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Decarbonisation in the shipping industry

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Decarbonisation in the shipping industry

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1. Abstract

This thesis attempts to describe and analyse the steps that shall be taken towards the decarbonisation of the shipping industry. In the global effort to reduce GHG and carbon emissions, there is great importance for the shipping industry to decarbonise and move forward into a greener future. For the purpose of this thesis, we have identified the new challenges that the shipping industry faces over the last decade. To this end we give an overall overview of the significant role of the IMO as a global standard-setting authority for the environmental performance of international shipping, analysing also the Initial Strategy of IMO for achieving the reduction of shipping GHG. In light of the above we also make reference to the regulatory context for the implementation of the Initial Strategy analysing its challenges and complexity, while we also present a discussion of the most common alternative marine fuels that could be use by the global shipping industry.

2. Acknowledgments

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Finally, I must express my very profound gratitude to my parents for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them.

3. Abbreviations

ABS: American Bureau of Shipping

CCS: Carbon Capture and Storage

CII: Carbon Intensity Indicator

CO: Carbon Monoxide

CO_2: Carbon Dioxide

ECAs: Emission Control Areas

EEDI: Energy Efficiency Design Index

EEXI: Energy Efficiency Existing Ship Index

GHG: Greenhouse gas emissions

HC: Unburned Hydrocarbons

HFO: Heavy Fuel Oil

ICE: Internal Combustion Engines

IMO: International Maritime Organisation

LDCs: Least Developed Countries

LNG: Liquified Natural Gas

MARPOL: International Convention for the Prevention of Pollution from Ships

MDO: Marine Diesel Oil

MEPC: Marine Environment Protection Committee

MGO: Marine Gas Oil

NO_x: Nitrous Oxides

$PM_{2.5}$: Particulate Matter

SDARI: Ship Design and Research Institute

SDGs: Sustainable Development Goals

SEEMP: Ship Energy Efficiency Management Plan

SIDS: Small Island Developing States

SO_x: Sulphur Oxides

UN: United Nations

UNFCCC: United Nations Framework Convention on Climate Change

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4.1 Introduction

Shipping refers to the business of transporting goods. Global economic development is supported by the commercial shipping industry which facilitates the completion of trade transactions. Global trade volume has significantly grown with rapid increases in global sourcing activities and dispersed production sites. On the other hand, public concerns about environmental issues such as air pollution and resource depletion caused by shipping activities have been growing rapidly with the globalization of business activities. (Lun, Y. 2016).

Ships have offered the cheapest and the most versatile mode of transport for centuries. In addition, they have been carriers of cultural and religious influence to far off places (Agarwala 2021a). Today, globalisation and maritime trade has allowed the benefits of trade and commerce to be spread evenly thereby helping developing nations to witness growth, sustainable development and uplifting of their people from poverty. They have helped create jobs and opportunities for numerous people while helping many to improve their living standards. Aptly so, the maritime transport sector has become the backbone of global trade and the global economy. It is no wonder that in the last four decades, seaborne trade has quadrupled in size to regularly move nearly 80% of global trade by volume and over 70% by value (UNCTAD 2018). This increase has been feasible due to over 50,000 merchant ships registered in over 150 nations moving on the oceans internationally.

Shipping is associated with various environmental impacts, such as pollutants discharged to air and sea. Much of this pollution appears to be unregulated, and global emissions from shipping are expected to more than triple between 2020 and 2050. Findings suggest that many policies are voluntary or, in ports, incentive-based; regulatory approaches are largely limited to Emission Control Areas. Policies also focus on efficiencies, they are not concerned with absolute pollutant and greenhouse gas levels. No policies incentivizing or forcing the transition to zero-carbon fuels were identified. As ports can define limits to pollution, for instance by demanding shore power use, they can significantly affect the clean development of the sector. Further legislation will be needed nationally to

counterbalance the lack of supranational ambition on pollutants and climate change mitigation (Gössling, S. 2021).
Ships carry three-quarters of the world's freight (ITF 2019), along with very significant passenger numbers on ferries and cruise ships (Cruise Market Watch, 2021). Shipping causes emissions to air, including carbon dioxide (CO_2), nitrous oxides (NO_x), sulphur oxides (SO_x), carbon monoxide (CO), unburned hydrocarbons (HC), and particulate matter ($PM_{2.5}$, PM_{10}). These contribute to climate change and air pollution (Richter et al., 2004; Traut et al., 2018). NO_x and $PM_{2.5}$ in particular can have serious health impacts (e.g. Andersson et al., 2009; Corbett et al., 2007; Künzli et al., 2000; Marelle et al., 2016; Pandolfi et al., 2011), and populations living in proximity to ports have been found to be exposed to particularly high levels of air pollution (Saxe and Larsen 2004). CO_2 is the most important greenhouse gas, and even though shipping makes only a small contribution to global warming, the sector's expected growth will challenge a global economy seeking to decarbonize by mid-century (UNFCCC 2018).
As this overview indicates, shipping is a source of significant amounts of air pollutants and emissions, even though the sector's contribution to global totals is low. Shipping's relevance is thus twofold: First, in a world seeking to decarbonize, its contribution to global warming will grow in relative and absolute terms. This is a problem specifically in regard to shipping's non-inclusion in the Paris agreement (UNFCCC 2018) and the global community's zero-emission goals to 2050. Second, shipping is a major factor in local air pollution, affecting in particular port and coastal communities. In these environments, shipping is often the major source of air pollution (Gössling, S. 2021).

4.2. New challenges in the shipping industry

Shipping companies are currently facing new challenges and opportunities in the global economy. The globalization of business activities has highlighted the debate surrounding the environmental questions of resource protection and conservation, as in the case of pollution from maritime transport, leading to an increase in research and deeper knowledge on the problems and potential solutions (Ostrom, E. 2008, Kaiser, W. 20100). Green shipping is becoming an important issue for a sustainable economy and environmental performance, with major implications for the shipping industry. However, little is known about the reasons why shipping companies adopt green shipping practices (Lun, Y. 2010, Lam, J. S. L. (2015), Poulsen, R. T. 2016). A multiplicity of studies limits research to the financial impact of the adoption of cleaner transportation technologies which does not address the plethora of other factors surrounding this issue (Viana, M. 2016). There is also insufficient understanding of the factors that make up green shipping development.

