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Fuel selection by the shipping industry due to a multifarious framework for achieving zero carbon and greenhouse gas emissions by 2050

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FUEL SELECTION BY THE SHIPPING INDUSTRY DUE TO A MULTIFARIOUS FRAMEWORK FOR ACHIEVING ZERO CARBON AND GREENHOUSE GAS EMISSIONS BY 2050

By

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Declaration

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views and are not necessarily endorsed by the University.

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Abstract

Title of Dissertation: **Fuel selection by the shipping industry due to multifarious framework for achieving zero carbon and greenhouse gas emissions by 2050**.

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This dissertation is the study of fuel selection and the combination of other pathways in the shipping industry by 2030 to achieve zero carbon and greenhouse gas emissions by 2050. An examination of current greenhouse gas reduction routes and their effectiveness was conducted. A study on different types of alternative fuels available by 2030 was examined. Various present legislative frameworks are examined, and future legal frameworks will be considered as a factor in the assessment of reduction effectiveness. Factors that will affect the decision-making to switch over to alternative fuels were examined.

The research has examined how the International Maritime Organization (IMO) and other global and regional regulations affect shipping and the potential strategies to minimize greenhouse gas emissions. Alternative fuel availability was analysed across the world's regions. The viability and cost of potential alternatives have been weighed in the decision-making process. Alternative fuels that are now accessible, as well as fuels that could be generated using green technology, were examined, and sustainability assessment in terms of technological, greenhouse gas reduction potential, availability, economics, safety, and energy density was carried out.

An expert questionnaire survey was carried out with a view to identifying the selection of alternative fuels by the shipping industry. The data gathered through questionnaires and literature were qualitatively analysed with the multi-criteria decision analysis. Analytic hierarchy process methodology was applied to evaluate the potential alternative fuel that will enable the shipping industry to achieve the goal of zero targets by 2050. Behavioural intervention, along with other measures, may contribute significantly to emission reduction.

The last chapter explores the results of the analysis of the primary and secondary data that was collected and has forecasted the potential selection of alternative fuels and methods. The research concludes that Ammonia is the most sustainable alternative fuel, and if selected in shipping along with methods like fitment of energy-saving devices and adaption of behavioural changes may lead to achieving zero carbon and greenhouse gas emissions by 2050.

KEYWORDS: Clean fuels, Decarbonisation, Greenhouse gas, Regulatory frameworks, Shipping emissions

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List of Abbreviations

AHP	Analytic Hierarchy Process
CBDRRC	Common But Differentiated Responsibilities and Respective Capabilities
CCS	Carbon Capture and Storage
CH4	Methane
CII	Carbon Intensity Indicator
COP	Conference of Parties
DNV-GL	Det Norske Veritas-Germanischer Lloyd
EEXI	Energy efficiency Existing Ships
EJ	Energy Joules
EU	European Union
FAO	Food and Agricultural organisation
GHG	Greenhouse gas
IGF	International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuel
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel Climate Change
LNG	Liquified Natural Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environment Protection Committee
SEEMP	Ship Energy Efficiency Management Plan
SOLAS	The International Convention for the Safety of Life at Sea
UNCTAD	United Nations Conference on Trade and Development
UNFCCC	United Nations framework convention on climate change
VAWT	Vertical Axis Wind Technology

1. Introduction

1.1 Background

Maritime transport covers 80–90% of worldwide trade, promoting global economic growth (Wang & Wright, 2021). International shipping consumes mostly fossil fuels and therefore emits greenhouse gas (GHG) into the environment. IPCC (Intergovernmental panel on climate change) working group-I reported in the month of August 2021 that controlling human-induced global warming will require net-zero CO_2 (Carbon Dioxide) emissions globally and considerable reductions in other GHG emissions (Intergovernmental panel on climate change [IPCC], 2021). Other factors, such as the limited oil supply and the long-term viability of the oil production chain, necessitate finding new means of propulsion in addition to the harmful emissions produced by fossil fuel combustion (Kroft & Pruyn, 2021).

Ships require fuels for propulsion purposes. The ship's main propulsion engine, which is an internal combustion engine, requires fuel so that when it is ignited converts mechanical energy into propulsion thrust by means of shafting. Most vessels diesel propulsion systems use fuel which is either heavy fuel oil (HFO) or diesel oil. When they burn, they emit various by-products in their exhaust. The main constituent of exhaust gas is Nitrogen, Carbon Dioxide, Carbon Monoxide (CO), Nitrogen Oxides (NOx), Sulphur Oxides (SOx) and a few other products. The by-products like oxides of Nitrogen and Sulphur are considered as air pollutants and are regulated in MARPOL (International convention for prevention of pollution from ships,1973 as modified by protocol 1988) Annex VI.

The International Maritime Organisation (IMO) has adopted and enforced reductions in Nitrogen oxides and Sulphur oxides. One of the by-products of exhaust gas is CO_2 which is of more concerned as it contributes to greenhouse gas emissions. It is predicted that the CO_2 emissions from international shipping to grow between 90-130% by 2050 to the 2008 emission level (International Maritime Organisation [IMO], 2020a). Various stakeholders like European Union (EU) have pushed the shipping industry to cut CO_2 and GHG emissions by zero per cent by 2050. Many research efforts have been carried out in order to find possible alternative fuels by the year 2050, taking cognisance of IMO 2018 initial strategy and goals of 70 % of CO_2 reduction and 50% of GHG reduction (Balcombe et al., 2019).

1.2 Problem Statement

The Paris Agreement's temperature goals could not be met solely with the current MARPOL Annex VI regulations, for reducing GHG emissions from ships (IMO, 2021). To reduce the environmental impact and meet zero targets, the international shipping industry must adapt to transition to renewable and alternative fuels. Many countries have agreed to emission reduction targets under international agreements such as the Kyoto Protocol through organisations such as the United Nations Framework Convention on Climate Change (UNFCCC) (Auvinen et al., 2014). According to much research, there is no widely available fuel to manage climate change and local pollutants for zero targets. Shipping can be decarbonised to achieve zero targets by 2050 by the use of alternative fuels along with operational and technical optimisation (Prussi et al., 2021).

1.3 Current Legislation on Greenhouse Gas Emissions

UNFCCC has set limits for global warming below 2°C in Paris agreement (Delbeke et al., 2019) which was held in the year 2015. The rise in fuel consumption associated with increased seaborne trade has resulted in an increase in international shipping emissions, which has drawn increasing global attention. In order to address this issue, IMO adopted an initial strategy (IMO, 2018) in the year 2018 for greenhouse gas reductions. Global initiatives to reduce GHG emissions from shipping, as outlined in the Paris agreement and the UN (United Nations) Sustainable Development Goals for 2030, are at the heart of the IMO's initial strategy (IMO, 2018).

