulk shipping company, regarding its actions and approach to the new opportunities and challenges brought in the shipping industry by the FuelEU Maritime Regulation. The final chapter primarily addresses the conclusions and limitations of the thesis.

2. Methodology

The relevant research has followed two axes. The first part attempts to conduct a comprehensive analysis of the literature review concerning the regulatory system and a detailed reference to the FuelEU Maritime Regulation and how its implementation affected the shipping sector. Several academic papers and researches have been examined in order to determine the implications of the regulation, whether the prospect of retrofitting or the investment in new building vessels is more attractive. The second part of the research is the data collection and analysis of a case study through interviews in order to practically answer how executives working in a ship owing and management company approach the new environmental and legislative challenges.

3. Regulatory System

As the problem of greenhouse gas emissions started to become more evident, the stakeholders of the shipping sector commenced to act in order for the emissions to be reduced. International institutes such as the International Maritime Organization (IMO), the United Nations (UN) and regional institutes like the European Union (EU) are fundamental pillars of setting standards in order to reach emissions neutrality targets (International Maritime Organization, 2023; United Nations 2016; Council of the European Union, 2021). Countries have likewise undertaken substantial efforts, with the Chinese government promoting green energy usage in its ports, while local initiatives, mostly from the port authorities, are implementing systems and procedures so as to mitigate the pollutant emissions (Azarkamand, Wooldridge and Darbra, 2020; Sun, Xu and Liu, 2023).

3.1 International Maritime Organization Regulations

The IMO, as the United Nations agency that holds the responsibility of regulation development, has attempted many times in the past years to prevent the atmospheric pollution from maritime sector. The first attempt was in 1997, when the Annex VI of MARPOL Convention was adopted. The Annex VI was about the Prevention of Pollution from Ships, initially aiming to set limits on sulfur oxides, nitrogen oxides and ozone depleting substances emissions. A few amendments were implemented in 2011, where the utilization of systems in the design of the vessel was introduced in order to improve its energy efficiency, thus further reducing environmental footprint (Zamboni et al., 2024). Additionally, in 2016, under the Data Collection System (DCS), vessels above 5000GT were obliged to record their fuel consumption and report it so that the IMO could proceed with further actions in order to mitigate the GHG emissions (International Maritime Organization, 2016).

The Ship Energy Efficiency Management Plan (SEEMP), under MARPOL Annex VI, is an operational tool that will require ship energy efficiency improvement through systematic management practices. Part III of SEEMP outlines a methodology to calculate the attained annual Carbon Intensity Indicator (CII) for ships above 5,000 gross tonnage. It involves reporting to the relevant administration on the implementation plan to achieve the CII targets within three years and self-evaluation to ensure compliance. SEEMP contributes to the decarbonization goal by including operational improvements in a more structured framework (DNV, 2023; Lloyd's Register, 2023).

The Carbon Intensity Indicator (CII) is a performance-based operational measure used to assess a vessel's energy efficiency on an annual basis. It was introduced as part of the IMO's 2023 regulations and it uses CO2 emissions relative to cargo capacity and distance traveled to determine an efficiency rating from A (best) to E (worst). Ships rated D for three consecutive years or E in a single year are required to produce corrective plans. This measure encourages the adoption of environmentally-friendly practices by introducing rating mechanisms that guide operators towards reducing emissions (IMO, 2023; DNV, 2023).

The Energy Efficiency Design Index (EEDI) is a technical measure that refers to certain types of new ships and establishes efficiency measures by calculating CO2 emissions per tonne-mile on the basis of design parameters. Shipbuilders have to ensure vessels meet these standards through innovative solutions, such as hybrid engines or optimized hull designs. Unlike the EEXI, which is applied retroactively, EEDI is focused on encouraging state-of-the-art technologies in shipbuilding to reduce the carbon footprint from the shipping sector (DNV, 2023; IMO, 2021).

The Energy Efficiency Existing Ship Index (EEXI), on the other hand, aims to extend design efficiency requirements to the existing field by targeting ships above 400 GT built that were constructed before EEDI regulations. It requires calculating a ship's "attained EEXI" based on its design and comparing it to required benchmarks. Ships must comply through technical upgrades, such as engine power limitations or renewable propulsion systems (IMO, 2021; Lloyd's Register, 2021).

3.2 European Union Actions

3.2.1 Fit for 55

The Fit for 55 is a package of regulations, new or revised, which was put forward in order to assist the EU to achieve its goal of a 55% reduction in greenhouse gas emissions by 2030, in comparison to 1990. This comprehensive package is a cornerstone initiative within the EU's broader agenda to achieve climate neutrality by 2050, as set forth by the European Green Deal, and constitues a series of legislation reforms that were first put forward by the European Commission in 2021. It was subsequently adopted in 2023 after several technical discussions and council meetings culminating in the Council's and Parliament's agreement. In reference to shipping, the main components of the Fit for 55 package that were introduced are the FuelEU Maritime Regulation, the Alternative Fuels Infrastructure (AFIR), revision of Renewable Energy Directive (RED), the Emissions Trading System (ETS), the Energy Taxation Directive (ETD) and the MRV Maritime Regulation (Council of the European Union, 2021).

3.2.2 Monitoring, Reporting and Verification (MRV)

The MRV Maritime Regulation, which was first adopted in January 2018 and has been revised in 2023, obliges passenger and cargo vessels operating in the ports of the European Economic Area (EEA) to monitor and report their greenhouse gas emissions. The vessels which are compelled to adhere to the relevant regulation are those with gross tonnage above 5000 which are loading and unloading cargo, making a ballast voyage, being in drydock or making repairs, undertaking ship-to-ship cargo transfer, making crew changes, carrying out bunkering operations etc. However, from January 2025 the offshore ships above 5000 GT and vessels above 400 GT will also have to comply with the regulation. The only exceptions are the warships, fishing boats, non-motorized ships, naval auxiliary vessels and non-commercial government fleet. In addition to the aforementioned, the greenhouse gas emissions that need to be reported from January 2024 will be carbo dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) contrary to the first years of regulation's implementation where only carbon dioxide was reported.

Under the MRV Maritime regulation, shipping companies are compelled to monitor each of their vessels on an annual basis and collect the necessary data that will subsequently be verified from an MRV authenticator. The required data are GHG emissions, fuel consumption and information such as the time each vessel spent at sea and the total covered distance. Each year by the end of March, the shipping companies should submit their reports for every vessel that has been operating in European Economic Area to the Commission, flag States and to the responsible regulatory authorities through THETIS MRV platform. It has to be mentioned that until 2024 the submission period was by the end of April. Last but not least, the documentation of compliance that states among others the monitoring plan, the accountability of the shipping company etc., needs to be on board the vessel until the end of June otherwise its absence may constitute a non-conformity in case of inspection (Council of the European Union, 2021).

3.2.3 Emissions Trading System (ETS)

EU Emissions Trading System (ETS) was initially established in 2005 and first discussed for shipping to be included in 2007. Shipping and aviation were excluded due to their difficulty in allocating among states the liability regarding the emissions. For the aforementioned reason, the shipping was excluded from the international climate agreement introduced by UNFCCC (Christodoulou et al., 2021). After years of debate, on July 2021, the topic emerged once again from the EC as a package of measures that intended to be implemented in the shipping sector in order to narrow down its environmental footprint (Lagouvardou & Psaraftis, 2022).

The revised version of EU ETS including shipping was adopted on May 2023 and came into effect on June 2023. It is legislated that from January 2024 each cargo and passenger vessel over 5000 gross tonnage that reaches EU ports or is within the port limits is obliged to cover its CO_2 emissions irrespective of the flag it flies. Additionally, from 2027 onward, offshore vessels of 5000 GT or above will be compelled to comply as well. In the event that the vessel commences or concludes its voyage on a non-European port, it is mandated to cover 50% of the applicable costs.

Under the current phase, only carbon dioxide emissions are measured, while methane and nitrous oxide emissions are set to be included on 2026. Shipping companies are committed to surrender allowances to the regulatory authority, with one allowance amounting to one ton of carbon dioxide. The submission deadline of allowances for the 2024 compliance period is set for the end of September 2025. With the intention of a more gradual change, full compliance will be established only by 2026, with companies having to submit only 40% of the applicable allowances for 2024 and 70% for 2025. The main goal of EU ETS is to decrease the amount of emissions by 62% from 2005 to 2030 (Council of the European Union, 202X).

EU ETS has the role of a Market-Based Measure (MBM) aiming to introduce financial initiatives to the shipowners in order to reduce their environmental footprint and simultaneously to convey the polluter-pays principle. Each year, a specific amount of EU allowances (EUA) is distributed among the compliant bodies in the form of cap and trade principle. The reference allowances are auctioned in markets where the shipping companies can either buy or sell them (Lagouvardou and Psaraftis, 2022). ETS has already been applied to other industries with notable results in emissions reduction, and is therefore projected to deliver similar success in the shipping sector as well. An advantage that is essential to be mentioned is that shipowners will gain benefits from selling the surplus of allowance if they invest in more fuel-efficient vessels, creating a new profit pathway. However, in light of the inclusion of shipping in the Emissions Trading System, short sea services may face increased operational costs, thus potentially shifting the competitive balance towards land transport routes, which may appear as a more cost-effective alternative. Moreover, vessels will reduce speed in order to consume lesser fuel and consequently there will be less vessels available in the market (Christodoulou et al., 2021). The risk of competition should also be considered as the European ports may not be favored due to the increased operational costs (Mallouppas et al., 2022).

3.2.4 Energy Taxation Directive (ETD)

Energy Taxation Directive (ETD) is a taxation system where the energy products and electricity used as fuels are taxed as per their environmental footprint. ETD was first established in 2003, while amendments were made in 2021 in order to launch a new structure and include more products or to cease existence of exemptions. The dominant principle is that there are several categories that the fuels are classified into according to their pollution rate and the Member States are responsible for the implementation on a national level. The tax rates will be annually reviewed and adjusted in any case needed in relation to the prevailing prices.

As far as shipping is concerned, this is the first time that heavy fuel oil is subject to tax in intra-EU voyages, while the rate of tax is expected to increase gradually within the current decade. The classification of taxed fuels is provided below in which needs to be mentioned that the actual content and performance of fuels has been taken into consideration, not the volume as in the previous directive. The use of conventional fossil fuels and non-sustainable biofuels will have a minimum tax rate of €10.75/GJ. Thereafter, NG, LPG and fuels that did not use renewable energy to be produced with non-biological origin will be taxed at €7.17/GJ. The next group of fuels are the non-sustainable biodiesels such as bioethanol where the tax rate will amount to €5.38/GJ. The last category is the one that is considered to support the most in decarbonization where the taxed fuels are sustainable biofuels, renewable fuels but not with biological origin and electricity where the tax rate will at least stand at €0.15/GJ (Council of the European Union, 2021).

Table 1: Taxed Rates of Fuel Categories

Fuel Category	**Fuel Tax Rate**
Conventional fossil fuels *(e.g. gas oil, non-sustainable biofuels)*	€10.75/GJ
Transitional fossil-based fuels *(e.g. NG, LPG, Non-renewable fuels of non-biological origin)*	€7.17/GJ
Sustainable biofuels *(e.g. Bioethanol)*	€5.38/GJ
Low emission and renewable fuels *(e.g. Electricity, Renewable fuels of non-biological origin)*	€0.15/GJ

Source: Council of the European Union (2021)

3.2.5 Other Regulations

The Alternative Fuels Infrastructure (AFIR) regulation that was imposed mandates that in the busiest sea ports at least 90% of containerships and passenger ships should have the capability to be electric-connected during their stay in ports, while the majority of inland ports are anticipated to provide at least one onshore electricity supply by 2030 (Council of the European Union, 2021).

In reference to the Renewable Energy Directive (RED), the latest revision set a goal of meeting at least 42.5% of the energy needs out of renewable energy by 2030. In relation to shipping transport, the member states have two options, either to mitigate by 14.5% the GHG emissions intensity by using renewable energy or use a minimum of 29% of renewable energy sources for the end-use consumption. Moreover, RED advances the increased use of biofuels and renewable fuels of non-biological origin by 5.5% with the 1% to be mostly hydrogen (Council of the European Union, 2021).

4. FuelEU Maritime Regulation

The FuelEU Maritime Regulation was first put forward by the European Council (EC) in June 2022, presenting two proposals. Both the EC and the European Parliament agreed on the relevant regulation system in March 2023 and was finally adopted by the Council in July 2023. The Fuel EU Maritime Regulation, as part of the Fit for 55 package, sets a regulatory system for the upcoming years in order for the Greenhouse Gas emissions to be eliminated by 2050. Each year, starting from 2025, the regulation establishes the limits for the vessels operating within the European Union ports, requiring a yearly reduction of their emissions by a specified percentage, with 2020 serving as the base year. All the vessels, regardless of their flag, having an average gross tonnage that exceeds 5000 deadweight are obliged to comply with the new regulation. As a matter of fact, the vessels meeting the aforementioned condition constitute 55% of all the fleet, while being responsible for 90% of the emissions in the sector. The yearly amount of GHG emissions will be measured by including the stage of the fuel extraction, transportation to the port, bunkering and eventually onboard usage. It is essential to be mentioned that the emissions required to be reported and reduced are carbon dioxide, methane and nitrous oxide. Moreover, primarily for the passenger and container ships which berth in ports that tend to be closer to residential areas, vessels will have to be able to connect in on-shore power supply (OPS) or use other technologies with zero GHG emissions.