Nowadays, maritime transport faces more challenges than at its beginning. Like any other industry, the maritime sector must adapt to the needs of the modern world and carry out its activities with respect for the environment. Continuous technological development and increased environmental awareness are the determining factors of changes in modern shipping. Therefore, one of the main challenges of maritime transport is to implement innovative solutions to protect the marine environment. However, it is quite challenging to achieve both ecological and economic benefits at the same time. That is why it is very important to apply the win-win principle, which refers to the sustainable development of maritime transport (Hasanspahić, N. 2021)

The IMO enforced stricter sulphur abatement regulations since shipping emission has become one of the most major cause of the atmospheric pollution. Experts from the industry and academicians try to find the balanced solution among low-sulphur fuel, clean energy, and purposely fit scrubber by conventional statistical methods however failed to reach a satisfying conclusion. In addition, maritime datasets are usually massive, multi-source, and heterogeneous, it seems imperative for the maritime industry to adapt to the worldwide trend of intellectualisation and promote sustainable development (Hu, Y. 2021).

5. GHG in the shipping industry

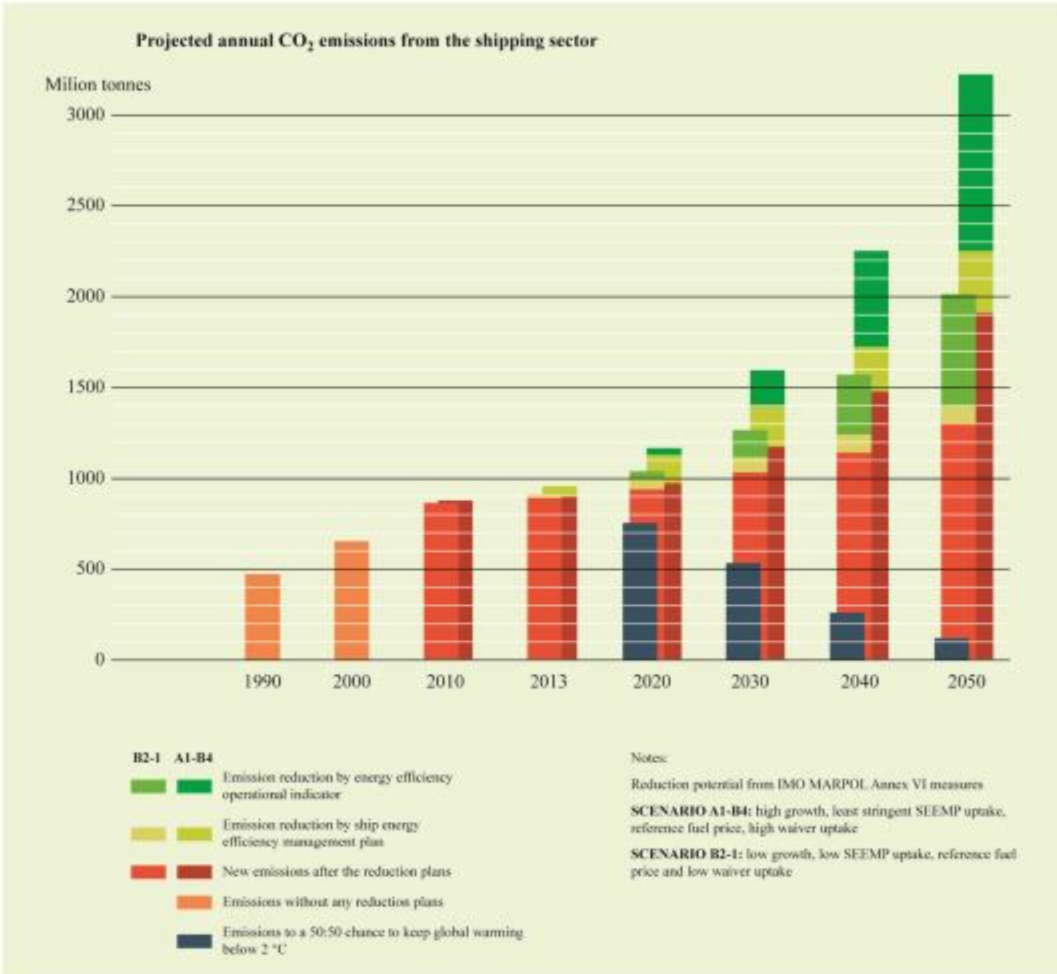
The greatest source of GHG emissions within shipping are from container ships, bulk carriers and oil tankers. This is due to these vessels conducting longer journeys to deliver their cargo – international and intercontinental, rather than domestic and coastline routes. The spatial distribution of these emissions covers most of the oceans and seas in the northern hemisphere.

Ship-source GHG emissions could increase by up to 250% by 2050 from their 2012 levels, owing to increasing global freight volumes. Binding international legal agreements to regulate GHGs, however, are lacking as technical solutions remain expensive, and crucial industrial support is absent. In 2003, IMO adopted Resolution A.963 to regulate shipping CO_2 emissions via technical, operational, and market-based routes. However, progress has been slow and uncertain; there is no concrete emission reduction target or definitive action plan. Yet, a full-fledged roadmap may not even emerge until 2023.

Ocean shipping, the most energy-efficient form of freight transport, is the backbone of global trade, but this sector heavily depends on fossil fuel. The lengthy debate on whether ship-source GHG emissions are classified as marine pollution has delayed the international regulation and subsequent implementation to limit the carbon emissions from the shipping sector (Shi, 2016a).