The IMO aims to cut CO_2 emissions by 40% by 2030 and 70% by 2050, as well as GHG emissions by 50% by 2050. Marine environment protection committee (MEPC) 203rd resolution of 62nd session has decreased shipping's carbon footprint since 2011 by implementing the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) (Balcombe et al., 2019)

). The measures adopted are technological efficiency, energy management onboard and thereby aimed at reduction of CO_2 emissions (Marine Environment Protection Committee [MEPC], 2011). As detailed in Appendix-B, revision to MEPC 75 has decreased the requirements for gas tankers, container ships, general cargo ships, and liquefied natural gas (LNG) carriers to Phase-2 (1st January 2020 to 31st March 2022) and Phase-3 (1st April 2022).

The goals set out in IMO's initial strategy and other similar measures adopted in many countries has resulted that the Paris's meeting goals may not be met. In the 26th session conference of parties (COP), which was held in 2021 at Glasgow, it was concluded that global greenhouse gas emissions are still much below the needed levels to maintain a liveable climate and support the country most at risk from climate change is woefully inadequate. Consequent to this, in the IMO MEPC 77th session, it was decided that IMO's initial strategy needs to be revised, and international shipping must reduce GHG emissions by 2050 to meet the Paris agreement temperature goals.

1.4 Aims and Objectives

The study is to analyse the sustainability of alternative fuel oils by 2030 and the selection of alternative fuels by the shipping industry due to numerous regulations that will be enforced, and commitments made by the IMO, many regional groups, governments in the UN COP for possible zero CO_2 and GHG emissions by the year 2050.

Objectives

- To study the availability and sustainability of alternative fuels by the year 2030 so that the shipping industry decides for adaption to alternative fuels.
- To discuss the various regulatory framework, including unilateral measures adopted by EU and other similar groups for the reduction of CO_2 and GHG emissions in the shipping industry.

- To determine how the shipping industry will adapt to alternative fuels by 2030 and recommend the best viable selection criteria mechanism of the fuels in order to achieve zero CO_2 and GHG emissions by the year 2050

1.5 Research Questions

1. What are the different types of alternative fuels available, and what will determine their availability by 2030?
2. Will the IMO measures like the 2018 Initial strategy for greenhouse gas reduction will alone be adequate, or other initiatives from EU or other groups' actions will drive more stringent measures?
3. How will the factors like economic, technical, environmental, IMO and EU measures etc. will, affect the decision-making of the shipping industry to switch over to alternative fuels or with the combination of other measures to achieve zero targets by 2050?

1.6 Methodology

As the target of zero greenhouse gas emission by 2050 in international shipping is not enforced and is expected to be in force in future, there won't be much readily available data. This research aims at what could be possible available of alternative fuels by the year 2030 so that ships are designed to adapt to alternative fuels and other renewable measures so that by the year 2050, all ships meet zero targets of GHG. Since the availability of alternative fuels on a regular basis in all regions of the world is not certain, the research intends to collect the data available from surveys, fuel manufacturers and literature database. The research will also aim to gather possible new regulatory frameworks that may be enforced in international shipping, and hence the required information will be obtained from the literature.

In order to achieve zero GHG targets by 2050, ships need to be built by the year 2030, which has a significant reduction in GHG emissions so that by the year 2050, international shipping will achieve zero targets. By analysing the availability of alternative fuel and thereby selecting the fuel and possible other renewable measures, ship design for construction and using a multicriteria decision analysis approach with input from industry stakeholders will be undertaken to assess the sustainability of alternative fuels. Inputs from shipowners, regulatory authorities, engine manufacturers, classification society, shipbuilders, chief engineers onboard, the effect of fuels on diesel engines, economical cost, availability etc., will be utilised in multicriteria decision analysis. Since the subject of the study is a new technology, it would be most suited to use qualitative research methodology, as shown below in Figure-1.

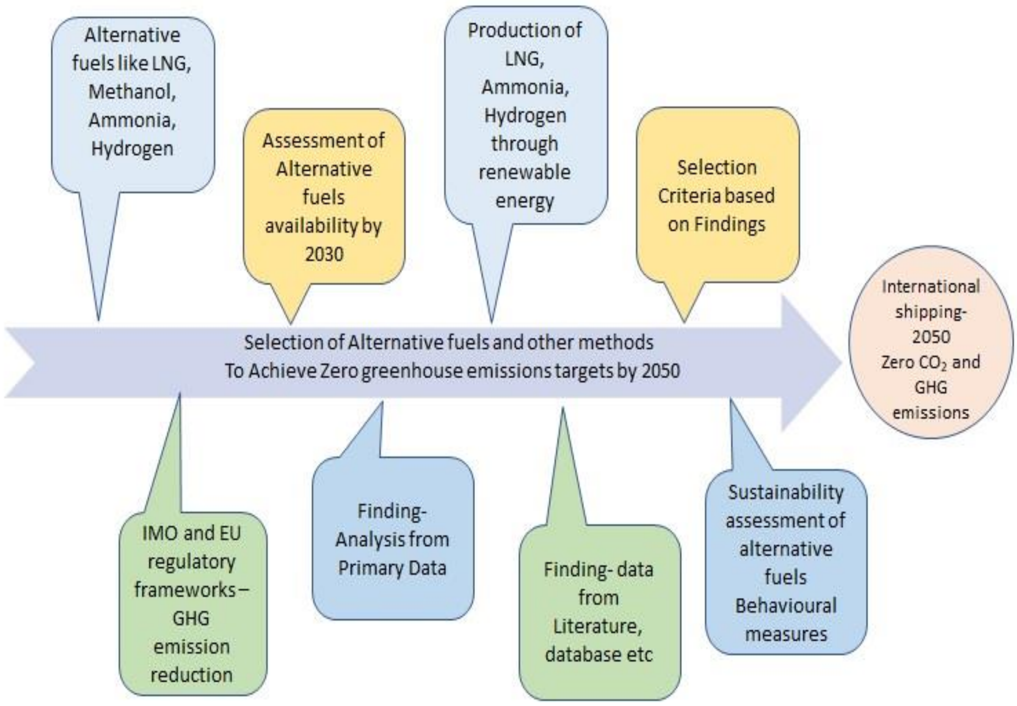

Figure 1 Research process adapted in this study to goal of zero GHG emissions

Note. Created by Author

The following methods are applied.