All of the above will impel shipping companies to research and develop new technologies and more eco-friendly fuels, or even greener ways of energy production, having also the flexibility to follow several different pathways. The Council is obliged to present a report by the end of 2027 to EC and the European Parliament with an evaluation of the function of the FuelEU Regulation and the Commission may implement amendments if deemed necessary (Council of the European Union, 2023). The FuelEU Maritime Regulation, except for the carbon intensity reduction targets and the fuel requirements, provides incentives and penalties such as reputation, inducement for the development of new technologies and construction of new infrastructure, aiming to promote green energy and grants the access in the EU ports (Council of the European Union, 2023; DNV, 2023).

4.1 Goals & Objectives

Maritime transportation is considered one of the greenest industries as it is reported that shipping is responsible only for 13.5% of GHG EU emissions based on 2018 data. FuelEU Maritime

Regulation stipulates that the reduction percentage will rise every five years, aiming to reach the zero-emissions EU target by 2050. The GHG emissions intensity for all the regulated gases (CO_2, CH_4 and N_2) are measured with a carbon dioxide equivalent. The fuel, technology or the combination of both that is opted for is up to the shipowners to determine, provided the objective reduction is reached. As mentioned before, the base year has been set as 2020 and the defined targets are as per below.

Table 2: Carbon Intensity Reduction Limits

Year	2025	2030	2035	2040	2045	2050
Reduction (%)	2%	6%	14.5%	31%	62%	80%

Source: Council of the European Union (2021)

Starting from 2030, both passenger and container ships [exceeding 5000 GT] will have to be connected with on-shore power supply (OPS) in all major EU ports. Additionally, starting from 2035, this requirement will expand to include any other relevant EU ports, provided that OPS is available. The only exception to this rule is vessels that are using emissions-free technology or/and are at birth for less than a 2-hours period.

Starting from 2025, not only GHG emissions will have to be monitored, but also the usage of Renewable Fuels of non-Biological Origin (RFNBOs). The relevant monitoring is aiming to provide incentives to the RFNBOs fueled vessels. Even so, if the use of RFNBOs is less than 1% of the fuel mix by the year 2031, then the target of 2% will be set in effect starting from 2034 (Lloyd's Registry, 2023).

4.2 Well-to-Wake Approach

As mentioned in chapter 2, the regulation existing until 2023 took into account only the emissions derived from the on board the vessel consumption. However, the approach that aims to mitigate the global warming should be considering a lifecycle assessment (LCA) of the emissions either in fuel production or when consumed on board the vessels. The FuelEU Maritime Regulation applied the above perspective to the imposed directive known as Well-to-Wake approach. In respect of the above, it is essential to refer to Well-to-Wake approach as it is the way that emissions will be calculated in the FuelEU regulation. Well-to-Wake is divided into two parts, the first being the

Tank-to-Wake which is the stage that the fuel is handled on board the vessel, all the way from the tank to the emissions end up in the funnel. The second is the Well-to-Tank and concerns the upstream emissions that occur from the extraction of the feedstock, its processing and the transportation to the vessel's tanks (Zamboni et al., 2024).

4.3 Time schedule for compliance

The compliance with the FuelEU Maritime Regulation burdens the ship owning company, the charterers company or the management company that operates the vessel under International Safety Management Code (ISM) or holds a Document of Compliance (DoC). The regulation comes into effect in 2025, although there exists one step that needs to be followed until the end of August 2024. The FuelEU Monitoring Plan has to be submitted for every vessel in order to be verified. In the reference plan, the way that the required data (emissions 'amount, type and energy used) will be calculated, monitored and reported has to be detailed. In case a vessel is subject to the FuelEU regulation after August 2024, then the plan should be submitted to the verifier within two months of the relevant vessel's first arrival in a port that belongs to the European Economic Area. As soon as the FuelEU regulation is activated in 2025, the responsible entity for each vessel is obliged to monitor the required parameters throughout the year. The aforementioned parameters are the precise time when the vessel arrived at the port, the total amount and type of fuel used in berth and sea, as well as every other alternative source of energy used.

Moreover, it is necessary to analyze the amount and type of emissions produced during both the fuel production and transportation process (well-to-tank) and the emissions generated when the fuel is used (tank-to-wake). Other data expected to be reported by the relevant authority includes the ship's ice class as well as the coordinates of the vessel when entering or leaving the port, the amount of fuel consumed in this condition, the distance traveled in ice conditions in order to be excluded from the calculation.

Regarding OPS, passenger and container ships must report whether they are connected to it while at berth. All vessel types, in general, should report if they use OPS and the amount of electricity consumed. After the completion of the reporting period, the deadline for submitting the required data is until the end of January. In case the vessel has changed ownership within the reporting year, then the new owner shall be held responsible for all year's emissions. The data collection will be based on the arrivals at and departures from the port. If both of them are within EEA then all energy used will be reported, whereas when one of them is a non-EU port only half the energy will be applicable. Thereafter, the verifier will have time until the 31st of March to send the notifications and verifications to the reference vessel including the FuelEU report which will assess if the vessel is in compliance with the regulation. In addition, verifiers will submit the greenhouse gas intensity, the energy consumption excluding OPS energy and the consumption of RFNBOs used onboard the vessel. Also, the times of non-compliance will be included.

Subsequently, the shipping companies should choose whether they are going to bank, borrow or pool surplus of GHG intensity relative to the reported usage until the end of April. According to the relevant mechanism, borrowing a maximum 2% from next year's compliance percentage is allowed, but it is not permissible to do so in successive years. Another mechanism is the pooling of compliance balances, where the compliance of multiple ships can be combined to achieve the targets. To bank or borrow surplus, the approval of the verifier is necessary, whereas in pooling the verifier records the transaction in the database. In the same period the verifier should revert with the balance of compliance of the vessel and when applicable, they should report the penalty or the RFNBO sub-target. In due course, the penalties, which will be 2400 euro per ton of VLSFO-equivalent for each vessel failed to comply with the regulation, should be paid from the 1st of May until the 30th of June and the reference gathered amount will be used with the aim of supporting the decarbonization of the shipping industry. The penalties shall be applicable in instances where emissions intensity is exceeded exceeds prescribed limits, the objective of RFNBO target has not been reached and, starting from 2030, if non-compliance in OPS is identified while the vessel was berthed. Each vessel will be provided with a Document of Compliance until the 30th of June that will be valid for one year and must be carried while being in the European Economic Area. The vessel will be subject to port entry ban in the event that two successive DoCs are missing. The DoC is issued from the verifier unless penalties were identified; in such cases the EEA regulatory authority is responsible for issuing the DoC upon settlement of the payment. As it relates to passenger and container ships, starting from 2030 they are obliged to be connected to OPS in all major Trans-European Transport Network (TEN-T) ports while at berth and starting from 2035 to all EEA ports, once accessible.

During the period from 2030 to 2035, certain exceptions to the rule shall apply, and non-OPS connection will not incur penalties. These exceptions include urgent or unexpected port call, as well as vessels that are using zero-emission technology at berth and whose call at port lasts for less than two hours (Lloyd's Registry, 2023; DNV, 2023).

5. Strategy

Under the FuelEU Maritime Regulation that comes into effect in the beginning of 2025, shipping companies will be required to select the most effective strategy to achieve the established intensity limits, both in the short and long term. Although certain operational adjustments may provide immediate benefits, their contribution to long-term carbon emissions reduction will be limited, making more substantial measures essential for success. Such measures, which will play a key role in reaching the ultimate goal, include retrofitting existing vessel engines or investing in new fuel-efficient vessels, although at a higher cost, since the ship owners will be exposed to capital expenditures and greater risk as shown below.

5.1 Control Emissions Technology

The implementation of Regulation 14 of MARPOL Annex VI which defined the mitigation of the sulphur oxides and particulate matter emissions in Emission Control Areas (ECA) led the shipping companies to adopt new technologies in order to comply. The prevailed solution was scrubbers, which essentially are exhaust gas cleaning systems (EGCS) that remove the SO_x and PM from the streams with either fresh or sea water. In an attempt to offset the high capital expenditure required to acquire scrubbers and to make them an attractive investment, usage of heavy fuel oil was permitted due to its low price point in comparison with the rest of the fossil fuels. However, scrubber usage leads to higher fuel consumption and emissions (e.g. carbon dioxide) increase, posing an adverse challenge to the new legislation (Abadiea, Goicoecheab and Galarraga, 2017).

5.2 Operational Measures

There is a wide variety of operational countermeasures in order to mitigate the carbon dioxide emitted from the shipping sector. In the following sections, some of them, such as slow steaming, voyage optimization and supply chain optimization will be discussed.

5.2.1 Slow Steaming

The first and most efficient practice is slow steaming, where vessels deliberately operate at speeds below their maximum potential. Most of the shipping companies have adopted slow steaming due to its great benefits, including fuel consumption, energy efficiency and reduced emissions. The average decrease in carbon dioxide emissions is up to 20 to 40% and might even rise up to 60% in certain cases. The greatest benefits of slow steaming will be realised with higher capacity vessels and those operating at medium to high speeds. However, barriers, such as significant market distortion, need to be overcome. Time spent per voyage will be increased, resulting in the overall reduction in the efficiency of the just-in-time system. The quality of transported goods, such as edible products, is at risk of diminishing, while energy consumption for refrigeration purposes is bound to increase. There might even be cases where the prohibitive voyage time will push merchants to explore alternative means of transportation, such as trucks or airplanes, essentially contradicting the very need for emissions reduction regulations, given that these transportation sectors are considered to be much more polluting compared to shipping.

In addition to the disruption of market dynamics, the need for vessels will be increased as the speed will be reduced and even if the required work remains the same the demand will not be satisfied, especially in case of a flourishing market. Moreover, the reduction in speed may cause negative effects in relation to the effectiveness of the engine, exhaust and waste heat recovery system, increasing in turn the maintenance and the off-hire time. Furthermore, the lack of a regulatory framework is another drawback that leads to unfair markets. Slow steaming's effectiveness cannot be refuted; however, research and investment in the development of new technologies should not be abandoned if the long term target of carbon neutrality is to be achieved (Xing, Spence & Chen, 2020).

5.2.2 Voyage Optimization

Voyage optimization through weather routing or speed optimization aim to mitigate the ship's resistance to the environmental elements and either maximize the profits or minimize the costs by identifying the less demanding path and speed. In terms of weather routing, it is generally used to shorten a voyage and improve the safety of the seafarers and the cargo while simultaneously decreasing the operational cost for the shipper. The chosen route does not remain the same through the voyage as the optimization process takes place during the voyage as well, protecting the seaworthiness of the vessel by avoiding bad weather conditions. In that way, emissions reduction and effective fuel consumption are achieved, though they are not the primary objective.

More enhanced optimizing systems for ship routing may be produced in order to design for emissions reduction and fuel saving parameters. Speed optimization is used in order to assist with the just-in-time system and avoid bad weather conditions while remaining in compliance with the designated timeframes of each contract. In respect of the just-in-time approach, adjusting the vessel's speed will lead to better fuel consumption throughout the voyage, while also minimising fuel emission from waiting outside the port due to capacity constraints by ensuring timely arrivals. However, the current first come first served system that is implemented in ports needs to be revised, along with the commercial priorities of the shipowners and charterers. Moreover, the communication of the port authorities with the operators of the ship have to be enhanced. Another factor that should be considered is the adjustment of the cargo stowage or the ballast water. The appropriate trimming and draft level will lead to the optimization of the voyage, therefore the fuel consumption and carbon emissions will be decreased (Xing et al., 2020).

5.2.3 Optimization of Supply Chain

The optimization of the supply chain is instrumental in achieving a reduction in carbon dioxide emissions through various implemented strategies.

The complex process of trading design, containing fleet deployment and vessel capacity, plays a key role in influencing emissions outcome. Furthermore, it is essential to recognize that regardless of the commercial interests, customers increasingly demand that their associates make efforts to minimize carbon emissions. Another measure frequently leveraged nowadays is the economies of scale. The concept is that large capacity vessels are built in order to lower the cost per unit of cargo transported, as more cargo can be carried at once, thus effectively spreading fixed costs (including operational expenses such as fuel) over a huge volume of goods. From another perspective, larger vessels also lead to fewer voyages, resulting in lower total emissions. However, optimal volume does not inherently translate to a higher volume, requiring a careful examination of the specific needs of each area, in order to ensure that economies of scale do not become counterproductive.