Ship-source GHG emissions could increase by up to 250% by 2050 from 2012 levels, owing to increasing global freight volumes (Table 1). Unchecked, such emission levels are projected to constitute 17% of the global CO2 emissions by 2050 from the current figure of approximately 2% (Cames et al., 2015). Yet, at the Paris Climate Agreement of 2015, the shipping industry was neither included in the global emissions reduction targets nor mentioned in the agreement (United Nations Framework Convention on Climate Change, 2015). Discussions regarding shipping emissions were simply left, like in the Kyoto agreement, to the IMO, who is expected to develop regulations, set emission reduction targets, and determine measures to facilitate their practical implementation.

Table 1



(Wan, Z. 2018)

6. Role of International Maritime Organisation

IMO – the International Maritime Organization – is the United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships. IMO's work supports the UN SDGs.

As a specialized agency of the United Nations, IMO is the global standard-setting authority for the safety, security and environmental performance of international shipping. Its main role is to create a regulatory framework for the shipping industry that is fair and effective, universally adopted and universally implemented.

In other words, its role is to create a level playing-field so that ship operators cannot address their financial issues by simply cutting corners and compromising on safety, security and environmental performance. This approach also encourages innovation and efficiency.

Shipping is a truly international industry, and it can only operate effectively if the regulations and standards are themselves agreed, adopted and implemented on an international basis. And IMO is the forum at which this process takes place.

International shipping transports more than 80 per cent of global trade to peoples and communities all over the world. Shipping is the most efficient and cost-effective method of international transportation for most goods; it provides a dependable, low-cost means of transporting goods globally, facilitating commerce and helping to create prosperity among nations and peoples.

The world relies on a safe, secure and efficient international shipping industry – and this is provided by the regulatory framework developed and maintained by IMO.

IMO measures cover all aspects of international shipping – including ship design, construction, equipment, manning, operation and disposal – to ensure that this vital sector for remains safe, environmentally sound, energy efficient and secure.

Shipping is an essential component of any program for future sustainable economic growth. Through IMO, the Organization’s Member States, civil society and the shipping industry are already working together to ensure a continued and strengthened contribution towards a green economy and growth in a sustainable manner. The promotion of sustainable shipping and sustainable maritime development is one of the major priorities of IMO in the coming years.

As part of the United Nations family, IMO is actively working towards the 2030 Agenda for Sustainable Development and the associated SDGs . Indeed, most of the elements of the 2030 Agenda will only be realized with a sustainable transport sector supporting world trade and facilitating global economy. IMO’s Technical Cooperation Committee has formally approved linkages between the Organization’s technical assistance work and the SDGs. While the oceans goal, SDG 14, is central to IMO, aspects of the Organization's work can be linked to all individual SDGs.

Energy efficiency, new technology and innovation, maritime education and training, maritime security, maritime traffic management and the development of the maritime infrastructure: the development and implementation, through IMO, of global standards covering these and other issues will underpin IMO's commitment to provide the institutional framework necessary for a green and sustainable global maritime transportation system.

6.1 IMO initial strategies towards decarbonisation

As a way of combating GHGs emission particularly CO2, the IMO in 2018 came up with the first ever initial strategy of reducing GHGs emission in the shipping industry with a final revised version set to come out in 2023 (Timperley 2017).
Due to the growing concerns of emissions from the shipping industry, the IMO has set strategies to reduce the CO2 intensity by 40% in 2030 and cut total GHGs emissions by at least 50% by 2050, with 2008 as a baseline. Clean alternative marine fuels are widely recognized and used as a viable solution for reducing ship-related air pollution. Several studies including traditional reviews have been conducted to examine the literature on cleaner alternative marine fuels and their role in decarbonizing the shipping sector. However, these studies fail to unpack the main research actors, evolutionary nuances, and emerging research hotspots in this field (Ampah, J. D. 2021).

This emission situation of the marine transport sector jeopardizes key global emission commitments such as the Paris Agreement, the Kyoto Protocol, etc. The IMO and the whole shipping industry thus have a role to play in reducing their emissions. IMO has instituted and proposed more stringent regulations for vessel operators and owners in the maritime sector to address these issues (Zou et al., 2020). IMO's ultimate goal is to completely decarbonize the marine transportation sector (Schnurr & Walker 2019). IMO's target is to reduce the CO2 intensity by 40% by 2030 and cut total GHGs emissions by at least 50% by 2050, both relative to 2008 levels (Rutherford and Comer, 2018). Thus, it is estimated that at least 70% of current marine fuels need to be changed or modified to meet these IMO regulations (Hsieh and Felby, 2017).

By combining energy efficiency measures with a switch to low or zero-carbon energy carriers, there is an excellent chance for very low and eventually zero GHG emissions from shipping to be achieved. Biofuels, electrofuels, and electricity produced from renewable energy sources such as biomass, solar, and wind are typical energy carriers associated with low or zero GHG emissions during their life cycle (Korberg et al., 2021). On the other hand, energy efficiency measures are those strategies that have to do with operational measures such as voyage optimization and capacity utilization, technical measures such as improvements in hull design, and changes in power and propulsion systems (Bouman et al., 2017). Bouman et al. (2017) have also reviewed the emissions reduction potentials of these measures, and their results revealed that to obtain the required emission reduction potential, a transition to alternative fuels is one of the best and fulfilling pathways. Thus, interest in alternative marine fuel research has gained momentum in recent years.

In early 2018, IMO and UN 2030 Agenda for SDG13 agreed to enhance the effort by addressing the GHG emissions from international shipping and to meet Paris agreement goals (IMO, 2018). For IMO to achieve its target, the Initial Strategy suggested short-(2018–2023), mid-(2023–2030), and long-term (after 2030) measures with possible timelines, and they are summarized in Table 2. In line with the initial strategy, there is a need to further optimize the logistic chain and its planning along with ports as a candidate short-term measure. This includes initiating research and development activities by launching several zero-carbon and alternative low-carbon fuels and innovative technologies to enhance maritime energy efficiency before 2023. In order to achieve GHG reductions and improve air quality in the short-term, governments and ship owners need to act decisively and invest in the handiest and ready-to-use solution vessels. This might improve the long-term sustainability of the shipping industry while safeguarding a competitive advantage for governments and ship owners who facilitate global trade.