1. Questionnaire
2. Multicriteria decision analysis

Figure-1 shows the research process that has been undertaken. This research has involved the study of the availability of alternative fuels in all global regions by 2030, considering the demand for seaborne trade that may also be expected to grow by 2030. The primary data source has been collected through survey questions and secondary data from literature and database. Literature database for regulatory frameworks were analysed and used as a criterion for selection. Survey questions were framed for carrying out qualitative research.

The Analytic Hierarchy Process (AHP) based technique to multicriteria decision analysis utilised by Hanson et al. (2020) has been applied in this study. Alternative fuels include a wide range of sub-criteria for selection, and an analytical hierarchy process is the best method for selection (Hansson et al., 2020).

1.6.1 Qualitative Research

Research is "a systematic process of investigation whose main goal is to add to the body of knowledge that shapes and guides academic and/or practice disciplines."(Powers & Knapp, 2006, *p.* 139). There is no simple definition for qualitative research. It relates to a variety of research techniques that associate one feature: they rely on qualitative judgments. Decarbonisation in shipping is a diversified context, and different entities have many views. Legislation is not implemented globally in a uniform manner. For purpose of studying the behaviour experiences of individuals and groups of people, qualitative research provides us with a broad range of cultures (Feldman & Hall, 2002).

"Humanistic commitment to study the world always from the perspective of the gendered, historically situated, interacting individual" is how Lincoln and Denzin (2000) describe qualitative research (Lincoln and Denjin, 2000). The views of different stakeholders may vary in achieving common goals. Shipowners tend to make a profit rather than invest in technology, and regulators want strict enforcement. The common man wants to have a clean climate. Few countries want development as an important agenda and consider strict enforcement in international shipping may burden their economies. The diversity in perception of zero targets is a key strength. Qualitative research offers numerous approaches to comprehending the variable and unpredictable nature of human nature and experience. It is genuine to use multidisciplinary perspectives and mixed methods to investigate situations involving multiple and complex layers of individual and group effort.

The design of ships needs to be in such a way that ships should be able to store fuels other than fossil fuels, and ships are to be constructed with all their equipment and piping that are suitable for alternative fuels. The input from industry stakeholders like shipowners, shipyards, classification societies etc., will be taken by way of a questionnaire or survey. The pursuit of knowledge through questioning is referred to as research. Researchers' questions are important tools for framing, focusing, giving feedback, and ultimately resolving research goals (Higgs et al., 2009). The question in qualitative research uses predetermined questions to get the thing rolling for the research and then reframed to honour the emerging concept of a phenomenon. The research questions reveal the research's intention, hinting at what is to come, insights, and knowledge that is likely to be discovered.

A good questionnaire is one that lets the respondent send accurate and useful information or data to the researcher. This is a complicated process that involves asking questions in a clear, unambiguous way so that the person answering can figure out what they mean and say what they mean. In this research, a survey questionnaire will be sent to stakeholders through the internet, and their feedback will be sought. The inputs received from industry stakeholders will be utilised in multicriteria decision analysis so that criteria may be evolved. To arrive at this decision questionnaire will be sent to the stakeholders, and after receipt of inputs, an analysis will be carried out.

The research will also involve the study of legislation which has not been yet finalised for zero targets. A review of the current literature is the most suitable way to carry out research. The new regulatory framework for zero CO_2 and GHG targets is not yet framed. In the 77th session of MEPC, it was decided to revise the 2018 Initial strategy and align the targets with the Paris Agreement targets to achieve zero emissions by 2050. IMO’s revised proposal document and other groups like the

European Union database/directives and available literature will be reviewed, and therefore qualitative research method will be adopted.

1.7 Limitation

This research is aimed at selecting the fuels and other viable energy-saving systems that will make ships emit zero CO_2 and GHG emissions by 2050. There are not many statistics available on the type of propulsion engine that will be required to use for the fuel which might be available in all parts of the world. The currently available research available envisages that fuels like Ammonia or Hydrogen may be used as an alternative to achieve zero CO_2 and GHG emissions. Regulatory frameworks are mandated to reduce 70% of CO_2 compared to the 2008 level and 50% of GHG by 2050 compared to the 2008 level. The new regulatory framework is expected to be adopted in the MEPC 80th session, wherein IMO 2018 initial strategy for GHG reduction may aim at zero targets; however, the pathway is not clear except for existing technical and operational measures.

2. Literature Review

2.1 Introduction

There is no denying fact that maritime transportation has a significant impact on global trade, contributing to both air pollution and climate change. Approximately 119,99 ships make for the global commercial fleet, which has a gross tonnage of 1.45 billion (Equasis, 2020) in 2020. Between 2008 and 2018, the average annual growth rate for both the number of vessels and the gross tonnage was 4.6 per cent and 5.0 per cent, respectively (Equasis, 2020). Between 2007 and 2012, annual marine fuel consumption averaged 250 to 325 million tonnes, while yearly maritime CO_2 emissions averaged 1016 million (IMO, 2014). The estimated rise of CO_2 emissions in 2050 may be in between 90 % to 130 % of the 2008 level based on several "business as usual" scenarios (IMO, 2020a).

In a study, it was identified that Hydrogen, Ammonia could play a key role in short sea shipping and domestic shipping, and Methanol could be adapted for global shipping if the production of Methanol is from renewable energy sources (Xing et al., 2021). Alternative fuel production contributes to CO_2 emissions; therefore, there is a need to switch to production from renewable energy. The role of LNG is limited as transition bunker fuel owing to its potential for methane slip (Cookson & Stirk, 2019).

A certain number of regulations are driving the shipping industry to cut CO_2 and GHG emissions by 2050. Many research effort have attempted to find possible alternate fuels by the year 2050, taking cognizance of IMO 2018 initial strategy and goals of 70 % of CO2 reduction and 50% of GHG reduction (Balcombe et al., 2019). The literature review identifies the selection of alternate fuel by the shipping industry in the year 2030 with a possible adaption of additional mechanisms in achieving the goal. It concludes that international shipping has to select alternate fuels in conjunction with energy-saving devices to achieve zero carbon and greenhouse gas emissions by 2050.

Shipping accounts for 2.89 per cent of worldwide yearly CO_2 emissions in 2020, in the latest GHG study by the IMO (IMO, 2020a). This figure is expected to rise to 17 percent by 2050 owing to the development in global commerce and reduction in emissions in other sectors according to a study conducted (Wan et al., 2018). The growth in seaborne trade will drive an increase in emissions, and hence efforts need to be addressed for emissions cuts. According to a study, global seaborne trade may grow to 22Gt in 2050 in a sustained growth scenario (Müller-Casseres et al., 2021). The consequence of this study is that greenhouse gas emissions may rise proportionately.