Moreover, opportunities to further decrease carbon emissions should be sought in new international routes. Representative examples can be seen with the expansion of the Panama Canal or the Artic route. Especially for the latter, distance between East Asia and Northern Europe will be reduced by 27 to 40%. Nevertheless, regardless of the percentage reduction in voyage distance, human activity in areas such as Artic might contribute to a noticeable increase of emissions in the area, thus disturbing the local environment. Comprehensive research and protective actions should undertake in order to mitigate the damage.

Last but not least, improvement of port services as a component of supply chain optimization can significantly contribute to reduction of emissions. Minimization of the time each vessel spends in anchorage will considerably reduce the fuel consumption and the ship's emissions. Port authorities need to enhance communication with the operators of the vessels and optimize their operations, including the allocation of vessels in berth positions, the assignment of cranes and the cargo handling planning, thereby reducing the downtime and aimless manoeuvring responsible for increased emissions (Xing et al., 2020).

5.2.4 Other Operational Practices

Another operational measure that could be implemented with the aim to reduce emissions while at berth is the onshore power supply which supplies the vessel with electrical power, allowing the fuel engine to be turned down. The electricity that is provided can be produced from renewable energy sources that very low or zero greenhouse gas emissions, such as wind, solar, hydro and nuclear power. An effective plan for the periodic maintenance of the hull and propeller will contribute to the fuel consumption efficiency. Losses of energy have been reported to be in the range of 11% to 18% and have occurred due to increased resistances that fall within the range of 10% to 40%. Several tools can support the decision-making process for the timely maintenance, such as monitoring of the energy consumption, performance monitoring system, data-driven diagnosis system and experience accumulated from the past.

Last but not least, human effort and judgement is required from both the seafarers and the vessel's operators. There are two ways to strength their ability, with the first one being proper education and adequate training in order to enhance their knowledge in energy saving matters and raise awareness of the management and maintenance procedures. The second one depends on the ability of the shipping companies to provide the appropriate incentives so as to boost willingness (Xing et al., 2020).

5.3 Technical Measures

Each vessel faces resistance from both the water and the wind that develop from the speed of the vessel. The more the speed is increases, the more fuel is consumed and carbon emissions are released. It has to be mentioned that in actual sea conditions the resistance is even greater and the need for measures to be applied is essential. There are several commonly used technical measures that are widely applied nowadays regarding the reduction of resistance.

Optimization of the hull hydrodynamics is one way that will contribute to this end. In order for this to be applied, hull coatings that can reduce the fuel consumption up to 10% are used, while the use of paints with hydrogel coatings rather than biocides are preferred. In addition, the air lubrication method is thought to have been met with widespread adoption over the last few years, where a film of air on part of the hull reduces the vessel's resistance. In relation to other measures, the displacement plays an important role. The use of advanced materials, the proper structure of the vessel according to the design and the dimensions will contribute to the lightship weight of the vessel, that guarantees energy efficiency. Also, mechanisms to provide the appropriate design to the vessels in order to have low or no need of ballast water have been introduced. Furthermore, the propulsion efficiency will contribute to less fuel consumption, improving the wake distribution into the propeller and leading to the reduction of losses in the working area of the propeller.

5.4 Engine Retrofitting

On the one hand, given that vessels of the current fleet have not reached their mature age, shipowners will move towards retrofitting their engines. The aforementioned procedure is projected to last one year and a half on average, with the majority of the time consumed by the feasibility check and design & engineering. The first steps required are the identification of the technology or fuel that will be chosen, taking into consideration the operational factor, as well as the assessment of the Initial Design and Safety Statement by the class. Following this, detailed designs need to be approved by the class after risk assessments have been conducted. After the completion of the steps outlined above, expected to take around 17 months, the next phase will be the stage of conversion. This process lasts for 2 months and includes surveying the equipment being built at the yard and certification that its installation aligns with the approved designs. Finally, approximately one week will be needed for the vessel to conduct a sea trial in order to test and validate that the retrofitted engine works correctly and efficiently. If the trial is deemed successful, the necessary certifications from both the classification society and the flag state will be issued, allowing the vessel to operate legally and safely (Sharp-Patel, 2023).

Another aspect that needs to be mentioned is the conversion process of the fuel storage system. The old fuel system needs to be removed, while the old tanks will either get modified or new ones will be installed. Existing pipe system has to be modified as well prior to the installation of all the parts of the new engine and fuel supply system. Last but not least, the wiring system will get activated and the project will be ready to put into operation (Sharp-Patel, 2023).

Nonetheless, retrofitting a vessel's engine is a challenging process whose required complexity narrows down the total number of yards that possess such level of expertise. As Sharp-Patel reports, only 15 yards are capable to conduct engine retrofitting, amounting to 308 conversions per year, a number that cannot meet the demand. Certainly, the mentioned yards are also occupied for repairs as well so the lead time for a vessel will increase. Another factor that needs to be considered is that engine constructors will be simultaneously occupied by the construction of engines for newbuilding vessels so the supply of specific components may be further delayed (Sharp-Patel, 2023).

Another aspect that is considered to be essential is the human factor. Amendments have already been made by the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) in order for the seafarers to be properly trained and qualified in handling the new fuel and engine system. Unfortunately, LNG is the only alternative fuel that a more comprehensive framework has been established for, with the rest of the candidate fuels being in early stages of development. The risk that the crew members will undertake needs to be eliminated as the hazards are significant. For instance, the usage of ammonia as a fuel, poses risks to the crew from exposure to harmful substances and environmental factors like noise and vibration, requiring improved safety protocols and specialized training (Sharp-Patel, 2023).

5.5 New fuel-efficient vessels

On the other hand, as the 2040 is approaching and the use of fuels produced from renewable energy becomes a necessity so that the defined carbon intensity limits are met, the approach of investing in new fuel-efficient vessels will be more attractive (Christodoulou and Cullinane, 2022). However, the implementation of these investments poses significant challenges that need to be addressed. The primary issue is the high capital expenditure required, as the cost of new vessels is inherently very high, and will rise further with the necessary technological modifications for using alternative fuels. Additionally, fuels such as hydrogen which demand both specialized and larger solutions to meet the fuel demands of a voyage, will increase the construction cost (Kishore et al., 2024; Patel and Singh, 2023). As for operational costs, they will rise since the cost of alternative fuels is notably higher than the cost of conventional fuels (Christodoulou and Cullinane, 2022). Another factor that at the moment is considered determinant to the decision-making process with regards to investments is the risk. The uncertainty over the reliability and performance of the new infrastructure, the fuels usage and availability are critical factors that hinder the reduction of the risk (Masodzadeh et al., 2022).

Technical and operational maturity are needed so that the investments in the new technology and fuels can become more feasible (Christodoulou and Cullinane, 2022; Kishore et al., 2024). Another challenge is that regulatory pressure could lead to the use of transitional fuels like biodiesel, since more prominent fuels like ammonia and hydrogen will be delayed due to availability issues and inadequate safety measures (Patel and Singh, 2023). Last but not least, the fuels that currently are more likely to be used may not be the ones that lead to the zero emissions target in the 2050. For example, the selection of a LNG fueled vessel will not remain a sustainable option that complies with the regulation after 2040, and further investment in an ammonia or hydrogen fueled vessel will ultimately be required (Christodoulou and Cullinane, 2022; Kishore et al., 2024).

6. Alternative Fuels

In the paragraphs below, the potential marine fuels that in a Well-to-Wake manner their emissions are limited according to FuelEU Maritime regulations will be mentioned.

6.1 Low Carbon Fossil Fuels

The emission reduction percentages regulated in FuelEU Maritime Initiative “permit” the use of fossil fuels only for the first few years of its implementation. The only two that seem to be compatible with the limits imposed by the regulation are Liquefied Natural Gas (LNG) and Liquefied Petroleum Gas (LPG). The main advantages of the aforementioned are the readiness of infrastructure in ports in order for the vessels to safely be supplied with bunkers and the availability of the fuels which is more secure at the moment (Christodoulou & Cullinane, 2022).

6.1.1 LNG

LNG is one option that especially for the upcoming years will be preferred but as will be justified below will only be used as a transitional fuel. LNG has less content of carbon compared to conventional fuels and it reduces significantly the sulfur emissions. In the temperature of -162^{o}C and below NG is in its liquid form enables simpler storage and transportation. Nevertheless, LNG’s low energy per unit volume requires at least the twice storage capacity. In addition, specialized engine and storage will be needed like double-walled fuel tanks and pipes and high capital investments are required (Solakivi, Paimander and Ojala, 2022). In comparison with the fuel oil emits 23% lesser CO_2 on board the vessel and has the potential for approximately 20 to 30 percent reduction of carbon but regarding its cost, even when the taxes will be actively used the price of LNG will continue not to be competitive. Another concern is the that LNG in well-to-wake basis releases methane, a greenhouse gas that may not be yet regulated from IMO but all indicate that soon will be 80 times more harmful to global warming than carbon thus, the reduction of carbon dioxide is decreased to 15% (Sharp-Patel, 2023; Solakivi et al., 2022). Moreover, if we consider the current stage of infrastructures and technology, retrofitting will cost to a company for a large vessel at least 9 months and 35 million US dollars (Sharp-Patel, 2023).

6.1.2 LPG

On the other hand, LPG is the fossil fuel that seems to be used more from 2030 as it contains 15% of CO_2 emissions (Christodoulou & Cullinane, 2022). LPG can be easily transported and stored as liquid with approximate pressure of 10-20 bar and in addition to that any major deterioration is not noted over long periods in the liquid state (Yeo, Kim & Lee, 2022). LPG is already used in vessels that carry the fuel and their engine systems appear to have striking similarities to ammonia-fueled engines. In view of the latter, as the years elapse and we approach zero-carbon targets, retrofitting the engine will occur with greater ease (Sharp-Patel, 2023). Moreover, LPG release less damaging emissions and as a result it protects the engine by 50% compared to conventional fuels. However, when a conventional fossil-fueled engine is converted to a LPG one issues may arise with regards to vibration and corrosion. In terms of carbon emissions reduction, LPG decreases GHG emissions by 17% in comparison to HFO an MGO, including the methane slips. It is evident that dual engines using diesel and LNG are more efficient concerning the power and torque at average and full load levels and they also emit lesser nitrogen oxides and hydrocarbon. LPG has lower ignition temperature than LNG but due to its density-driven pooling it has to stores in properly ventilated tanks. In addition, LPG contains propane which in cold climates should be more in quantity as their boiling temperature is lower. It is essential to mention that LPG imports has been increased by 18% only in two years in international basis (2016-2018) and there are no markets worldwide that LPG is not supplied. Finally, existing infrastructure for LPG as cargo can be used for the supply of LPG as fuel and new facilities can be constructed with lower costs in comparison to LNG ones, making the investment more appealing despite the lower LNG's price as fuel (Yeo et al., 2022).

6.2 E-fuels

Electrofuels or e-fuels are considered the hydrogen, the ammonia and each fuel with e-prefix. E-fuels are produced from dioxide of carbon source and hydrogen obtained from the electrolysis of water. E-fuels are deemed to be carbon-neutral but that statement is contingent on the carbon as feedstock and the use of renewable energy for its production (Solakivi et al., 2022). On the one hand, apart from their significant advantage of carbon neutrality, e-fuels have still some notable techno-economic issues to face. One of them is the cost of production in comparison with the conversional fuels and their relation with electricity price. In addition, if the e-fuels are entirely installed in the world's fleet then the demand for electricity will be increased 2 to 3 times. The latter mentioned increase requires a significant advancement in electricity sector as not only shipping will have enhanced needs for electricity but other industries as well (Lindstad et al., 2021;

Solakivi et al., 2022). Other costs that are worrisome are the cost of capture of carbon and the cost of electrolysis (Solakivi et al., 2022). On the other hand, e-fuels have proven that in comparison with ammonia and hydrogen have substantially less emissions while they are produced. Furthermore, e-fuels based on fossil fuels such as e-Diesel, e-Methanol and e-LNG are more competitive regarding their cost as they are less dependent on electricity contrary to e-Ammonia and e-Hydrogen which are preferred due to their energy efficiency (Lindstad et al., 2021).

According to, Lindstad et al. (2022), the pathways that can be feasibly implemented in order to achieve EU goals with e-fuels are described below. In newbuilding vessels, the preferred fuel would be e-Hydrogen that requires whole different infrastructure. A more conservative strategy which avoids economic risks and capital expenditures is to continue to operate with diesel and when the margins are narrowing to use e-Diesel as drop-in fuel. Another path could be to retrofit the current engines in order to use LNG which is currently used as a fuel and then proceed with a transaction to e-LNG. Last but not least e-Methanol and e-Ammonia will lead to large initial expenditures with the required investment but they are presenting higher flexibility concerning the fuel choice in mid-term and long-term period.