Table 2

Short-term	Medium-term	Long-term	
Timeline	**2018–2023**	**2023–2030**	**Beyond 2030**
Measures	• Improve energy efficiency framework • Develop technical and operational energy efficiency measures • Encourage national policies, incentives, and port activities • Initiate research on alternative fuels and innovative technologies • Undertake additional GHG emission studies	• Implement program for the effective uptake of alternative fuel • Operational energy efficiency measures • Innovative emission reduction mechanism • Enhance technical cooperation • Develop feedback mechanism to learn and share lessons learned	• Pursue the development and provision of alternative fuels • Encourage and facilitate the general adoption of other possible innovative emission reduction mechanisms

The initial strategy represents a framework for Member States, setting out the future vision for international shipping, the levels of ambition to reduce GHG emissions and guiding principles; and includes candidate short-, mid- and long-term further measures with possible timelines and their impacts on States. The strategy also identifies barriers and supportive measures including capacity building, technical cooperation and research and development.

Levels of ambition directing the initial strategy are as follows:

1. **Carbon intensity of the ship to decline through implementation of phases of the EEDI for new ships**: to review with the aim to strengthen the energy efficiency design requirements for ships with the percentage

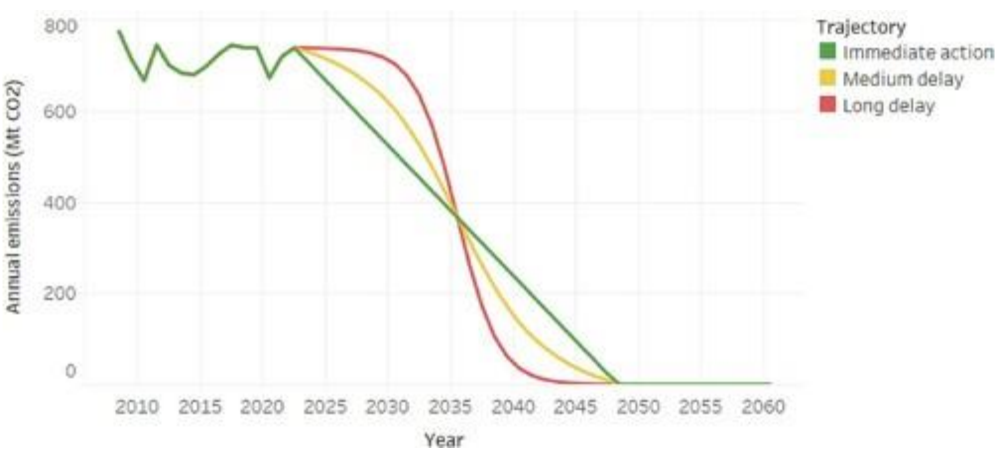
improvement for each phase to be determined for each ship type, as appropriate;

2. **Carbon intensity of international shipping to decline**: to reduce CO2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008; and

3. **GHG emissions from international shipping to peak and decline**: to peak GHG emissions from international shipping as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008 whilst pursuing efforts towards phasing them out as called for in the Vision as a point on a pathway of CO2 emissions reduction consistent with the Paris Agreement temperature goals.

The strategy includes a specific reference to "a pathway of CO2 emissions reduction consistent with the Paris Agreement temperature goals". The below table 3 presents CO_2 pathways to zero emissions, using 2008 IMO baseline for calculating carbon budgets.

Table 3



Ezinna, P. C., Nwanmuoh, E., & Ozumba, B. U. I. (2021).

The MEPC on June 2021 adopted amendments to MARPOL (Annex VI) that will require ships to reduce their greenhouse gas emissions. These amendments combine technical and operational approaches to improve the energy efficiency of ships, in line with the targets established in the 2018 Initial IMO Strategy for Reducing GHG Emissions from Ships and also provide important building blocks for future GHG reduction measures.

The new measures will require all ships to calculate their EEXI following technical means to improve their energy efficiency and to establish their annual operational CII and CII rating. Carbon intensity links the GHG emissions to the transport work of ships.

Attained and required EEXI

The attained EEXI is required to be calculated for ships of 400 gt and above, in accordance with the different values set for ship types and size categories.

Annual operational CII and CII rating

The amendments apply to ships of 5,000 gross tonnage and above (the ships already subject to the requirement for data collection system for fuel oil consumption of ships). These ships are required to have determined their required annual operational carbon intensity indicator (CII).

Ships will get a rating of their energy efficiency (A, B, C, D, E - where A is the best), which will be incorporated in their mandatory Statement of Compliance to be issued by the Administration. Administrations, port authorities and other stakeholders as appropriate are also encouraged to provide incentives to ships rated as A or B.

Entry into force

The amendments to MARPOL Annex VI (adopted in a consolidated revised Annex VI) are expected to enter into force on 1 November 2022, with the requirements for EEXI and CII certification coming into effect from 1 January 2023. This means that the first annual reporting on carbon intensity will be completed in 2023, with the first rating given in 2024.

Review by 1 January 2026

A review clause requires the IMO to review the effectiveness of the implementation of the CII and EEXI requirements, by 1 January 2026 at the latest, and, if necessary, develop and adopt further amendments.

The Committee also agreed to keep under review the impacts on States of the aforesaid amendments to MARPOL Annex VI, paying particular attention to the needs of developing countries, especially LDCs and SIDS, so that any necessary adjustments can be made.

6.2 Regulatory Context

The context for the implementation of the Initial Strategy is challenging and complex. The maritime shipping sector is highly dynamic and transnational. It involves a range of stakeholders, including States and private actors (such as shipping companies and their corporate customers), all subject to different laws, values and cultures (Mia Mahmudur Rahimn (2016) 69 Marine Policy). While the Initial Strategy is directed to IMO Member States, implementation will be shared among coastal, port and flag states, which have different approaches and incentives to implement and enforce obligations. There are also notable power imbalances in international maritime governance, within both nation states and the industry.