Methanol has evolved as promising alternative fuel produced from natural gas and has the advantage of reduction of 20% of CO_2 than fossil fuels. However, its production leads to CO_2 emissions, and therefore methanol production with a combination of carbon capture storage is most advantageous (Forsyth, 2022). Carbon capture and storage (CCS) and natural gas are utilised in the production of 'blue' Methanol. It is the technique of collecting CO_2 before it is released into the atmosphere and stored or recycling.

Bio-methanol obtained from renewable energy has the potential to generate a fuel that produces zero GHG. However, the cost and availability is considered as challenging. According to Wan et al., (2018) fuel cells, waste heat recovery, solar or wind power, and shore-to-ship power have all emerged as viable alternatives to fossil fuels, but they are unable to lead to a low-carbon future because they demand not only engineering advances in an economically viable manner, but also a shift in the industry's outlook.

2.2 Challenges in Alternate Fuels

The harmful emissions caused by the combustion of fossil fuels and other factors such as the finite oil supply and the sustainability of the oil supply chain create the need for alternative propulsion solutions (Kroft & Pruyn, 2021). Few research has identified that LNG may reduce CO_2 emissions; however, it contributes to GHG emissions. LNG contributes to Methane slip, and this contribution to GHG emission offsets the benefits in reduction of CO_2 emission. “Any significant methane slips can wipe out the advantage of LNG in GHG emission reduction” (Wang & Wright, 2021).

Drop in Biodiesel, Hydrogen and Ammonia are not available in all parts of the world. Production of Hydrogen from renewable energy sources could become competitive in the long run (2030–2050) if capital costs decrease significantly (Brändle et al., 2021). Technology readiness is the key factor in switching to alternative fuels. The economic viability of each fuel is influenced by its energy density, volumetric density, and temperature.

Liquid Ammonia takes more storage space to produce the same amount of energy as Marine gas oil(MGO) and LNG, respectively, due to less volumetric energy density (International Renewable Energy Agency[IRENA], 2021a). Due to Hydrogen's 3.6- to 4.5-fold greater capacity, long-distance vessels may not be ideal candidates for hydrogen use since their storage volume is so much higher than HFOs. Relative cost assessment for alternative fuels was carried out in a study and assessed that alternative fuels cost around 2 to 185 times higher than heavy fuel oil (Law et al., 2021).

A report from IPCC 2022 working group-III states that worldwide net anthropogenic GHG emissions were 59.6 gtCO2eq in 2019, a 12 per cent increase from 2010 and 54 per cent increase from 1990, a total of 59.6 gtCO2eq in 2019 indicating that international shipping may have to move to clean fuels from fossil fuels by 2050. Access to capital can be the biggest challenge in investing in energy-efficient technology and ships. Several shipowners have made investments in LNG ships, but these investments are now in peril due to methane slip problems.

The fourth IMO GHG report (IMO, 2020a) has indicated that methane emissions have increased from 59000 tonnes in 2012 to 148000 tonnes in 2018, and the main cause is attributed to methane slip from LNG ships. The propulsion engine for the use of Ammonia will be tested by 2023, and if proven to be successful, the selection of Ammonia as fuel can be promising. According to the world energy outlook 2021, a new energy economy is on the horizon, propelled by legislative action, technological innovation, and the pressing need to combat climate change (Cozzi & Gould, 2021). However, it is not expected to be smooth and has to face challenges to achieve the roadmap of net zero targets (Cozzi & Gould, 2021).

Emissions throughout the entire production chain, including manufacturing, storage, transportation, and distribution to end-users, need to be considered when evaluating alternative fuels for their ability to support reductions in emissions and their related environmental implications (Wang & Wright, 2021). The assessment of fuels in this approach is a big challenge, and research is needed in this aspect. World economies are not at equal levels, and any regulatory framework to adopt to achieve zero targets may affect the developing countries and jeopardise their economies.

2.3 Multifarious Regulatory Framework and Goals

In 2018, the IMO announced an initial strategy to cut GHG emissions by half by 2050 compared to 2008 (IMO, 2018). In 2021 the 26th session of Conference of Parties (COP 26) reiterated that global emissions from international shipping should adopt more stringent measures by 2050 to keep the global temperature rise within 1.5 Deg. Based on the conference's new announcements, experts estimate the path is between 1.8°C and 2.4°C (Vice-president & Timmermans, 2021). The IMO's approval of the Energy Efficiency Design Index (EEDI) at the MEPC 62nd session in July 2011 was the sole obligatory regulatory step restricting GHG emissions from ships.

Two and a half years following the approval of the 2018 Initial IMO Strategy, MEPC 75th session in November 2020, approved short-term measures, and the MEPC 76th session in June 2021 adopted the short-term measures. IMO's fourth GHG report (IMO, 2020a) has confirmed that international shipping contributes around 2.89% of the global total anthropogenic emissions. The amount of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), measured in CO_2e, emitted for the year 2012 is1076 million tonnes. IPCC(2022) has confirmed that IMO's 2018 Initial strategy for GHG reduction will be kept under review by the MEPC until 2023 when a new revised strategy will be adopted (IPCC, 2022), and the same was adopted in the MEPC 77th session. Behavioural interruption may also push the GHG emission reduction efforts.

According to IPCC (2022) “With policy support, socio-cultural options, and behavioural change can reduce global GHG emissions of end-use sectors by at least 5%” (p. 46). Policymakers should attempt to balance disruption across technology deployment and behaviour change in order to enhance the likelihood of rapid and successful emission reduction (Nelson & Allwood, 2021). Yuen et al. (2017) have identified that sustainable company practices are influenced by stakeholders’ pressure and behaviour patterns. In a study, the external and internal factors that may affect the behavioural measures of a company were explored, and it was found that both factors can significantly affect behaviour (Zhang et al., 2022). An estimation was forecasted for the effect of behaviour measures on the contribution of CO_2 reduction by 2050 (International Energy Agency [IEA], 2021).

IMO's initial strategy covers short-term, medium and long-term policies (2018-2030) for attaining its emissions reduction objectives, including two potential market-based measures in the medium-to-long term (Ölçer et al., 2018). Conflicts between the common but differentiated responsibilities and respective capabilities (CBDRRC) concept of the climate regime and the conventional non-discrimination approach and notion of no more favourable treatment entrenched in MARPOL and other IMO treaties impede further development of market-based initiatives.