6.3 Methanol

Methanol is an alcohol-based fuel that can operate as single fuel or used as drop-in fuel in the order of 20% content with fossil fuels used at the moment with straightforward adjunctions to the engine. (Solakivi et al., 2022). As a matter of fact, big shipping companies have been already operating their vessels with methanol fuel engines for a couple of years (McKinlay, Turnock, and Hudson, 2021). Methanol-gasoline and methanol-diesel blends have been commercialized with success but with regards to the latter, if the content of methanol is low then the carbon emissions are not sufficiently reduced (Xing et al., 2021). The feedstock for the production of methanol is mainly natural gas and coal at the moment which due to the consumption of substantial energy in the process and because they remain compatible fuels they release a great amount of emissions. However, feedstock for methanol can also be biomass and agricultural waste. Another interesting method for the production of methanol without emitting is supply of dioxide of carbon, hydrogen and electricity from renewable sources. Nonetheless, the aforementioned method is not sustainable as a consequence of large energy inefficiencies (McKinlay et al., 2021).

Methanol's form in ambient pressure and temperature is liquid so the bunkering time would be kept to a minimum, its transportation and storage would not cause any particular problem except the excessive space needed for storage owing to methanol's lower energy content per volume in comparison with HFO. The latter issue can be solved with adjustments in the current double hulls of the vessels (Solakivi et al., 2022; McKinlay et al., 2021). The production of methanol has been already taking place in big quantities for other industrial purposes but still the required methanol is estimated to have an increase of 859% compared with today. Thus, technological improvements need to be taken but as far as it concerns the produced capacity but also a more sustainable pathway as coal and NG as raw materials will not comply with the requirements of the regulation. Nevertheless, even in that case the reduction of emissions is around 25% without release of sulfur (Solakivi et al., 2022; McKinlay et al., 2021). The latter does not apply to nitrogen oxides as well as with the nitrogen from the air can still be formed but compared to HFO NO_x emissions the percentage is 40 times down. In terms of carbon emissions, the emitted amount is similar to LNG ones and the capture and storage of them would be considerably simpler (McKinlay et al., 2021).

In reference to the technical aspects, methanol's low flashpoint eases the ignition, being easier than HFO, LNG and ammonia. Moreover, methanol can be extinguished with water and can be contained without significant efforts due to its reduced heat output. Methanol has also biodegradability and is water-soluble and as a result will not have catastrophic consequences if spills in aquatic environment occur. However, with regards to high toxicity to humans, especially in case of ingestion, additional measures should be implemented and enhanced monitoring procedures should be followed. The previously mentioned concerns may lead to financial uncertainties and excessive engineering research but factor the technology needed regarding safety is deemed as well-developed (Solakivi et al., 2022; McKinlay et al., 2021). Last, though not less important is the comparison made regarding the cost of retrofitting existing engines, where a methanol transaction is considered less expensive and demanding than an LNG one. The above statement does not apply to new buildings installations (Brynolf, Fridell and Andersson, 2014).

Renewable methanol on the other hand is also an alternative solution that has been evaluated and has as feedstock forest and agricultural residuals, residential waste and black liquor following the same procedures as methanol with the difference that if green energy is used for its creation then renewable methanol can be deemed carbon-free. One way that renewable methanol can be produced is called Power-to-Liquid (PtL) where hydrogen electrolyzed with electricity from renewable energy and carbon dioxide captured from other procedures or industries, with the assistance of a catalyst they produce the final synthesis. Another way could be the use of glycerol which is a derivative of biodiesel's production. The main advantages of renewable methanol are that both ways that mentioned before have been operated and commercialized and the availability in many major ports around the world. However, the cost of production of renewable methanol compared to conventional methanol is increased by 1.5 to 4 times (Xing et al., 2021).

6.4 Biofuels

Biofuels can be found in liquid or gaseous form and its production can be conducted with several feedstocks production methods. However, the latter may cause issues regarding the amount and variety of emissions which depends on the feedstock used. Biofuels are considered the non-fossil fuels that the industry is more prepared to apply in its vessels but no without their challenges. One of the biggest concerns is the concept that feedstocks are preferred for the production of fuels from the use as food production. Already governmental bodies have established guidelines but the issue should be legislated not only for the human and animal feed but also for carbon expansion reasons handled by primary forests.

Another issue is that biofuels do contain carbon like all the other fossil fuels but they emit only onboard the vessel while combustion is taking place. Therefore, it is misleading for the biofuels to be deemed as zero carbon fuels because they absorb carbon while their growth. In addition, different industries will also have needs for biofuels and availability will be tested. High demands for biofuels aviation have but if compare the amount that theoretically will cover all fuel consumption for the whole fleet, the requirement is greater. Despite all the above, the economic and technological limitations are both considered the first barriers for the biofuels to be commonly used. Biofuels provision in the environment is noteworthy as the decrease of carbon pollution is from 60% up to 100% and the sulfur emissions are viewed as low, thus any obstacle should be addressed (Solakivi et al., 2022). Below will be reviewed the different biofuels.

6.4.1 Bioethanol

The main categories that constitute resource of ethanol are starchy and sugar, agricultural residuals and algae. Bioethanol can be produced through fermentation of saccharides or hydration of ethylene while its main use is in internal combustion engines. From all the biofuels is the most available currently in the market though 85% of bioethanol production is taking place in USA and Brazil, so it could be characterized as unevenly distributed. In terms of storage, environmental temperature and pressure does not require large amount of capital expenditures neither onboard the vessel for storage and transportation facilities nor with regard to bunkering process. However, there is the need for additional storage space as density of bioethanol is bigger than the one of fossil fuels and the materials that will be used its construction require to be tested as bioethanol can be corrosive with the commonly used materials. Ethanol can be used in gasoline fueled engines with small modification only if the content of ethanol is high on order of 85%. Despite that, ethanol is not helping with the ignition of the engine due to its low cetane number thus it cannot be used as the only fuel (Xing et al., 2021).

6.4.2 BioDME

BioDME is in gas state if it is under atmospheric conditions, similar to LPG, but it can be in liquid form in low temperature (under -25°C) or high pressure (above 25 bar). BioDME's production can be conducted with the assistance of a catalyst either with the synthesis of syngas from biomass or with the dehydration of methanol which is currently preferred. The primary feedstock that is used is NG, coal, oil, biomass, wastes or even CO_2. A project is carried out, called SPIRETH, where methanol is converted onboard the vessel and DME is used as fuel to auxiliary diesel engines as in general a few changes need to be made in that kind of engines in order DME to be feasibly used. Another advantage of bioDME is that compared to diesel has higher engine efficiency as the auto-ignition point is lower and the cetane number bigger and when it comes to emission release, bioDME shows a reduction in nitrogen oxides as well. In terms of transportation and storage bioDME is analogous with LPG and ammonia, less demanding than LNG and hydrogen but more complex than bioethanol, methanol and MDO. Nevertheless, the need for double storage space in relation to diesel cannot be disregarded but facilities can be installed simpler and are more inexpensive than LNG and hydrogen. Further to that, the noise production is pretty decreased the level of toxicity is zero and biodegradable. Last but not least, bioDME cannot meet the level of efficiency of a methanol or ethanol engine in terms of combustion, greater production expenditures and more well-to-wake carbon emissions (Xing et al., 2021).

6.4.3 Biodiesels

Biodiesels can be easily used as drop-in fuels with small or no modifications in current diesel engines especially for the liquid ones, which can be confirmed from the leading marine engine manufacturers that from content of biodiesel of 5-30% or even 100% the above statement can feasible (Xing et al., 2021; Solakivi et al., 2022). Therefore, biodiesels will be used in dual-fuel engines by blending them with diesel, methanol or gaseous fuels with low content of carbon. Biodiesels can be produced from renewable energy leading to a reduction of emissions from the start of their being, though nitrogen oxides emissions are considerably higher. However, their increasing demand of land and water resources will be a challenge. Nonetheless, a greater challenge that biodiesel will have to overcome is the complex procedure that must be followed onboard the vessel in order to be used as well as the high cost of the facilities that will be needed.

In addition, biodiesels also need to be processed in order to be reformed and purified before the final use onboard increasing the total costs. Biodiesels have favorable ignition traits and emissions efficiency, but all the same lower level of volatility, poor stability, combustion performance and decreased oxidation stability. The first category of biodiesels is called FAME (Fatty Acid Methyl Ester) which can be created from more than 350 oil-containing crops. In greater detail, FAME is produced from consumable or non-consumable plant-based food oil, waste oil and animal fats which they react with short chain alcohol using a catalyst or not. After the reaction the derivatives will be FAME and glycerol. The most simple and cost-effective production of FAME maintaining the quality of biodiesel first-rate is the transesterification with methanol as alcohol although several methods are applicable.

The second biodiesel category has as base the biomass i.e. HDRD (Hydrogenation-derived renewable diesel) that is produced from the same oil and fat products as FAME but through hydrotreatment and F-T (Fischer–Tropsch biodiesel) that is produced from coal or NG to liquid fuels. Both derivatives have one main drawback, the capital cost that must invested in the infrastructure is significantly higher than the one of FAME and the use of transesterification process. Despite that, especially HDRD has a more extensive range of feedstock as it can be used agricultural and forest residuals, pulp and paper residues if they are processed before the hydrotreatment. Furthermore, the current technology used for the refining of diesel and the equipment that the process is conducted are the same as diesel production. In addition, in comparison with FAME, the release of nitrogen oxides is decreased and better storage stability (Xing et al., 2021).

6.4.4 BioLNG

BioLNG can be considered as the Renewable Natural Gas (RNG) produced from biomass. The used feedstock for its production can be from agricultural and residential waste to bioenergy crops which contain proteins, fats, sugars, cellulosic and hemicellulosic fibers. BioLNG has similar t properties to LNG so for example the transportation and storage requirements are the same. However, the higher cost of bioLNG, the limitations in distribution in ports and the low volume of production are only some of the challenges bioLNG has to overcome (Xing et al., 2021).

6.5 Ammonia

Ammonia is considered one of the most suitable fuel pathways. Starting with its structure which is carbon and sulphur free as its components are nitrogen and hydrogen. Additional, ammonia can be produced both from fossil fuels and renewable energy such as wind and solar power, being able to have zero contribution to global warming in wake-to-tank. In comparison of hydrogen, another promising fuel that is described below, ammonia's production, storages and transportation are more cost efficient. (Wu et al., 2023). In terms of storage, ammonia requires the temperature of -33ºC and environmental pressure in insulated tanks. Moreover, the high-octane energy density of ammonia enables it to be used in internal combustion engines and fuel cells with small retrofits and the contribution of an ignition fuel (Solakivi et al., 2022).

Another comparison can be made with gasoline as the engine can be twice more efficient or more with ammonia as a fuel by increasing the compression ratio. In addition, ammonia can be used as air conditioning system due to its ability to absorb heat when transforming from liquid to gas, without incurring any further cost as heat is absorbed. Furthermore, as for already existing gas stations it would be easier to convert them to stations for liquid ammonia (Wu et al., 2023).

When it comes to fire, ammonia has a high autoignition point and low flame velocity so there is no significant risk presented (Solakivi et al., 2022). However, while the risk of explosion is lower than with other fuels this is only the case in its solid state. The conversion of ammonia should be made with heating reaction or hydrolysis, otherwise the possibilities of explosion in liquid form are high. (Xing et al., 2021). In spite of its positives, there are still some challenges that need to be tackled such as the increased toxicity for humans and aquatic environment and its corrosive property that may lead to leakage in storage tanks or pipes. Another drawback that should be mentioned is the excessive amount of nitrogen oxides (NO_x) that are produced in combustion (Solakivi et al., 2022). As for infrastructure, it may easily modifiable but more technological advancements are required in order to be appropriate for bunkering operations as in the current state research shows that more time is consumed for its completion compared to MFO (Yang and Lam, 2023).

6.6 Hydrogen

Hydrogen holds the position of the most promising alternative fuel as the emissions during the combustion are zero. In addition, it can be easily produced from renewable energy as from electrolysis the water breaks down to hydrogen and oxygen and the electricity in order to be conducted for the above procedure can come from wind or sun. Therefore, this green hydrogen, as it called, can meet the target of decarbonization from the production to the use on board the vessel. However, the cost of green hydrogen is significantly higher than the one of gray and blue hydrogen which emphasizes the need for technological improvements. Even so, hydrogen has the highest performance from any other alternative option of fuel used in engine. (Wu et al., 2023).

As mentioned before, hydrogen can be found in water in compound form so the availability is abundant. Nonetheless, an important amount of energy is lost in order for this conversion to be successfully completed and the hydrogen to be able to use as a fuel (Solakivi et al., 2022). The main supply of hydrogen can be produced with the steam reforming of methane which is viewed as an efficient and mature technique, having an annual capacity of 50 million tones but still not without the emission release (McKinlay et al., 2021). It is essential to mention at this point that one of the major issues that come up against hydrogen is its storage.

In more detail, hydrogen is in gas form in ambient pressure and with its low volumetric energy needs to be stored compressed at pressure of approximately 300 bar or in very low temperature in liquid state on the order of -253°C. Facilities which will store hydrogen require to be from insulating material and extremely specialized, so from an economic perspective the cost of the investment and the operational cost will be high. Additionally, due to hydrogen's low volumetric energy, the required tanks for its storage will be four to eight times bigger in comparison with fossil fueled ones. As the energy needed is high, hydrogen is considered more suitable for short distance routes, with some indications that longer ones with the use of internal combustion engines. As far as toxicity, hydrogen is considered nontoxic but leakages should be deal with caution as they can be hazardous. Despite that, it can be classified as explosive and flammable with high flame speed (Solakivi et al., 2022).