For example, IMO Member States with strong economies are generally host to the top global shipping corporations that contribute most to GHG emissions. Developing countries contribute lower levels of vessel-sourced emissions but have limited resources and capacity to implement higher environmental standards. In sectors like shipping—where extensive technology, research and innovation are required to meet environmental goals—the lack of financial resources and technical expertise, particularly in developing countries, remains a significant barrier to implementation. Even in the case of an established treaty such as MARPOL, the ratification and implementation record by States has been uneven (Rahim, Islam and Kuruppu (n 60) 162).

Further, while international obligations are imposed on states, the actors that effectively bear the burden of reducing emissions are shipping companies. Yet the industry itself is heterogenous, with many small and medium-sized enterprises with varying capacity to develop and deploy low-carbon technologies. Moreover, the ability of the industry to make the necessary investments is impacted by economic downturns, such as those currently experienced with the coronavirus pandemic (Robert Armstrong and others, ‘Ports Feel Coronavirus Impact on Global

Trade' (*Financial Times*, 18 March 2020)). How the industry will perform in the face of a global economic recession remains highly uncertain.

Given this complexity, the IMO leadership faces considerable challenges in securing agreement on crucial candidate measures and implementing these in a timely fashion (Apollonia Miola et alnEnergy Policy 5491, 5495). As the sector's regulator, the IMO plays the role of 'orchestrator' (Jane Lister et al 'Orchestrating Transnational Environmental Governance in Maritime Shipping' (2015) 34 Global Environmental Change 188, 185) in engaging stakeholders towards achieving common goals. In the past, the IMO has been criticised for failing to play this role effectively or for not moving quickly enough (Roe (n 13) 3). Even if successful in engaging at least the most relevant actors, there are still limits to what the IMO can do. In terms of regulatory design, decisions on regulatory tools adopted under the IMO will be mediated between Member States and influenced by large shipping companies. The IMO can, however, seek to ensure that its decision-making processes are transparent and, as far as possible, based on the best available data and science.

7. Potential alternative marine fuels

International shipping has been the reason behind the emission of about 2.5-3% of CO_2 in the worldwide pollution. In 2015, it accounted for 932 million tons and 2.6% of emissions. All forms of transport account for 24% of global emission. CO_2 emission depends on total fuel consumption and carbon concentration in the fuel used. CO_2 is the one of GHG. Due to the emission of other GHGs such as nitrogen and sulfur oxides from marine diesel engines, equivalent CO_2 emissions have sometimes been used.
In this context, the environmental IMO regulations have changed the approach to the use of fuels. The decarbonization process of marine fuels started in 2020. Researchers, shipping companies and classification societies provide different scenarios for the contribution of marine fuel types in shipping. In the years to

come (2022–2030), the IMO regulations will have a decisive impact on the use of preferred marine fuels considered greener. *(Ezinna, P. C., Nwanmuoh, E., & Ozumba, B. U. I. (2021))*.

Currently, there are several cleaner alternative fuels for the shipping sector. Below there are presented discussions for LNG, green electricity, hydrogen, methanol, biodiesel, and ammonia as potential marine alternative fuels (Ampah, J. D., Yusuf, A. A., Afrane, S., Jin, C., & Liu, H. 2021).

7.1 LNG

The use of LNG as a marine fuel has grown significantly in recent years. As a liquified gas, it occupies a volume corresponding to 1/600 of the product in a gaseous state, making it space-efficient to be stored on-board ship as a bunker (Wang and Notteboom, 2014). The advantage of using LNG is more environmentally driven than economical. LNG combustion in ships could eliminate SOx emissions, significant reduction of NOx, particulate matter, and GHG emissions. However, its CO2 emission reductions are not acceptable levels that could significantly address climate change (DNVGL, 2014). Compared to HFO, LNG reduces a ship's NOx, SOx and PM, and CO2 by 85–90%, 100%, and 15–20%, respectively (Wang and Notteboom, 2014).

On the other hand, the relatively low calorific value of LNG (33.75 MJ/m3) compared to that of conventional oil (38.44 MJ/L) means the former consumes more fuel to achieve the same power output as the latter (Wan et al., 2015). Thus, debunking the argument of low LNG prices as the main drivers to push the fuel into the marine fuel mix. Also, significant initial investments are required for sophisticated LNG engines and cryogenic double-walled fuel tanks (Wang and Notteboom, 2014). However, among the fuel alternatives to marine bunker oil, LNG is the most prolific with around 300 ships in operation or in order (currently 165 ships in operation and 154 confirmed orders), and applications around the globe and in most ship segments (DNVGL, 2019b).

7.2 Biodiesel

The main feedstock for marine biodiesel is soybean oil, but other acceptable sources include palm oil, sunflower oils, and waste cooking oil (Mohd Noor et al., 2018). Recently, several large engine manufacturing companies began large-scale research and testing of biodiesel in their engines. Caterpillar, Cummins, and MAN diesel provide blend approvals of 30%, 5–20%, and up to 100% biodiesel fraction for their modern marine diesel engines (Mohd Noor et al., 2018). Biodiesel is miscible with petroleum-derived products and can be blended with traditional marine oils in any ratio to combust in the marine engine without requiring major changes to the engine's hardware (Lin, 2013b). Some reports suggest that biodiesel decreases pollutant emissions when combusted directly or blended with marine fuels. Moreover, the key fuel properties of biodiesel are superior to traditional marine fuels, and combustion could lead to improved performance and combustion characteristics. The most common practice for biodiesel application in marine engines is as an additive and can be poured directly into fuel tanks; however, they can replace MDO and MGO in low to medium speed diesel engines (Hsieh and Felby, 2017). Despite these observations, the main drawback to the uptake of biodiesel in the maritime transportation sector includes but is not limited to biodiesel's oxidation stability, controversial food versus fuel issue, high production cost, material compatibility, cold flow properties, and lack of marine-grade biodiesel specifications (Lin, 2013b).