Due to the challenges faced in adopting global market-based regulations for shipping emissions under the IMO, the EU-ETS (European Union Emission Trading System) has been extended to include emissions from maritime activities. (Christodoulou et al., 2021). The European Union has adopted "Fit for 55" in the new EU Climate law and aims at a 55% reduction of GHG by 2030 to the 1990 level in the European region. This measure is considered more ambitious than IMO's 2018 initial strategy for GHG reductions.

2.4 Selection of Alternative Fuels by International Shipping

The availability of particular alternate fuel by the year 2030 is not very clear. However, there is a high likelihood that Ammonia and Hydrogen will be available for international shipping (Serra & Fancello, 2020). In the medium to long term (2023-2030) to beyond 2030, IMO intends to create a program for the shipping industry to stimulate the use of low-carbon alternative fuels. (Wang & Wright, 2021). LNG has been widely used since IMO has enforced strict rules for SO_x and NO_x emissions, and many ships have switched to this fuel. LNG, which comprises methane primarily, is preferred over HFO because it contains less sulphur and carbon and produces fewer NO_x emissions from engines (Brynolf et al., 2014).

Biofuel can also be considered as an alternative fuel. However, the cost of the adaption of biofuels is not very encouraging. Emission reductions of up to 80% relative to HFO are expected at fuel prices of roughly 900-1050 Euro/ton (Kroft & Pruyn, 2021). Many research has identified the benefits of Biofuels even though switching to this particular fuel does not achieve the zero-emission target. Ammonia must be produced using renewable energy in order to reduce GHG emissions (Hansson et al., 2020).

Studies have reflected that the use of LNG or Methanol has limitations due to the disadvantage of methane slip; therefore, LNG may be used as transition fuel till 2030, and after 2030 ships should be able to switch to Ammonia or Hydrogen, which has to be produced using sustainable methods like from renewable energy sources. Data has been collected from the stakeholders by survey questionnaire and collected data with literature review data has enabled the researcher to provide the selection criteria. When many alternative fuels are available, and each fuel has sub-criteria to select, multicriteria decision analysis is the most suitable tool. Multicriteria decision analysis (MCDA) is a decision-making technique used to deal with difficult choices (Hansson et al., 2019).

2.5 Conclusion

Alternative fuels are required to significantly reduce greenhouse gas emissions associated with shipping. The overall goal of this research effort was to evaluate the potential sustainability of alternative fuels by 2030 and provide a selection criterion for international shipping to achieve zero emissions in 2050. Also, to aid to prepare the ships to adapt to alternative fuels and other energy sources to achieve zero greenhouse gas emissions and zero CO_2 emission by 2050 compared to the 2008 level. While much research has been carried out for the selection of alternate fuels considering IMO targets of the 2018 initial strategy, there is not much research carried out for achieving zero CO_2 and zero greenhouse gas in 2050.

This research, more specifically, contributes to a knowledge synthesis on how international shipping should adopt multifarious regulatory measures which aim at zero carbon and zero greenhouse gas emissions by the year 2050. The next chapters will elaborate on how the goal will be achieved in this research.

3. Fuels and Reduction of GHG

3.1 International Shipping Contribution to GHG Emission

Examining the nineteenth century, the addition of steam power from the sceptical perspective of the ship allows us to consider the multiple geographies of steam and its global production in space (Stafford, 2017). It was Rudolf Diesel who invented the diesel engine in 1892, and it took another two decades for the first four-stroke diesel ships to sail the seas. As ships grew larger and faster, two-stroke engines began to take the lead due to the availability of fossil fuels (Corbett, 2004).

Over the course of World War-I and II, the percentage of oceangoing ships powered by marine engines rose to approximately 25% of the total tonnage. The M.V “The Princess of Vancouver” was the first ship to pioneer the use of heavy fuel oil. To counteract the acids produced by the combustion of high sulphur residual fuels, cylinder lubricants with high alkalinity became available in the mid-1950s, and wear rates were like those found when using distillate diesel fuel. In the 1960s, motor ships outnumbered steamships in terms of both number and gross tonnage, and this trend continued till the 1970s. Motor ships made up 98% of the world's fleet by the turn of the twenty-first century.

Figure-2 reflects the comparison of fuels consumed in international shipping for the years 2019 and 2020. It is estimated that the total fuel oil consumption for the period 2019 and 2020 are 213 MT and 203 MT, respectively, as per IMO fuel data collection system reporting (IMO, 2021). The use of LNG increased to 5.9% in 2020 when compared to 4.92 % in 2019. Light fuel oil has increased from 4.7% in 2019 to 29% in 2020, and the corresponding reduction in heavy fuel oil consumption.

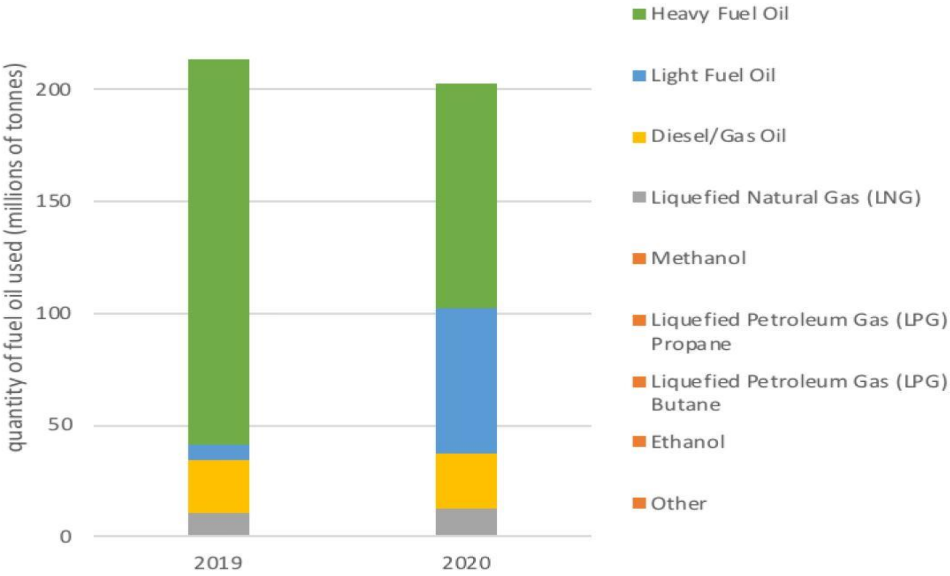

Figure 2 Comparison of Fuel Consumption for the years 2019 and 2020 in International Shipping

Source (IMO, 2021)

According to the fourth IMO GHG report (IMO, 2020a), the GHG emissions may rise in the year 2050 up to 90-130 % as compared to the 2008 level and as per this report, around 2.89% is the contribution of shipping emission to global anthropogenic GHG emissions. In comparison, a study predicted that GHG emissions might rise by 250% to the 2012 level, considering the dynamic growth in global seaborne trade (Wan et al., 2018). Population growth, resource utilisation, technological innovation, and modernisation together seek to be catalysts for growing maritime transportation, leading to a higher CO_2 emission resulting from increased voyages.