Another scenario that has been tested is the use of a mixed fuel with ammonia and hydrogen. Some of the advantages of that scenario can are quite interesting. The mixture of a small amount of hydrogen with ammonia, approximately 1 to 9 ratio, will accelerate the combustion process. Moreover, another case could be a mixture with higher content of hydrogen in ammonia. Ammonia can be dissolved by combustion or oxidation without any significant environmental footprint. Also, ammonia can be used simultaneously as a fuel but also as a source of hydrogen. However, if the percentage of hydrogen is high, i.e. 30%, this will lead to flashbacks and if the content of ammonia is bigger that 30% then the flame will lead to blow-off (Wu et al., 2023).

6.7 Renewable Energy Sources in Propulsion

6.7.1 Electrification

The electrification of the shipping sector constitutes a pathway that can lead to the accomplishment of the emissions neutrality targets. There are three ways that electricity can assist with the propulsion of the vessel. The first is the hybrid vessel which is using conventional fuels such as diesel in an internal combustion engine and also has an electric motor with battery storage. The above technology can be used simultaneously and separated as well (Nguyen et al., 2020). The second one is the plug-in hybrid vessel. The third one and most promising is the full electric which will use energy only from storage thus, the emissions will be zero if the stored energy was from renewable sources.

The battery that seems to be more suitable concerning its efficient and economic aspect is the Lithium-ion battery (Li-ion). The advantages of the battery-powered vessels are the zero-emissions operating, the mature technology of the batteries in transportation and the safety of the energy supply. In addition, research on Lifecycle Cost Assessment in vessels using several marine fuels and battery-powered vessels has indicated that the latter are both the least emission pollutant and also the most cost-effective option. However, the drawbacks are evenly significant as the period that a vessel can operate without recharging is very limited with regards to other alternative and fossil fuels as the capacity of the batteries on board the vessel are small. The operators will have to arrange may stops along the voyage in order to charge the batteries which will not only extend the time of the journey but also will include delays due to the demand of the service. As the situation stands now, the battery-powered vessels are preferred mainly in short-sea shipping but the possibility of development of metal-air batteries will make feasible the long-distance voyages with batteries. Another issue is the absence of the appropriate charging infrastructure in the most of the ports globally (Mimica et al., 2022).

6.7.2 Wind Energy

The wind energy was one of the first propulsion systems in the history of sailing. In an effort to reduce carbon emissions and simultaneously reduce the economic risk from the increased fuel prices the wind power has been an attracted solution to many shipping companies. It has been developed a wide range of wind-assisted ship propulsion products (WASP) which race categorized into wind turbines, soft sails, rotors, suction wings, rigid sails, towing kites and hull sails. The WASP has shown great results concerning the energy-efficiency of the vessels. They can be used in order to maintain the same speed of the vessel but with reduced engine power and reduced fuel consumption or they can increase the speed while maintaining the same energy power. However, the capital expenses are considerably high and there is still uncertainty in the technology regarding the reduction of the fuel consumption thus, it is not largely implemented (Chou et al., 2021). In relation to uncertainty, technological improvements have occurred which can both provide the wind direction in order to be optimized the system and collect the maximum power and also offer a power prediction with regards to the weather (Li and Tang, 2024).

6.7.3 Solar Energy

Solar energy is considered a clean energy as it can assist in the propulsion of the vessel with zero emissions reinforce the effort to meet the requirements of the regulations. In relation of the latter, solar energy can be also be cost-efficient for the company as it decreases the operational expenses from the decreased utilization of the fuels (Rutkowski, 2016). Solar photovoltaic (PV) is a technology that is considered mature so the implementation can be proceed easily in the short term (Yang et al., 2020). Research has indicated that the annual reduction that can be achieved in carbon oxides is approximately 2-5% in bulk carriers' sector. The solar panels can be classified in the following three categories as per their construction material: monocrystalline, polycrystalline and amorphous silicon cells. The most preferred are the first one as they are the most efficient while the polycrystalline ones are selected often for the less expensive manufacture. The average cost of a solar module to be installed is $3000 per kilowatt. In certain periods, the solar power may exceed the amount of needed energy so the surplus of energy cab be stores in batteries (Nyanya et al., 2021).

However, the greater obstacle of solar energy production is the extensive space that requires in order for the solar modules to be installed reducing the practical aspect of cargo vessel and in some case the functionality can be minimized so as the unshaded area to be as limited as it gets. Nevertheless, the solar energy appears in systems along with wind energy such as the use of rigid sails. In that case, the system stores the energy in batteries, utilizing in the best manner the renewable energy on board the vessel and use the preserved energy in not favorable weather or in bad weather where the rigid sails can be stored (Rutkowski, 2016). Another way that solar energy can contribute in emissions reduction is the development of a hybrid solar-diesel system on the vessel. The optimization of the energy efficiency of the solar panels and their combination with diesel generator is a primary matter that have to be faced in order to be economically efficient concerning the handling of the fuel consumption. The above method can mitigate the GHG emissions and save energy but in an excessive use can be less effective. More specifically, when the maximum use of solar power is injected into the system the diesel engine is underperforming. The reference low performance of the engine leads to deterioration, damages the engine parts and as a result shortens the lifecycle of the engine (Yang et al., 2020)

6.7.4 Nuclear Energy

Nuclear energy use in commercialized fleet is considered one of the most promising pathways for the zero-carbon objectives of the EU. The nuclear energy has only been used from a few countries in military vessels except some rare cases such as icebreakers which used for civilian purposes. Nevertheless, many shipping companies are currently on research process in using nuclear power in the propulsion system of their fleet (Wang, Zhang and Zhu, 2023). Nuclear energy could be used directly for the propulsion of the vessel or support more indirectly with the production of the fuel.

On the one hand, there is the case where the nuclear power is used for the propulsion then there are installed on board the vessel small modular reactors with space-efficient designs. The main advantage is that the relevant reactors produce electricity with zero emissions with no need for storage space with batteries. In addition, the technology used is considered mature so, it can be more easily implemented. Another advantage is that unless there are crew or damage related reasons there is no need for intermediate stops for refueling thus, the operating time is increased and the voyage time is reduced (Bhattacharyya, El-Emam and Khalid, 2023). However, the obstacles are of great significance so they cannot be disregarded. The most important barriers are concerning safety issues such as the effect that a collision, a leakage, a damage in the mechanism of the unit or an explosion could have in the environment and to the seafarers. In reference to seafarers, their training must be very extensive and to be given due importance with the aim to handle emergency situations and daily tasks in the proper most way (Bhattacharyya et al., 2023; Wang et al., 2023). Moreover, it must be defined an exclusion zone around of the vessels and floating power plants for safety reasons which will lead to advanced marine traffic requirements and avoidance of narrow straits. In addition, the insurance expenses for the reference vessels will be noticeably higher as per the increased risk they assume. With regard to the risks, they are expected to show a rise in relation to piracy as the possibility of sabotage is bigger. Last but not least, the required percentage of highly enriched uranium fuel, that will have to be more than 20%, will increase the risk of proliferation.

On the other hand, nuclear energy will support the production of green fuels in land-based power plants. In that scenario, there is no need for nuclear reactor on board the vessel. In this way, the risk arises from nuclear energy is mitigated at least on board the vessel but the need for extra space for batteries rises. Furthermore, new infrastructure for nuclear power plants and storage for the produced fuels, especially near the ports and coastal areas, will have to be deployed. Also, for the fuels which need CO_2 in order to be formed, capturing technologies have to be created in a commercialized level as well. The most promising fuels for the achievement of zero emissions, as mentioned in previous paragraphs, and can be reinforced in their formation procedure by nuclear energy are green hydrogen, green ammonia, green methanol and sustainable biofuels. The necessity of technology development is one of the most crucial matters, so as to be created the safest reactors, primarily for the ones that will be installed on board the vessel (Bhattacharyya et al., 2023). Another issue that need to be addressed is the international regulatory framework, which have to be amended as there are many insufficiencies and environmental challenges that have not been regulated from the current requirements. In the aforementioned regulation, it is essential to be defined the shipping corridors that vessels which having on board nuclear energy need to follow for the safety of the environment, the inhabitable areas and the rest of the vessels (Bhattacharyya et al., 2023; Wang et al., 2023).

7. Implications

The FuelEU Maritime Regulation will introduce significant implications in the shipping sector and the impact will not be limited only within EU's trade or ports, but will also affect the whole maritime industry (Hughes, 2021). In an effort to gather the implications the initiatives will have on the shipping sector, a PESTEL or PESTLE analysis was conducted. PESTEL is a tool which assists with the macro-environmental analysis of the factors affecting a sector or business. PESTEL can be notably useful when applied to an environment with upcoming changes or newly introduced elements. The analysis is categorized into 6 different levels, namely political, economic, social, technological, environmental and legal (Dathe et al., 2022).

7.1 Political

The FuelEU Maritime Regulation reinforced the regulatory system regarding the reduction of GHG emissions, contributing to the IMO's strategy aiming at carbon neutrality. The international regulatory bodies will consider developing corresponding regulations, in line with the FuelEU, and may proceed with the enforcement of global measures (Hughes, 2021). The initiative will encourage governments to apply pressure for the increased adoption of fuels like biofuels and to provide incentives for their use. Regulatory bodies, like the IMO or the EC, will introduce policies in order to increase the demand for relevant fuels that may be beneficial - to a varying degree - for each country (Mallouppas et al., 2023).

Moreover, regulatory requirements stemming from the EU regarding emissions reduction will directly influence the infrastructure of ports. This international agreement will impact the business sector of ports, as the operational strategies that will be followed by each port will lead to favoritism among ports from the shipowners. As a result, a competitive landscape will emerge in the sector and may shift the balances (Council of the European Union, 2021). In addition, given the fact that the EU will try to ensure that the fuels sold outside its ports will be according the standards that have been established, non-EU States may proceed to assume that the EU is attempting to control and direct the marine fuel supply industry. As a consequence, there is a potential for political tension to arise between the European bodies and foreign governments, leading to possible diplomatic friction (Hughes, 2021).

7.2 Economic

Economic implications are very important for the feasibility of the FuelEU Regulation, as the future of sea transportation and shipping companies depends on their financial success and stability. Shipping companies themselves are not the only ones to be economically affected, as both the trade routes and the freight rates will be impacted by the shift in shipping patterns. The impact of the regulation will be experienced by the final consumers as well, while technology companies will be among the beneficiaries.

7.2.1 Shipping Companies

On the front line of the impact of the regulations are the Shipping Companies, as many actions need to be taken in order for them to comply with the new rules. Large amount of money will be allocated for the investments in order for the company to choose the strategy that seems to be more feasible to implement, in a way that not only follows the established rules but also considers the company as an economic entity with liabilities and the need for profit margin (Christodoulou and Cullinane, 2022). Despite that, alternative scenarios highlight the necessity of establishing a new and promising research and development department, as the margins for emissions will be progressively narrowed down each year, and the options for viable fuels will be increasingly limited. (Lagouvardou, Psaraftis and Zis, 2022).

Market Based Measures (MBMs) are expected to be introduced after 2030, in order to support the relevant R&D. There is also a concept that has been proposed, advocating for the allocation of revenue accumulated from the emissions release penalties to either port infrastructure or R&D (Masodzadeh et al., 2022). The MBMs can also support the uptake of several fuels as economic initiatives will have a favorable effect on the investment adoption (Mallouppas et al., 2023). Nevertheless, most of the capital will be needed for investments pertaining to retrofitting the old engine in order to use an alternative fuel or / and building new eco friendlier vessels that use fuels that have never been used for the propulsion of vessels before (such as ammonia and hydrogen). Both ways lead to large spending of company assets and diminish profits, especially in case of engine retrofitting that requires the vessel to be off hire for several months, thus suspending its operational capabilities and resulting in income loss (Sharp-Patel, 2023).

Another notable economic obstacle is the cost of training the seafarers and the engineers to properly and safely use the new equipment and to get acquainted with the new procedures

(Masodzadeh et al., 2022). Regarding administrative and enforcement costs, expenses will be incurred for the additional information required to ensure compliance, as well as obligations related to audits and inspections. Moreover, a notable amount will be given in order for the vessels to be verified and approved (Council of the European Union, 2021).

Another aspect that needs to be mentioned is the risk that shipowners will have to undertake. The selected technology may turn out to be less profitable than the one chosen by the competition; or even if it works in the beginning it may lead to a non-sustainable future for the company a few years down the road (Zhang, Bao and Ge, 2021). The operational costs will also be affected by the transition to alternative fuels, as not only their price of is greater and more volatile compared to the conventional fuels, but also heavier taxation will not be completely avoided, since some of the alternative fuels are in fact not pollutant-free (Mallouppas et al., 2022; Tsvetkova et al., 2024). However, the initiative promotes the use of alternative fuels, which, as their adoption becomes more widespread, will lead to economies of scale that reduce the initially anticipated price. Moreover, non-scheduled port calls or smaller vessels that may need to stop several times for bunkering will encounter increased costs, as logistics issues may occur concerning the availability of the compliant fuels (Hughes, 2021).