7.3 Methanol

Methanol as a shipping fuel is comparable to LNG in some aspects. One of the main differences is that methanol is liquid at standard temperature and pressure and, therefore, much easier to handle (Brynolf et al., 2014a). Several methanol projects have been conducted on marine vessels in the current century. The most recent testing project was the SUMMETH in 2018. The project aims to investigate methanol combustion in smaller marine engines (about 250–1200 kW) and propose viable options for the penetration of renewable methanol into the marine fuel market (Joanne and Kim, 2016)., there were seven methanol-fueled ships in operations worldwide (Methanex, 2018). Emissions of SOx, NOx, and PM have been reported to be lower in methanol-powered vessels. An emission test on Vasa 32 marine engine showed that NOx emissions of 3–5 g/kWh were emitted by the engine when fueled with methanol, whereas MGO was about 11.8 g/kWh

(Radoslav, 2019). PM, SOx, and CO2 were reduced by 95%, 99%, and 7% by methanol compared to HFO380. Thus, the combustion of methanol in marine vessels has proven to comply with ECAs regulation. However, GHG emissions from non-renewable methanol from natural gas are 10% higher than HFO and MDO (Brynolf et al., 2014a). On the other hand, if renewable methanol from biomass feedstock is used, GHG impact can be about 56% lower than that of HFO (Yuanrong et al., 2020). From an economic perspective, methanol investments are relatively low compared to LNG. It is cost-competitive with MGO, provided the price on an energy equivalence basis is lower. If methanol utilization in marine vessels were to increase, it would greatly depend on its carbon credentials being proven and incentivized (Balcombe et al., 2019).

7.4 Hydrogen

The simplest and most abundant element on earth is hydrogen, and it offers the best energy-to-weight storage ratio of all fuels (Xing et al., 2021b). Hydrogen is a promising alternative fuel for combustion in ICE due to its carbon-free attributes and unique combustion characteristics, with the only harmful emissions being NOx. Electrolysis of renewables or reforming natural gas remains the main technique in producing hydrogen (Bicer and Dincer, 2018). However, mostly all hydrogen is produced today from natural gas. The life cycle emissions of hydrogen may be close to zero, but it should be noted that, because hydrogen exists in compound forms, a huge amount of energy is consumed during its production (DNVGL, 2019b; Xing et al., 2021b). Hydrogen can be used as a fuel in fuel cells (efficiency between 50 and 60%), or applied in an adapted combustion engine (efficiency 40–50%), or as a blend in existing conventional marine fuels such as HFO (DNVGL, 2019b; ITF, 2018). At low levels of blending, hydrogen can be combusted as “drop-in” fuel in marine diesel engines without significant risks of engine damage (Linus et al., 2015). Hydrogen also retains the advantage that no CO2, PM, and SOx are emitted during combustion. However, significant additional infrastructure and system design are required due to its availability and low volumetric energy density (Andrews and Shabani, 2012). The diversity of potential feedstocks and the high proportion of renewable electricity make hydrogen a promising energy carrier in the future. Technical maturity, infrastructure investment, stringent legislation, and policy support in coastal states are crucial and could be the determining factors for the growth and success of hydrogen fuel amongst its peers (Xing et al., 2021b).

7.5 Ammonia

Ammonia could play a key role in IMO's decarbonisation plans for the shipping industry due to the absence of carbon and sulfur atoms in its chemical formula. Ammonia is one of the top three chemicals transported annually; it has already been transported by ships, and hence there are wide storage and delivery systems (Kim et al., 2020). Ammonia can be stored at significantly lower pressure and/or higher temperature than liquified hydrogen and LNG. Furthermore, transporting and storing ammonia is easier and less expensive than hydrogen and has higher volumetric energy density, well-established infrastructure, and relatively mature operational experience (Xing et al., 2021b). However, the main issue has to do with the development of bunkering infrastructure. The Haber-Bosch process is employed in the commercial production of ammonia which combines hydrogen and nitrogen with the help of high temperatures and catalysts (ITF, 2018). Ammonia can be a carbon-free fuel, and life-cycle CO2 emissions depend on energy sources for ammonia production (Xing et al., 2021b). Production of ammonia from HFO or coal would result in larger CO2 emissions per energy unit. However, electrolysis pathways could see ammonia production from renewable energy sources such as wind energy or solar power. The latter pathway, a carbon-free one, would enable the production of carbon-free ammonia since the tank-to-propeller phase does not emit any carbon (DNVGL, 2019b). It is worth noting that green ammonia is currently not cost-competitive to conventional ammonia, as 90% of its production depends on fossil fuels. Aside from the bunkering of ammonia, other issues slowing down the adoption of this fuel in the shipping industry has to do with its poor ignition quality, toxicity, corrosivity, higher NOx emissions, and lack of developed policies/regulations.

Nevertheless, the potential of using ammonia as a marine fuel has been explored in recent years. For example, Wärtsilä with Knutsen OAS Shipping AS, Repsol, and Sustainable Energy Catapult Centre are collaborating and are planning to test ammonia in a marine four-stroke engine under the Norwegian Research Council through the DEMO 2000 program (Wärtsilä, 2020). In addition, MAN Energy Solutions, Shanghai Merchant SDARI and ABS have a development project for an ammonia-fueled feeder container vessel intended to use this technology (Hansson et al., 2020).