Figure-3 reflects the CO_2 emissions from international shipping from 1990 to 2020. CO_2 emissions from international shipping for the year 2020 are about 765 million metric tonnes and has doubled since 1990. There has been a decrease in emissions from 2010 to 2013 due to the enforcement of EEDI measures adopted by IMO in 2011 (MEPC, 2011).

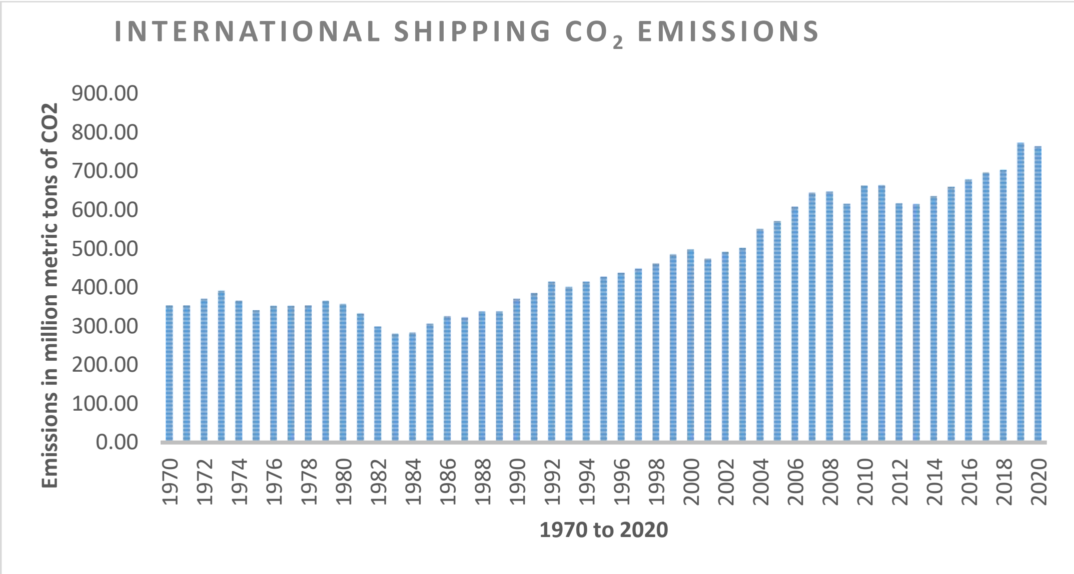

Figure 3 Carbon dioxide emission from international shipping worldwide from 1970 to 2020

Created by author by adapting from (Statista, 2022a)

3.2 Regulatory Frameworks and Ways Ahead

Shipping is a global industry, and the ocean serves as its main means of transportation when correlated to other modes of transport; thus, emissions occur in international waters. National and regional policies would be unlikely to attain the carbon-free ambition by 2050. IMO on 5th December 2003, adopted resolution A.963 (23) factored the technical, operational, and market-based solutions to reduce GHG, whilst there were no regulations (Wan et al., 2018).

The best method to reduce CO_2 emissions from international shipping is to implement global legislation to ensure that the same rules apply to everyone (Gritsenko, 2017). CO_2 pollution levels in 2019 were the greatest in at least two million years (IPCC, 2021). Shipping is an important core of trade, accounts for 80–90% of international trade, and may rise to 17% of total global GHG emissions by 2050 (Serra & Fancello, 2020).

In June 2021, the 76th session of MEPC has adopted amendments to Annex VI of MARPOL, mandating ships to decrease GHG emissions, focusing on the technical and operational measures to improve ship energy efficiency (MEPC, 2021a). The measures adopted are aimed as a short-term measure. Energy Efficiency Existing Ships Index (EEXI), Carbon Intensity Indicator (CII), which includes an A to E ship rating system, and the strengthening of the SEEMP were all adopted by MEPC 76 as a combined short-term measure. Proposals to reduce carbon dioxide emissions by 1 per cent per year until 2023 and 2 per cent per year between 2023 and 2027 were accepted by MEPC 76. The remaining reductions until 2030 were left open for a future review in 2026.77th session of MEPC has adopted to revise IMO 2018 initial strategy with the aim of achieve of higher targets, and the outcome is expected to approve in the 80th session of MEPC.

MARPOL Annex-VI is aimed to reduce ship-borne pollutants like SO_x, NO_x, Ozone depleting substances, Volatile organic compounds, resulting in higher carbon emissions due to lesser regulation to curb emissions (Bouman et al., 2017). On 14th July 2021, the European Commission released its "Fit for 55" bundle of recommendations, which aims to reduce EU GHG emissions by 55 per cent by 2030, paving the road for complete EU decarbonisation by 2050 (Schlacke et al., 2022). Integrating technology into law and regulation (Bouman as cited by Joung et al. l, 2020) will sufficiently help in regulating carbon emissions. States differ in the number of emissions, the more industrialised, the higher the emittance. Setting up a global regulatory regulation, technological advancements, efforts from various stakeholders and could be a realistic technique for moving in the correct direction to regulate such pollutants (Hackmann, 2012).

The shipping sector urged the IMO at its 26th Conference of Parties session to achieve its aims of decarbonisation by minimizing carbon emissions. Cooperation with other UN agencies and all maritime value chain stakeholders on climate, like UNFCC, is vital in the process of making a treaty on carbon emissions. The earlier we implement regulations to curb carbon emissions, it's better the entire biodiversity because of the irreversible nature of biodiversity loss and the ever-increasing quantities of carbon emissions into the atmosphere.

3.3 Availability of Fuels for Shipping

Almost all of the energy used in the maritime sector comes from fossil fuels, mostly heavy fuel oil. With the technology we have now, the IMO's goal of reducing emissions by 30% by 2030 can be met through a mix of short- and medium-term steps, such as slowing down, making operations more efficient through data analytics, using less low-carbon fuels, and making designs that use less energy. To reach the 2050 goals, however, shipping needs to switch globally to alternative fuels and energy sources and other measures like behavioural intervention.

With a 0.5 per cent sulphur limit becoming mandatory due to IMO regulations on 1st January 2020, the demand for distillate fuels has increased. Many shipowners have considered the use of scrubbers for exhaust gas washing on existing ships so that fuel with a sulphur content of 3.5 per cent can be used onboard. According to United Nations Conference on Trade and Development's (UNCTAD) 2021 report, seaborne trade is expected to grow at a rate of 2.4 per cent between 2022 and 2026 (Uniten Nations Conference on Trade and Development [UNCTAD], 2021). As a result, the demand for shipping fuels may rise.