7.2.2 Freight Rates and Trade

As costs rise due to research and investments, the company will need to increase freight rates to maintain profitable operations. The operational cost of each vessel will increase, making the expenses of transferring goods greater for cargo owners and charterers, as a premium of 11% is expected to be charged just to cover the cost of a retrofitting (Sharp-Patel, 2023). As a matter of fact, the prevailing non-stability will lead to volatility in freight rates caused by uncertainty around fuel availability and technological adoption speed, and consequently shipping demand will be affected. Moreover, trade may be allocated differently, as transporting goods by vessel from distant locations will be restricted, even if the sales cost is significant lower. Trade with larger vessels will become more challenging, as smaller vessels will need less energy capacity or will pollute in a more cost-effective manner. Buyers of cargo might shift towards domestic suppliers, while global supply chain and trade volumes are likely to be disrupted (UNCTAD, 2021). However, it is expected that the global fleet will be divided into a two-tier market, where there are vessels that abide by the initiative and the vessels that do not. As a consequence, this will shift the balance of the trade market dynamics, as the costs and penalties will differ for each category, vessel or shipping company (Hughes, 2021).

7.2.3 Impact on Other Stakeholders

The final consumers of the goods will bear the cost of the changes that will occur in the industry from the regulations. Rises in the cost of common goods will emerge, if the increased freight rates are not absorbed by other market participants. Marine technology and equipment suppliers will we directly affected by the regulation, as the necessary developments required for the successful implementation of the initiative will enable these companies to gain a competitive advantage over their competitors. Concerning fuel suppliers, the cost impact will be neither significant nor negligible, as their trade will not be limited to EU ports. Additionally, there will be costs associated with fuel certification. National administrations will be affected by the increased time spent on audits and inspections required to assess the overall compliance with the FuelEU Maritime Regulation. Also, an initial expenditure will be necessary to acquire a reporting system (Council of the European Union, 2021). Moreover, as a result of the regulation impact on EU ports, intra-EU trade will be degraded, as products from extra-EU ports will be more competitive (Mallouppas et al., 2022).

7.3 Social

Organizations ESG reports will benefit from the regulation since it will draw attention to alternative fuels usage, showcasing a greater commitment to environmental awareness. The reputation of the companies will be enhanced by the increased adoption of alternative fuels, making the adoption of greener energy practices more favorable (Mallouppas et al., 2023). In addition, the enforcement of the legislation raised social and public awareness of the climate crisis, which consequently led to an increase in customer requirements. (Mallouppas et al., 2022). Furthermore, the workforce implications with regards to the seafarers need to be mentioned. The initiative indirectly affects the seafarers due to the fact that engine maintenance and bunkering procedures will be altered, therefore introducing the need for them to be properly trained and educated. Particularly, with respect to their safety, they are vulnerable to a number of risks following the adoption of new technology or the switch to alternate fuels. Exposure to health risks associated with both the nature of fuel themselves and the processes surrounding them have risen social concerns, making the need for adequate training crucial (Sharp-Patel, 2023).

7.4 Technological

The FuelEU Maritime Regulation will affect the direction of the development towards green energy (Tsvetkova et al., 2024). However, apart from setting carbon emissions limits, the initiative does not provide any particular guidance regarding the direction the shipping companies need to follow. The options for alternative fuels and different technologies that are promising reduction in emissions are many and the uncertainty concerning the technological path that have to be pursued is high. The regulation caused the need for research and development in multiple directions. The rationale behind this is due to the existence of many alternatives that have the potential to meet the requisite limitations at various stages of the regulation, not only in terms of the legislation's needs but also for a different purpose, such as transitional fuel. Except for the alternative fuels, niche technologies like different vessel designs, new engines and novel propulsion concepts will be developed. Another critical parameter that will affect the technological improvement is the constraint of limited capital allocation capacity given the need for rapid changes (Mallouppas et al., 2022).

Ports are indirectly affected as they will have to proceed with technological advancements for the vessels to be able to comply with the regulation. The OPS facilities will have to promptly be developed as the regulation compels passenger and containerships to be able to connect with onshore electricity by 2030. The bunkering infrastructure should likewise be improved in order for it to be able to provide the forthcoming alternative fuels, such as hydrogen and ammonia. New technologies are expected to be introduced for both the provisions of bunkering services and for the completion of the aforementioned procedure with respect of the emissions reduction policy (Council of the European Union, 2021).

7.5 Environmental

From an environmental perspective, the FuelEU Maritime Regulation will bring significant changes in the environment as its aim is to eliminate the greenhouse gas emissions, targeting the neutrality of the European Economic Area and reduce the environmental and climate burden. Nevertheless, the regulatory targets are going to be met only if the regulation is properly implemented and the potential of the alternative fuels is realized (Mallouppas et al., 2022). In relation to shipping companies, given the fact that they will have to reassess their environmental criteria aiming to comply with the regulation, opportunities will arise for the adoption of more environmentally aware policies (Mallouppas et al., 2023). In addition, the initiative will enable the shipping companies to provide services to their customers with reduced emissions and environmental footprint. The points mentioned above will satisfy customers 'demand for lowering emissions throughout their processes while contributing to the reinforcement of the overall decarbonization of the supply chain (Hughes, 2021).

7.6 Legal

From a legal perspective, the regulation will impose several penalties. Shipping companies will have to deal with stricter rules within the EU ports, especially within the ECAs (Mallouppas et al., 2023). The penalties will impact port accessibility, as consecutive non-compliance will result in restricted access to EU ports (Council of the European Union, 2021). Ship operators are bind to comply with the initiative and reduce the carbon intensity of the fuels used by making adjustments in their procedures with prompt and adequate supply of appropriate fuels prior to EU port calls (Hughes, 2021). As for the fuel suppliers, the requirement to certify that the provided fuels comply with the regulation on a Well-to-tank basis. In relation to national administrations, no significant burden should be expected, as the registration of the document of compliance will be conducted electronically and the auditing will be performed by third party companies (Council of the European Union, 2021).

In addition, shortcomings in the existing framework regarding the global availability of alternative fuels from suppliers around the world should be resolved. Failure to regulate this will result in the vessels not being adequately supplied for their upcoming EU calls (Hughes, 2021). The ports will also have to indirectly comply with the regulation. The establishment of the best-practice guidance is expected, necessitating the development on a national level in order to improve safety in fuel handling procedures (Council of the European Union, 2021). However, it has to be mentioned that concerns have been expressed regarding the alignment of the regulation with the international maritime law, as the initiative impacts the legal standards that fuel suppliers and port authorities abide by (Hughes, 2021).

Table 3: PESTEL Analysis

Political	• Contribution in IMO's carbon neutrality strategy • International regulatory bodies to develop corresponding regulation

	• Governmental pressure for the adoption of fuels • Regulatory bodies to introduce policies that will benefit or harm different countries • Impact the business sector of ports • Possibility of political tension concerning the assumption that EU attempting to control marine fuel supply industry
Economic	Shipping companies • Large amount of money consumed for investments to choose a feasible strategy • Capital expenditure for research and development department (MBMs support after 2030) • Capital will be needed for retrofitting the fleet • Diminished profits • Additional costs for the seafarers and engineers training • Costs for additional information required to ensure compliance, audits and inspections • Costs for verification and approvals • Cost of high-risk exposure • Increased operational expenses but when the fuels will be more widespread the economies of scale will lower the relevant costs • Higher costs for smaller vessels which need several stops for bunkers • Higher cost of non-scheduled port calls due to limited availability of bunkers Freight Rates and Trade • Freight rates will be increased due to the higher operational expenses and retrofitting costs • Prevailing non-stability will lead to volatility of freights • Trade may be allocated

	• Trade with bigger vessels will be more challenging (more energy and fuel consumption) • Buyers of cargo may turn to domestic suppliers • Market dynamics will shift due to two-tier market (vessels abide by initiative and vessels that do not) Other Stakeholders • Final consumers will bear the costs • Rises in the costs of common goods • Increased revenues for the marine technology and equipment suppliers • Fuel suppliers will have a neutral economic impact • National administration will need an initial expenditure for the acquisition of the reporting system • EU-ports may have less profits
Social	• Enhancement of the ESG reports • Greater reputation of the complies shipping companies • Increased public awareness • Concerns regarding safety of seafarers and need for adequate training
Technological	• Improvement of research and development regarding fuels and technologies • Development of ports infrastructure (OPS facilities, bunkering infrastructure etc.)
Environmental	• Elimination of GHG emissions • Reassessment of shipping companies' policies • Provision of greener services from shipping companies
Legal	• Port accessibility • Ship operator's compliance • Certification of fuels from suppliers • Shortcomings in framework regarding availability • Ports compliance • Alignment of the regulation with the international maritime law

8. Case Study: Starbulk

This case study has been conducted with information gathered from the 2022 ESG report of Starbulk and interviews from executive employees within the company responsible for the implementation of the FuelEU Maritime Regulation and the transition towards carbon neutrality. Starbulk is a global shipping company with a fleet of over 160 owned vessels with an approximate cargo capacity of 15.5 million DWT. Starbulk provides dry bulk cargo transportation services, supported by a fleet averaging roughly 11 years. The majority of cargoes being transported are minerals, iron ore and grain, while fertilizers, steel products and bauxite are transported with less frequency. The company is listed in the American stock market and is part of the Nasdaq Global Select Market index.

The company actively promotes emissions reduction policies in order to comply with all the established regulations, while also monitoring and reporting through in-house systems all the emissions and energy consumption of its vessels. Energy efficiency is improved through technical and operational measures, and investments in R&D projects that research new technologies and alternative fuels targeting zero emissions are made.

In its 2022 ESG report, the company set targets to reduce the carbon intensity of the entire fleet by 12% by 2026 and at least 40% by 2030, compared to 2019 levels. Additionally, the company aims to reduce GHG emissions by at least 20% by 2030, 70% by 2040, and achieve net-zero emissions by 2050. In full compliance with IMO regulations, EEXI values for all vessels have been verified, with measures such as shaft power limitations or propeller trimming in place, and the CII is being closely monitored. The Energy Efficiency Operational Indicator (EEOI) has been measured at 6.45 (gr CO2 / ton-mile), reflecting a 3% decrease from 2021, to track the vessel's fuel efficiency in relation to its transport work. Another indicator that the company measures is the Annual Efficiency Ratio (AER) that monitors the energy performance of the vessel; the reported amount was 3.29 (gr CO_2 / DWT-mile), showcasing a 4% reduction compared to 2021.

In line with the EU's regulation and the Fit for 55 package, the company aims to reduce CO_2 emissions by improving the CII and reducing the economic impact, as charterers will bear the cost of emissions from voyages within the EU. Additionally, the company is committed to lowering GHG emissions intensity as imposed by the FuelEU Maritime Regulation. Carbon intensity trend measurements have indicated that in 2022, the tons of carbon dioxide equivalent per thousand U.S.

dollars of voyage revenues was 1.91, reflecting a 34% reduction compared to the average value from previous years. In 2022 alone, the total distance covered by the entire fleet was 7.185.004 NM, with 865.560 MT of fuel consumed, resulting in roughly 2.7 million metric tons of CO_2 equivalent emissions. The average daily fuel consumption of a vessel was 18.53 MT and the energy consumption from non-renewable sources of the whole fleet was 35.112.805 GJ, reflecting a 7.9% and 4.8% reduction respectively in comparison to 2021. The overall emissions decreased by 4.6% in 2022.

Table 4: Fleet Performance Indicators for 2022

Metric	2022 Value
Carbon Intensity (t CO_2eq / $ '000s voyage revenue)	1.91 (34% reduction vs. previous years average)
Total CO_2 Emissions	2.706.226 MT CO_2eq
Total Distance Covered by Fleet	7.185.004 NM
Total Fuel Consumption	865.560 MT
Average Daily Fuel Consumption per Vessel	18.53 MT (7.9% decrease from 2021)
Total Energy Consumption (Non-Renewable)	35.112.805 GJ (4.8% decrease from 2021)

Source: Starbulk (2023)

The company's main trading routes are China, Singapore, South Africa to South America for capesize vessels, while smaller vessels, such as the supramax and the kamsarmax primarily operate routes in the Persian Gulf and Arabian Sea, but may also make voyages in EU, mostly in Belgium, Spain and Italy. Although it is evident that the company has limited interactions with ports within the EEA, it is headquartered in Greece and holds a responsibility to its investors and shareholders to pursue a more sustainable environmental footprint.