7.6 Electricity (fully electric)

The electric-powered marine vessel is not a new concept. In the late 1830s, German inventor Moritz Hermann Von Jacobi invented a simple DC motor with small boats that could convey a dozen passengers by electric propulsion (Espen et al., 2015). Since then, great strides have been made to promote electrically powered ships. Electricity generated from wind (conventional wind turbine), biomass, and solar photovoltaics could be used for the ship's propulsion system. No modern prototype for wind turbines in ships exists, but the increased progress in wind turbine technology could likely see to its dissemination in the shipping industry. For solar-powered marine vessels, several existing practical examples are available. The Auriga leader project is the first ship to direct solar power into the ship's main electrical grid; about 328 solar panels were fitted to a 60000 gross tonnage car carrier generating about 10% of the ship's power stationary dock (Linus et al., 2015). Electricity generated from biomass for the shipping industry has also been reported. The port of Rotterdam has two large power plants able to generate clean electricity from biomass (Hsieh and Felby, 2017). Alternatively, conventional power plants could supply marine vessels with the required electricity (DNVGL, 2014), as renewable sources are intermittent and unreliable energy sources. However, choosing this pathway would mean that shipowners may have to install exhaust cleaning systems such as scrubbers or CCS. The promotion of electricity in marine vessels has attributes of improving energy management and fuel efficiency, reducing energy losses, power redundancy, noise, and vibrations (DNVGL, 2014). Currently, there is no existing cost assessment of electrical fueled ships. Still, cost-effectiveness will be impacted greatly by battery costs, which are falling rapidly (Schmidt et al., 2017), and the cost of electricity or fuel used for charging (Balcombe et al., 2019).

8. Strategies for achieving decarbonization

8.1 Description of Low- to Zero-Emission Technology in Maritime Transport

Maritime transport takes advantage of a variety of optimizing, and frequently innovative, solutions aimed mainly to reduce fuel consumption by the ship engine (Rehmatulla and Smith, 2015). In that sense, the obvious direction for ship owner community efforts is consistent with the sustainable development goal relating to reduction of ship-derived emissions. The literature points out various methods of classification and analyses of areas in which emissions from ships can be reduced, using—for example—emission-reducing technology as the classifying criterion. Accordingly, Seddiek et al. (2013) have distinguished three areas for possible reductions: ship engine, fuel quality, and fuel usage. Another classification applies emissions-reducing technology as its basic criterion (Bouman et al., 2017), classing the following five stages: (1) design, (2) modernization of existing drive systems, (3) retrofitting, (4) alternative fuels, or adding alternative power sources for on-board devices, and (5) time in commercial service. The most widespread emissions-reducing technologies can be segmented into the following areas: hull design, power and propulsion system, alternative fuels, alternative energy sources, and operation.

The measures that are being developed and applied to reduce ship-derived emissions primarily rely on the quality of fuel used. The resulting reductions are possible due to technical progress which is, on the one hand, elicited by ship owners themselves pushing for more fuel-efficient solutions. On the other hand, standards, and regulations in international law are becoming noticeably more restrictive, setting increasingly rigorous limits on emissions from ships during the sea voyage and port stoppage. Ship owners can quickly transition through these stages by, first, placing news ship-building orders and second, modernize the existing fleet. A detailed look at the process includes:

1. Exhaust gas treatment — all kinds of technologies bringing emission levels from traditional marine fuels into compliance with the applicable limits; note, these do not eliminate exhaust gases.

2. Cleaner fuels — technologies allowing for the use of cleaner fossil fuels, such as LNG and MGO, for compliance with the applicable emissions limits. LNG results in a 15% saving on CO_2 emissions, while MGO—being a more energy-rich fuel than HFO—leads to 1.3% increase in emissions.

3. E-fuels — cutting-edge technologies using fuels for on-board power generation and allowing ships to be driven by electrical energy incorporates all kinds of renewable energy sources.

4. e/H_2 - one of the only two technologies nowadays (i.e., except renewable energy sources on electrically powered ships) allows for zero-emissions shipping by using renewable energy sources to generate power for hydrogen production or to charge the ship's batteries.

8.2. Ship-port interface measures

Ports can facilitate shipping decarbonisation by adopting technical and operational measures in the ship-port interface (Alamoush et al., 2020, Winnes et al., 2015). The measures include i) provision of Onshore Power Supply (OPS) (Hall, 2010, Zis et al., 2014) preferably from renewable sources and the hyper powered vessel battery charging system for electric ships, ii) provision of bunkering with alternative fuels[7] (Styhre et al., 2017) such as LNG, ammonia, methanol, and hydrogen, iii) facilitation of shipping virtual arrival, Just-In-Time (JIT) berthing, and the Vessel Speed Reduction (VSR) (Chang and Jhang, 2016, Poulsen et al., 2018) through utilisation of electronic data exchange, PortCDM, and other digital technologies, iv) reduction of ships turnaround time (idling) (Alamoush et al., 2020), through berth allocation, yard allocation and scheduling, container terminal automation and operation system (TOS), automated mooring systems (AMS) and mid-stream operations, and v) provision of miscellaneous services such as hull cleaning and propeller polishing and electric shore-side pumps for bulk liquids (IMO, 2015). The shipping emissions in ports, however, amount to 5% of total shipping GHG emissions (ITF/OECD, 2018), which could be equal to 50% of port emissions in certain ports (Winnes et al., 2015). Other studies indicated that 15% of ships emissions are when ships are stationary, i.e. at a port's anchorage or berth (Mjelde et al., 2019), and thus the intensity could reach to three times higher than when ships are underway, as cited in (Cullinane and Cullinane, 2019). Nonetheless, ship-port interface measures may contribute to the reduction of 1% of shipping emissions in addition to 3% through provision of OPS (Halim et al., 2018), which is equivalent to 29.6 Mt CO_2 of international shipping emissions. It could be argued that the reduction of shipping GHG emissions may exceed the percentage of reduction in the ship-port interface, considering that ports have a key role in environmental upgrading and in greening shipping and supply chains (Notteboom et al., 2020, Poulsen et al., 2018, Puig et al., 2017).