3.3.1 Oil Fuels

Heavy fuel oil and marine diesel oil account for 98 per cent of the fuel used in the fossil fuel industry, and while carbon-free fuels such as Hydrogen and Ammonia are being developed, and they are still economically immature. It is expected that the availability of fossil fuels will increase further in coming years. Figure-4 reflects the estimate of fossil fuel production in energy joules up to 2040. Around 225 EJ/year as an estimate for production of fossil fuel may be anticipated in the year 2040 as per the report (United Nations Environment Programme [UNEP], 2021). According to the 2021 production gap report of the UNEP, to meet their climate goals, countries have not expressly acknowledged or planned for the rapid decline in fossil fuel production required to meet these targets and governments around the world are aiming to burn more fossil fuels by 2030 than is necessary to keep global warming to 1.5°C. Availability of heavy fuel oil/distillate fuels for shipping will not pose a shortage; rather, it might not be used if stricter regulatory frameworks are enforced.

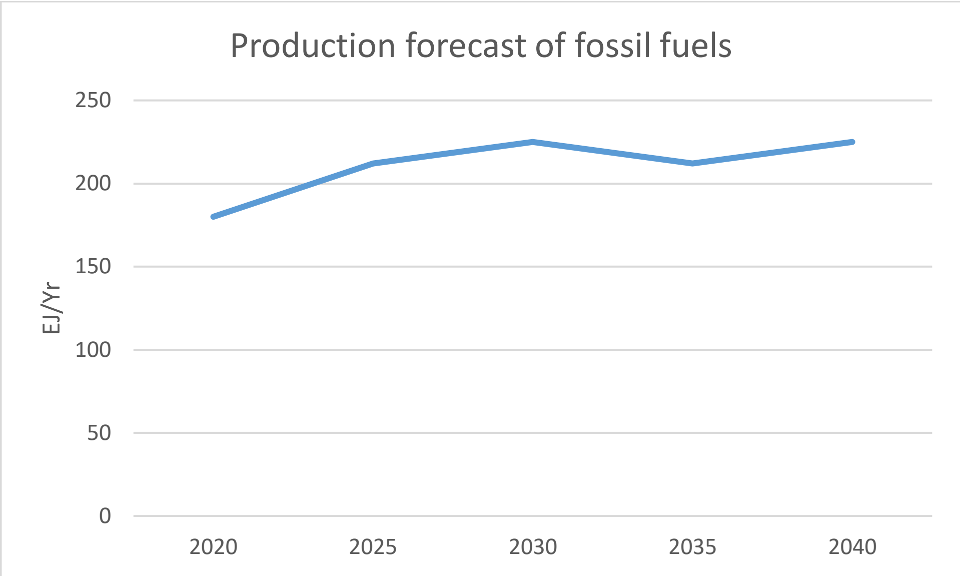

Figure 4 Forecast of Fossil fuel Production in Energy Joule/Year up to 2040

Created by author by adapting from (UNEP, 2021)

3.2.2 Liquified Natural Gas

With the IMO's tightening of SOx (Sulphur oxides) regulations introduced in January 2020, the introduction of LNG-fuelled vessels that do not use heavy oil has gained attention. Because of the pre-liquefaction process in which LNG removes sulphur, it produces almost no SOx or particulate matter (PM) when burned, and it emits significantly fewer NOx) and CO_2 than other fossil fuels . In addition, its specific gravity is lower than air, and it diffuses easily, reducing the risk of an explosion. As a result, it has a significant advantage over oil in terms of proven reserves and the ability to provide a steady supply for more than 50 years.

Figure-5 reflects global natural gas production from 2011 to 2021. According to the British Petroleum (BP) statistical review report published in the year 2021, natural gas production was around 4036 billion cubic metres for the year 2021(British, 2022). The production is much sufficient for the use of LNG as a fuel on ships.

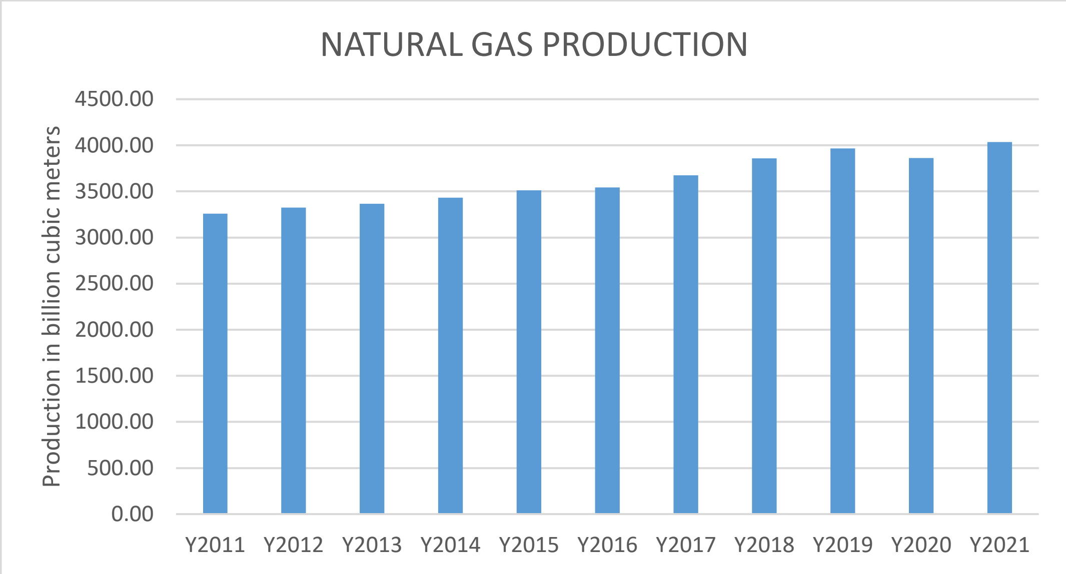

Figure 5 Year wise Natural gas production between 2011-2021 in billion cubic metres

Created by author by adapting from (British, 2022)

The development of new LNG bunkering facilities is also required for the widespread use of LNG-fuelled ships. LNG bunkering is possible at the ports of Rotterdam, Amsterdam, Zeebrugge (Belgium), Barcelona (Spain), and other major ports. According to Lowell et al. (2013), high methane emission scenarios produce more GHG than liquid fossil fuels. Methane is a powerful greenhouse gas, and the smallest emission may cancel out the carbon benefits of switching from HFO or MDO (Lowell & Bradley, 2013).