8.1 Current Strategy - Biofuels

As of now, the company's fleet is fueled with High-Sulfur Fuel Oil (HSFO) in vessels that have scrubbers installed and Very Low Sulfur Fuel Oil (VLSFO) in vessels without scrubbers, while vessels operating in ECAs are using Marine Gas Oil (MGO). As the FuelEU Maritime Regulation comes into effect from the start of 2025 and the existing fueled strategy contains only the SO_x and NO_x new measures should be taken in order to meet the requirements.

The strategy that has been chosen for compliance with the regulations entails the usage of certified biofuels, in particular the B30 biofuel. Certified biofuels have been produced responsibly concerning the environmental and social standards from sustainable feedstocks with regards to the GHG emissions reduction policy. The B30 is a blend of 30% biofuel and 70% fossil fuel, either HSFO or VLSFO. The biofuels which will serve as transitional fuels meet the imposed 2% reduction of GHG emissions intensity and are a method that will also sufficiently cover the 6% reduction starting from 2030. However, given the fact that biofuels will be added as part of the blended fuel, for the period 2030 to 2035 the percentage of B30 will need to be increased in order to comply with the regulation. In relation to the operational cost of B30, a notable increase will be noted, but the transition to more sustainable fuels appears to be more beneficial.

Discussions were held before the conclusion was reached to assess the possibility of down payment of taxes and penalties for the first few years of the regulation being a more cost-efficient solution. Nevertheless, maintaining the fossil fuel consumption as it stands will further increase the operational expenses. After a cost benefit analysis of the case, the break-even point of the price of biofuels appears to be USD 500 per ton of B30. The company has already come to an agreement with fuel suppliers in ARA, Singapore etc. to both maintain the price of biofuels below the brake-even point and to provide the required amount in the upcoming years. In terms of engine compatibility, the current fleet is well-prepared to consume the B30 with little to none engine modifications being required. It has to be mentioned that in the past, vessels from the current fleet have already made successful voyages with the use of biofuels according to charterers request. The main aspect that needs to be addressed with caution is the possibility of bacteria developing in the stored biofuels, thus requiring the addition of proper chemicals in order for the quality to remain on a high level.

8.2 Short Term Measures

Another mechanism that will be employed by the company is pooling, especially when the limits become more stringent, as one vessel operating with green fuel will provide the required allowances to enable plenty of the rest of the vessels of the fleet to operate with less fuel-efficient fuels, with the high costs of green propulsion being mitigated. It is essential to be mentioned that in case of a time charter party contract, which happens to be the most usual type of contract for the company, the responsibility for the bunkers burdens the charterer and thus, pool allocation is more complex.

In accordance with the regulation, the same vessel cannot simultaneously participate in more than one pool. Hence, in case a vessel has been chartered for a year by two different charterers, for a duration of 10 and 2 months respectively, and both of them have expressed the desire to include the vessel in a pool, it is up to the company to choose the pool that the vessel will be part of. Most likely the vessel will be included in the pool proposed by the charterer that hired the vessel for the longest period (i.e. 10 months in the above example), meaning that the owning company is held liable against the regulation for the period that the vessel has remained without a pool. To this end, the company could, for instance, come into an agreement with the latter charterer to increase the quantity of biofuels used, albeit at a reduced freight rate.

The company has also taken short term measures in order to reduce fuel consumption. Efforts have been made to reduce the electricity on board the vessel, thus reducing the overall energy consumption. The LED-Lamp Retrofit Project was a project involving the substitution of conventional light with LED lights in the 55 youngest vessels of the fleet. Operational measures, involving weather routing systems and speed optimization, have also been taken. In addition, the hydrodynamic characteristics of the vessels have been enhanced in an effort to reduce resistance in the water, low friction paints are used for the hull and Energy Saving Devices (ESD) are assisting the improvement of energy efficiency.

Investing in technologies in which the propulsion is assisted from renewable sources such as WASP products have been examined as an option. However, the high capital expenditure that has to be made for the acquisition and installment of the relevant products, deemed the investment economically unsustainable. More specifically, the payback period of such an investment, considering the company's usual trade routes, has been proven to be 15 years. The payback period would be reduced to 5 years only for fleets that operate mostly in EU, thus making the investment more appealing, but as mentioned above the company operates primarily out of EEA ports.

8.3 Future Strategy - Methanol

In regard to the last years of the regulation where more strict limits have been set, further action should be taken and new fuel-efficient vessels should be introduced in order to ensure compliance.

The company states that the current strategy to be followed has not yet been determined, as several challenges hinder the process. One of the issues is the level of uncertainty regarding the established regulations and the ones that may arise in the upcoming years. Another barrier that should be overcome is the safety concerns of alternative fuels, such as hydrogen and ammonia, which may be very promising in terms of emissions reduction, but whose high level of toxicity may lead to human and environmental damages. Moreover, the demand of alternative fuels will have a significant increase, as other sectors like aviation and land industries, will be in need of these fuels, meaning that their availability, and in turn the promised green future, remains questionable.

Given the preceding points, the alternative fuel that minimizes drawbacks and simultaneously provides emissions efficiency is methanol. Its great advantage as a fuel lies primarily on the existence of engines powered by conventional fuels, which are able to function on methanol with minor modifications. The aforementioned provides an advantage regarding the adaptability of the investment. In the forthcoming years, new building vessels can be constructed to operate on methanol as soon as the groundwork is favourable. However, methanol contains carbon which is released in the atmosphere during the combustion, so measures as carbon storage in liquid state on board the vessel should be taken. Yet, a major issue is the handling of the released carbon, requiring new infrastructure to be developed in order to safely transport it from the vessel to the port storage facilities, and eventually in its final storage destination. It has been proposed that the carbon be stored in existing underground holes in depleted gas fields. The EU has already approved the relevant procedure, but the IMO is still skeptical of its adoption due to the imminent reduction in alternative fuel investments that would stem from the continuation of conventional fuels consumption that would rely on the existence of the carbon capture facilities.

8.4 Implications to the Stakeholders

It is essential to mention that all the above planning for the upcoming changes may be adherent to the FuelEU Maritime Regulation, but the increased cost will not be avoided. The final consumers of the products or the services will eventually have to bear both the cost of investments and the greater operational cost of the vessels. Only in the case of MBMs could it be possible to avoid the extra cost for the consumers. An example could be the Netherlands which grants an amount to the companies to encourage investments in new technologies and alternative fuels.

In conclusion, the FuelEU Maritime Regulation definitely contributes positively to the application of alternative fuels in the maritime sector. In relation to other established monetary measures from the EU, such as the ETS and the ETD, the transition to greener energy is more cost-efficient than persisting in usage of fuels with high intensity in carbon. One challenge that the ship owning companies will have to overcome is the increased complexity in logistics, especially if the regulation affects only the EEA. However, the FuelEU Maritime Regulation will influence the legislation system globally as the IMO, despite the political obstacles, is expected to announce measures relevant to the ones legislated in the EU until 2026, that could possibly be valid starting from 2027. By extend, a worldwide need for transition towards greener energy and alternative fuels could be established, with the infrastructure and supply of the fuels having a greater development.

9. Conclusions

The aim of the current diploma thesis is to assess the possible pathways towards carbon neutrality in respect to the FuelEU Maritime Regulation implemented by the European Union. Through this study, an analysis of the initiative has been conducted, and the role of the introduced limits, regarding carbon emissions reduction within EU ports, in the decision-making process of the shipowners has been examined. In more detail, the compatibility of various candidate fuels with the regulation was explored, considering the economic and practical issues that may arise from their selection. Akin to that, the various methods that will ensure compliance with the regulation and are available to the shipowners, such as operational and technical measures implemented in the current fleet, retrofitting the existing engines or investing in new fuel-efficient vessels, have been examined in order to identify the most efficient one.

Additionally, through comprehensive research on the existing literature, the implications of all these forthcoming changes have been compiled and categorized into political, economic, social, technological, environmental and legal groups. The key findings of the research focus on the stage that each method or selection of fuels is more suitable for, given that each of them serves a specific cause in the process of ensuring a smooth transition towards green propulsion. The main direction to be followed in the short-term period by the shipowners is the maximum utilisation of both operational and technical measures, achieving reduction in the fuel consumption, and as a result, reduction in the carbon emissions as well. Some of the techniques have already been in use for several years due to safety or economic reasons, so the parameter of fuel preservation will be easily accomplished with the optimization of the systems towards minimization of the emissions reduction.

However, as the years go by and the limits become stricter, the shipowners will shift towards measures such as retrofitting the engine of their existing fleet, especially the younger vessels, with the aim to make the investment favorable. Simultaneously, concerning the older vessels, investments may not be appealing enough to ensure a payback within their remaining lifespan. Therefore, mechanisms offered by the initiative, such as pooling, will be utilized. The alternative fuels that can be used for the propulsion of the vessels with the fewest to no modifications are biofuels and methanol. Nonetheless, particularly from 2040 onward, when carbon intensity limits will impose a reduction of 31% or more, the adoption of specific fuels such as LNG, LPG, biofuels, e-LNG, or e-Diesel is unlikely to achieve the required percentage reduction. The investment into new technologies and fuels in new fuel-efficient vessels is inevitable. The alternative fuels or renewable energy promising a great reduction in carbon emissions and are capable of reaching carbon neutrality are ammonia, hydrogen, methanol, nuclear energy, as well as some synthetic fuels (e-fuels) like e-Hydrogen and e-Ammonia. However, high capital expenses will be incurred, and there is also concern about the availability of the relevant fuels in sufficient amount for all the industries, not just shipping. Moreover, safety issues have arisen pertaining to the use of the nuclear energy, ammonia and hydrogen due to the great risk that they pose for both humans and the environment, in case of engine malfunctions or leakages; these issues should be addressed prior to wide commercialized use of these fuels.

Apart from nuclear energy, alternative fuels have higher volumetric density in comparison to conventional fuels, therefore requiring excessive storage space and calling for specific storage conditions to be met. Shipping companies are considering the option of combining multiple strategies over the years in order to minimize capital expenses. Such a promising combination is the use of biofuels until 2035 shifting to methanol thereafter. Regarding renewable energy sources, the capital investment costs are considered excessively high, and operations must be limited to EU ports for the strategy to be viable.

Another aspect the relevant research tried to analyze are the implications of the FuelEU Maritime Regulation in the maritime sector. The greatest impact will be on the environmental sector as the regulation will lead the shipowners to adopt practices that mitigate the carbon emissions and reduce the environmental footprint of all the shipping sector. However, the economic impact will be significant to all the stakeholders of the sector. In relation to the shipowners, the need for high investment expenditures and increased operational cost will be necessary. Measures as MBMs or the avoidance of the penalties cost (ETS, ETD) will not be enough to maintain the costs in the current levels. The freight rates will be increased and the trade routes in some case may alter. The final consumers will have to bear the increased cost while the technology development companies will benefit from the increased demand for their services and products. In relation to technology factor, several technological advancements are expected in more than one direction, as there are capital and time-based limitations which will favor the development of a variety of alternatives. Additionally, political tensions may be triggered as the EU may be perceived as trying to control the global fuel sector with its standards. Nevertheless, the initiative will set the basis for the implementation of an international regulatory system regarding the emissions reduction strategy. From legal perspective, the penalties that will be implemented in case of non-compliance in the form of port access restriction and the compliance of the fuel suppliers with regards to the standards require special attention. Finally, the social impact of the regulation primarily revolves around the safety concerns that will emerge and the fostering of a more environmentally conscious society.

Although this research provides a comprehensive analysis of the available investment opportunities, it is important to acknowledge limitations in the quantitative aspects of implementing these investments. The suggested approaches have not been validated through a statistical model. Moreover, the research supported its results on current data without taking into account the economic revaluations or inflation. Future studies could address this consideration in order to further build on the findings of this study. Furthermore, evaluating the regulation after several years of enforcement and assessing its effectiveness, as well as whether the proposed investments were eventually implemented, could be interesting research question.

In conclusion, this research presents how the implementation of the FuelEU Maritime Regulation will impact the whole shipping sector, particularly in terms of decision making and choosing a strategy in order to comply with it. Methods and alternative fuels were presented as potential immediate solutions for reducing emissions, aiming to contribute to Europe's carbon neutrality by 2050. The research highlights the necessity of the cooperation of the shipping industry with the regulatory framework aiming to achieve the long-term target of decarbonization.

References

Abadie, L.M., Goicoechea, N. and Galarraga, I. (2017). Adapting the shipping sector to stricter emissions regulations: Fuel switching or installing a scrubber? *Transportation Research Part D: Transport and Environment*, [online] 57, pp.237–250. doi:https://doi.org/10.1016/j.trd.2017.09.017.

Azarkamand, S., Wooldridge, C. and Darbra, R.M. (2020). Review of Initiatives and Methodologies to Reduce CO2 Emissions and Climate Change Effects in Ports. *International Journal of Environmental Research and Public Health*, 17(11), p.3858. doi:https://doi.org/10.3390/ijerph17113858.

Bhattacharyya, R., El-Emam, R.S. and Khalid, F. (2023). Climate action for the shipping industry: Some perspectives on the role of nuclear power in maritime decarbonization. *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, [online] 4, p.100132. doi:https://doi.org/10.1016/j.prime.2023.100132.