Shipping is the most energy-efficient way to move large volumes of cargo. Yet ships emit NO, SO, CO_2 and PM into the atmosphere. Worldwide, from 2007 to 2012, shipping accounted for 15% of annual NO emissions from anthropogenic sources, 13% of SO and 3% of CO_2 (Smith, T. 2015). In Europe in 2013, ships contributed 18% of NO emissions, 18% of SO and 11% of particles less than 2.5 micrometres in size. For road transport, the figures were 33%, 0% and 12%, respectively. Aviation, by contrast, accounted for only 6%, 1% and 1%, respectively, and rail just 1%, 0% and 0%.

Energy efficiency is the IMO's present focus. Starting in 2013, its EEDI and SEEMP aim to lower CO_2 emissions from shipping through tighter technical requirements on engines and equipment, maintenance regimes and voyage plans. No absolute emissions-reduction targets were set. Long-term expansion in global trade and growing ship numbers mean that even if these measures are fully implemented, total shipping emissions are projected to quadruple from 1990 to 2050 (Anderson, K. 2012).

As Wan Z. et al notice (Wan, Z. 2016) implementing the following recommendations could save thousands of lives each year, ensure cleaner coastal air and reduce ecological damage from shipping:

Clean up ship scrapping. The IMO adopted the Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships in 2009, but only Norway, Congo and France have acceded as of February 2016. The IMO's priority should be to ensure that the principal scrappers — India, Bangladesh and Pakistan — adhere to these guidelines. The first step is to set up local offices in these countries to collect and analyse monitoring data independently and to propose improvements to local governments. International loan or aid programmes to these countries, sponsored by the World Bank or the Asian Development Bank, for example, should demand clean ship-scrapping practices as an incentive. To discourage transfer of scrapping elsewhere, a watch list of poorly performing countries needs to be updated by IMO regularly until an international convention enters into force.

Control emissions. Stricter IMO emissions regulations are needed, including a cleaner worldwide standard for sulfur released by combustion of marine fuel. A 97% cut in SO_x can be achieved by reducing the sulfur content from 35,000 p.p.m. to 1,000 p.p.m. fuel oil. Today's low oil price provides a great opportunity for this transition to happen. The current cost of 1,000-p.p.m.-grade fuel oil (around US$300 per tonne in Singapore, for example) is less than half of that of the cheapest dirty fuel four years ago.

Marine fuel is a sideline for oil refineries — only 2–4% of the total fuel market. Stricter emissions standards will stimulate demand for high-quality fuel. Incentive programmes (tax rebate and subsidies for producers) will be needed to ensure a reasonable profit margin to recover the initial high investment in developing countries, where there is little current capacity. Government interventions will be needed in countries with state-run oil companies, such as in China and India.

An alternative is to install scrubbers for exhaust-gas cleaning on ships. Scrubber units blend the exhaust gas with water or caustic soda to remove up to 99% of SO and 98% of particulate matter from high-sulfur fuel. At the moment, scrubbers are expensive, costing $2 million for one ship. But China, for instance, could equip its entire container fleet in one year by funding a 50% subsidy for scrubbers. The total cost? Just 0.5% of the $150 billion per year it has spent since 2013 to fight pollution. Shipping companies could recoup the other 50% in one year from fuel savings. With a stricter emissions standard, the demand for scrubbers would go up, and the costs down, as production scales.

Improve port management. Port authorities should review the environmental impact of their previous construction and disclose information on their future development plans to demonstrate responsible management of public assets. They should coordinate with transport-planning bureaus to seek the most economical and environmentally friendly strategy to dispatch goods; the optimal capacities of its terminals; and how to assist ships to load and unload quickly. Making port-business statistics and the results of environmental-impact studies accessible will allow the research community to be involved in the decision-making process. Environmental non-governmental organizations should campaign to increase public awareness of port development.

9. Conclusion

The main purpose of this thesis was to give an overview of how the shipping and the maritime industry may achieve the major environmental and climate change goals towards decerbonisation. This particular thesis utilised 78 internationally peer reviewed journal articles to understand how maritime transport has decarbonised between 2010 and 2020 and particularly how the shipping industry will achieve the ultimate goal of net zero emission by 2050. This thesis reviewed the potential for a multitude of options to decarbonise international shipping, including fuels, energy efficiency technologies, operations and policies. There is no single route to fully decarbonising the maritime industry, so a multifaceted response is required. While rooted within a complex international regulatory framework, decarbonisation could be supported by long-term, consistent and effective policy to enable the industry to effectively reduce emissions.

LNG is the main alternative to marine diesel and heavy fuel oil, and could provide a cost-effective reduction in CO2 emissions whilst meeting SOx and NOx emissions regulations. LNG is currently cheaper than the incumbent marine fuels, but infrastructure must be expanded to increase market share. Biofuels have great potential as a renewable source of energy and would be most commercially viable when used in conjunction with other liquid or gaseous based fuels. However, emissions, costs and applicability vary widely across different biofuels and the long-term ramifications of a dependency on biofuels for transport could be ultimately detrimental to achieving a sustainable industry.

Due to the emissions profile and flexibility of hydrogen as a fuel, the potential to reduce emissions in shipping and enable renewable industries is high, for example by utilising on-shore nuclear and renewable power generation to store hydrogen. The capital-intensive infrastructure requirements may leave hydrogen as a longer-term solution, but it may be more economically feasible to initially select a specific large vessels (e.g. tankers) and 'point to point' routes to be hydrogen fuelled, minimising infrastructural requirements.

The rationale of this thesis is that the incentives encompass the potential to facilitate the implementation of the IMO's ambitious targets to decarbonise shipping, and maritime supply chains, taking into consideration that strict regulations and market based measures need to be supplemented by such policy tools to avoid hampering shipping activities.

There are currently a range of exciting ideas for delivering decarbonisation, particularly for shipping, where the IMO-level agreement of 2018 has catalysed a range of stakeholders into action, across maritime, energy, infrastructure and finance sectors. With further collaboration across these sectors, supported by national governments and international organisations, shipping has the potential to become a catalyst for a broader, global energy transition, unlocking the market for zero-emission fuels more broadly (Global Maritime Forum, 2019).

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