Brynolf, S., Fridell, E. and Andersson, K. (2014). Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. *Journal of Cleaner Production*, 74, pp.86–95. doi:https://doi.org/10.1016/j.jclepro.2014.03.052.

Chou, T., Kosmas, V., Acciaro, M. and Renken, K. (2021). A Comeback of Wind Power in Shipping: An Economic and Operational Review on the Wind-Assisted Ship Propulsion Technology. *Sustainability*, 13(4), p.1880. doi:https://doi.org/10.3390/su13041880.

Christodoulou, A. and Cullinane, K. (2022). Potential alternative fuel pathways for compliance with the 'FuelEU Maritime Initiative'. *Transportation Research Part D: Transport and Environment*, 112, p.103492. doi:https://doi.org/10.1016/j.trd.2022.103492.

Christodoulou, A., Dalaklis, D., Ölçer, A.I. and Ghaforian Masodzadeh, P. (2021). Inclusion of Shipping in the EU-ETS: Assessing the Direct Costs for the Maritime Sector Using the MRV Data. *Energies*, 14(13), p.3915. doi:https://doi.org/10.3390/en14133915.

Council of the European Union (2021). *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC*. [online] EUR-Lex. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:562:FIN.

Council of the European Union (2021). *Fit for 55 - The EU's plan for a green transition*. [online] Consilium. Available at: https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55/.

Dathe, T., Dathe, R., Dathe, I. and Helmold, M. (2022). *Corporate Social Responsibility (CSR), Sustainability and Environmental Social Governance (ESG)*. S.L.: Springer.

DNV (2019). *Global Sulphur Cap 2020*. [online] www.dnv.com. Available at: https://www.dnv.com/maritime/global-sulphur-cap/.

DNV (2023a). CII - Carbon Intensity Indicator. [online] www.dnv.com. Available at: https://www.dnv.com/maritime/insights/topics/CII-carbon-intensity-indicator/.

DNV (2024). *FuelEU Maritime*. [online] DNV. Available at: https://www.dnv.com/maritime/insights/topics/fueleu-maritime/compliance/ [Accessed 12 Oct. 2024].

DNV. (2023b). SEEMP Part III. [online] Available at: https://www.dnv.com/maritime/insights/topics/seemp-part-iii/ [Accessed 20 Nov. 2024].

EUR-Lex (2021). *EUR-Lex - 52021SC0635 - EN - EUR-Lex*. [online] Europa.eu. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021SC0635 [Accessed 12 Oct. 2024].

European Commission (2023). *Reducing emissions from the shipping sector*. [online] climate.ec.europa.eu. Available at: https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-shipping-sector_en.

Ghaforian Masodzadeh, P., Ölçer, A.I., Ballini, F. and Christodoulou, A. (2022). A review on barriers to and solutions for shipping decarbonization: What could be the best policy approach for shipping decarbonization? *Marine Pollution Bulletin*, 184, p.114008. doi:https://doi.org/10.1016/j.marpolbul.2022.114008.

Hughes, E. (2021). *FuelEU Maritime – Avoiding Unintended Consequences*. [online] Ics-shipping.org. Available at: https://www.ics-shipping.org/resource/fueleu-maritime/ [Accessed 12 Oct. 2024].

International Maritime Organization (2023). *Data collection system for fuel oil consumption of ships*. [online] www.imo.org. Available at: https://www.imo.org/en/OurWork/Environment/Pages/Data-Collection-System.aspx.

International Maritime Organization (2023). *IMO Data Collection System (DCS)*. [online] www.imo.org. Available at: https://www.imo.org/en/ourwork/environment/pages/data-collection-system.aspx [Accessed 12 Oct. 2024].

Kishore, K., Gupta, P., Kurien, C. and Mittal, M. (2024). Prospects and Challenges of Green Ammonia as an Alternate Fuel for Internal Combustion Engines. *Energy, environment, and sustainability*, pp.117–148. doi:https://doi.org/10.1007/978-981-97-0507-8_6.

Lagouvardou, S. and Psaraftis, H.N. (2022). Implications of the EU Emissions Trading System (ETS) on European container routes: A carbon leakage case study. *Maritime Transport Research*, 3, p.100059. doi:https://doi.org/10.1016/j.martra.2022.100059.

Lagouvardou, S., Psaraftis, H.N. and Zis, T. (2022). Impacts of a bunker levy on decarbonizing shipping: A tanker case study. *Transportation Research Part D: Transport and Environment*, 106, p.103257. doi:https://doi.org/10.1016/j.trd.2022.103257.

Li, Z. and Tang, J. (2024). Circulation-controlled wind-assisted ship propulsion: Technical innovations for future shipping industry decarbonization. *Energy Conversion and Management*, 319, pp.118976–118976. doi:https://doi.org/10.1016/j.enconman.2024.118976.

Lindstad, E., Lagemann, B., Rialland, A., Gamlem, G.M. and Valland, A. (2021). Reduction of maritime GHG emissions and the potential role of E-fuels. *Transportation Research Part D: Transport and Environment*, 101, p.103075. doi:https://doi.org/10.1016/j.trd.2021.103075.

Lloyd's Register (2023a). *FuelEU Maritime Regulation | LR*. [online] www.lr.org. Available at: https://www.lr.org/en/services/statutory-compliance/fit-for-55/fueleu-regulation/

Lloyd's Register (2021). *EEXI and CII Regulation Awareness | LR*. [online] Lr.org. Available at: https://www.lr.org/en/services/training/understanding-rules-and-regulations/eexi-and-cii-regulation-awareness/ [Accessed 20 Nov. 2024].

Lloyd's Register (2023b). *Frequently asked questions for SEEMP Part III | LR*. [online] Available at: https://www.lr.org/en/services/technical-advisory/seemp-part-iii-ship-energy-efficiency/faqs/ [Accessed 20 Nov. 2024].

Mallouppas, G., Yfantis, E.A., Ktoris, A. and Ioannou, C. (2022). Methodology to Assess the Technoeconomic Impacts of the EU Fit for 55 Legislation Package in Relation to Shipping. *Journal of Marine Science and Engineering*, 10(8), p.1006. doi:https://doi.org/10.3390/jmse10081006.

Mallouppas, G., Yfantis, E.Ar., Ioannou, C., Paradeisiotis, A. and Ktoris, A. (2023). Application of Biogas and Biomethane as Maritime Fuels: A Review of Research, Technology Development, Innovation Proposals, and Market Potentials. *Energies*, 16(4), p.2066. doi:https://doi.org/10.3390/en16042066.

McKinlay, C.J., Turnock, S.R. and Hudson, D.A. (2021). Route to zero emission shipping: Hydrogen, ammonia or methanol? *International Journal of Hydrogen Energy*, [online] 46(55), pp.28282–28297. doi:https://doi.org/10.1016/j.ijhydene.2021.06.066.

Mimica, M., Perčić, M., Vladimir, N. and Krajačić, G. (2022). Cross-sectoral integration for increased penetration of renewable energy sources in the energy system – Unlocking the flexibility potential of maritime transport electrification. *Smart Energy*, 8, p.100089. doi:https://doi.org/10.1016/j.segy.2022.100089.

Nguyen, H.P., Hoang, A.T., Nizetic, S., Nguyen, X.P., Le, A.T., Luong, C.N., Chu, V.D. and Pham, V.V. (2020). The electric propulsion system as a green solution for management strategy of CO_2 emission in ocean shipping: A comprehensive review. *International Transactions on Electrical Energy Systems*, 31(11). doi:https://doi.org/10.1002/2050-7038.12580.

Nyanya, M.N., Vu, H.B., Schönborn, A. and Ölçer, A.I. (2021). Wind and solar assisted ship propulsion optimisation and its application to a bulk carrier. *Sustainable Energy Technologies and Assessments*, 47, p.101397. doi:https://doi.org/10.1016/j.seta.2021.101397.

Patel, K. and Santosh Kumar Singh (2023). Environmental sustainability analysis of biofuels: a critical review of LCA studies. *Clean Technologies and Environmental Policy*, 25(8), pp.2489–2510. doi:https://doi.org/10.1007/s10098-023-02596-y.

Rutkowski, G. (2016). Study of Green Shipping Technologies - Harnessing Wind, Waves and Solar Power in New Generation Marine Propulsion Systems. *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation*, [online] 10(4), pp.627–632. doi:https://doi.org/10.12716/1001.10.04.12.

Sharp-Pate, C. (2023). *Applying alternative fuels to existing ships | LR*. [online] www.lr.org. Available at: https://www.lr.org/en/knowledge/research-reports/applying-alternative-fuels-to-existing-ships/.

Solakivi, T., Paimander, A. and Ojala, L. (2022). Cost competitiveness of alternative maritime fuels in the new regulatory framework. *Transportation Research Part D: Transport and Environment*, [online] 113, p.103500. doi:https://doi.org/10.1016/j.trd.2022.103500.

Stopford, M. (2020). *Coronavirus, Climate Change & Smart Shipping*. [online] p.32. Available at: https://webinars.capitallink.com/2020/stopford/pres.pdf [Accessed 9 Nov. 2024].

Tsvetkova, A., Hellström, M., Schwartz, H., Rabetino, R. and Syed, H. (2024). A transition towards clean propulsion in shipping: The role of PESTLE drivers and implications for policy. *Marine Policy*, [online] 161, p.106002. doi:https://doi.org/10.1016/j.marpol.2023.106002.

UNCTAD (2021). *High Freight Rates Cast a Shadow over Economic Recovery | UNCTAD*. [online] unctad.org. Available at: https://unctad.org/news/high-freight-rates-cast-shadow-over-economic-recovery.

United Nations (2015). *The Paris Agreement*. [online] United Nations. Available at: https://www.un.org/en/climatechange/paris-agreement.

Wang, Q., Zhang, H. and Zhu, P. (2023). Using Nuclear Energy for Maritime Decarbonization and Related Environmental Challenges: Existing Regulatory Shortcomings and Improvements. *International journal of environmental research and public health*, [online] 20(4). doi:https://doi.org/10.3390/ijerph20042993.

Wu, Y., Chen, A., Xiao, H., Jano-Ito, M., Alnaeli, M., Alnajideen, M., Mashruk, S. and Valera-Medina, A. (2023). Emission reduction and cost-benefit analysis of the use of ammonia and green hydrogen as fuel for marine applications. *Green Energy and Resources*, [online] 1(4), p.100046. doi:https://doi.org/10.1016/j.gerr.2023.100046.

Xing, H., Spence, S. and Chen, H. (2020). A comprehensive review on countermeasures for CO2 emissions from ships. *Renewable and Sustainable Energy Reviews*, 134, p.110222. doi:https://doi.org/10.1016/j.rser.2020.110222.

Xing, H., Stuart, C., Spence, S. and Chen, H. (2021). Alternative fuel options for low carbon maritime transportation: Pathways to 2050. *Journal of Cleaner Production*, 297, p.126651. doi:https://doi.org/10.1016/j.jclepro.2021.126651.

Yang, M. and Siu, J. (2023). Operational and economic evaluation of ammonia bunkering – Bunkering supply chain perspective. *Transportation Research Part D: Transport and Environment*, 117, pp.103666–103666. doi:https://doi.org/10.1016/j.trd.2023.103666.

Yang, R., Yuan, Y., Ying, R., Shen, B. and Long, T. (2020). A Novel Energy Management Strategy for a Ship's Hybrid Solar Energy Generation System Using a Particle Swarm Optimization Algorithm. *Energies*, 13(6), p.1380. doi:https://doi.org/10.3390/en13061380.

Yeo, S.-J., Kim, J. and Lee, W.-J. (2022). Potential economic and environmental advantages of liquid petroleum gas as a marine fuel through analysis of registered ships in South Korea. *Journal of Cleaner Production*, [online] 330, p.129955. doi:https://doi.org/10.1016/j.jclepro.2021.129955.

Zamboni, G., Scamardella, F., Gualeni, P. and Canepa, E. (2024). Comparative analysis among different alternative fuels for ship propulsion in a well-to-wake perspective. *Heliyon*, [online] 10(4), pp.e26016–e26016. doi:https://doi.org/10.1016/j.heliyon.2024.e26016.

Zannis, T.C., Katsanis, J.S., Christopoulos, G.P., Yfantis, E.A., Papagiannakis, R.G., Pariotis, E.G., Rakopoulos, D.C., Rakopoulos, C.D. and Vallis, A.G. (2022). Marine Exhaust Gas Treatment Systems for Compliance with the IMO 2020 Global Sulfur Cap and Tier III NOx Limits: A Review. *Energies*, [online] 15(10), p.3638. doi:https://doi.org/10.3390/en15103638.

Zhang, X., Bao, Z. and Ge, Y.-E. (2021). Investigating the determinants of shipowners' emission abatement solutions for newbuilding vessels. *Transportation Research Part D: Transport and Environment*, 99, p.102989. doi:https://doi.org/10.1016/j.trd.2021.102989.