3.3.3 Low carbon fuels

Methanol is being used in international shipping as restrictions are imposed on emissions from fossil fuel use (Forsyth, 2022). Fig-6 reflects that production of Methanol and it was 160.46 million tonnes in the year 2021 as compared to 140 million tonnes in 2018. Production of Methanol from fossil fuels leads to the emission of greenhouse gases, and hence a lot of campaign is gained momentum for production from biomass and renewable energy sources, leading to cost escalation (Ahad Al-Enazi a, Eric C. Okonkwo a, b, Yusuf Bicer a, 2019).

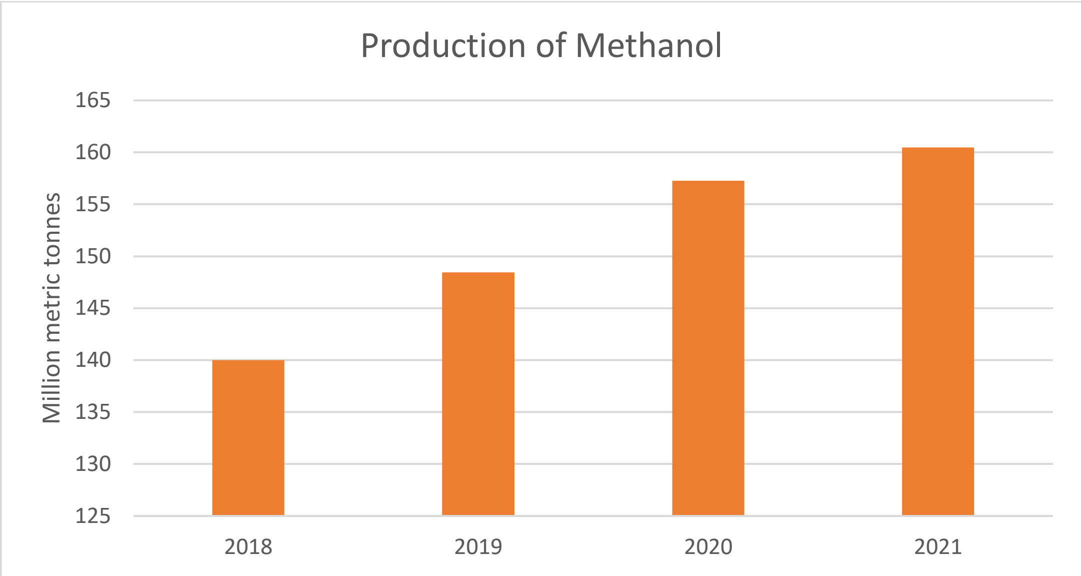

Figure 6 Production growth of Methanol in Million metric tonnes from 2018 to 2021

Created by author by adapting from (Statista, 2022b)

Production has increased from 2018 to 2021 (Statista, 2022b) and expected to grow further till 2030

Ammonia and Hydrogen are expected to use as an alternate fuel in shipping by 2030 (Ölçer et al., 2018). Ammonia is currently manufactured primarily from natural gas and coal (72% and 22%, respectively) and it's production in the year 2020 was 183 metric tonnes and may reach 333 metric tonnes by 2050 in a sustainable scenario (IRENA, 2022). Carbon-free fuel and Hydrogen carriers made from renewable Ammonia have been proposed but have yet to be deployed on a large scale.

Figure-7 shows the demand growth of Ammonia by 2050 in a sustainable environment for various uses. Additional new applications for Ammonia are likely to emerge during the next few decades, particularly in the maritime industry, as a Hydrogen carrier, stationary power and heat source, and transportation fuel. Energy markets may account for a significantly greater growth rate beyond 2030 than present markets. A 1.5°C scenario predicts that worldwide Ammonia demand will reach 688 Mt by 2050, more than three times the amount predicted in 2025 (IRENA, 2022). Around 220 Mt demand for Ammonia in shipping is expected by 2050.

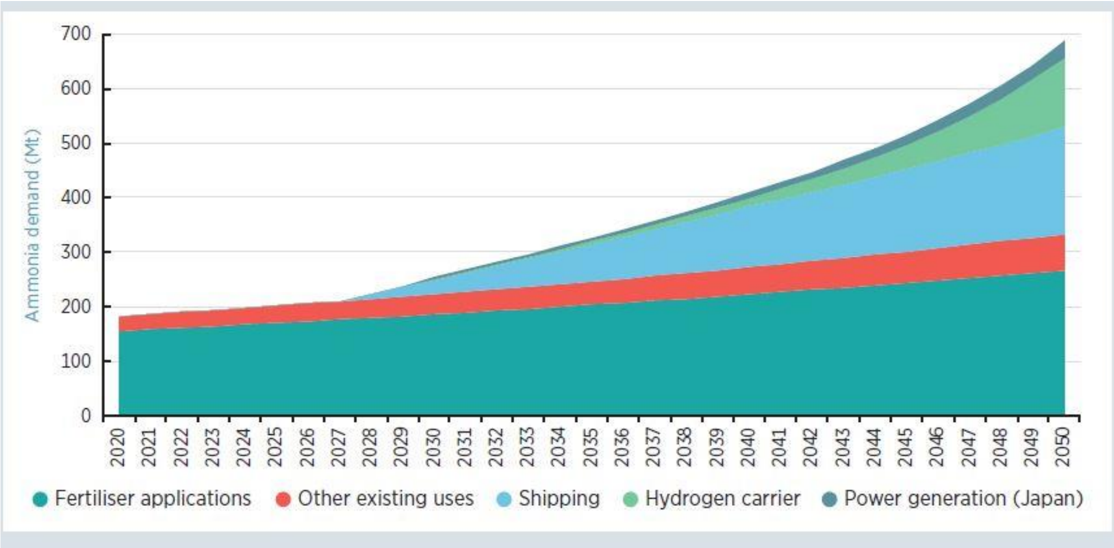

Figure 7 Global Ammonia demand forecast in all sectors by 2050 for 1.5° C scenario

Source (IRENA, 2022). Demand for Ammonia in shipping increases by 2050 as compared to use of Ammonia in 20220.

Because Ammonia fuels are in short supply, they are not widely available throughout the global region, and they need to be produced in anticipation of demand in shipping. Few ships use Methanol as a fuel, and safety precautions are implemented according to IMO (IMO, 2020b) interim guidelines; however, the economic viability is of main concern for shipowners. Ammonia, which is a high-density carbon-free hydrogen carrier, has been considered a potential energy storage medium, therefore providing a practical and clean alternative to fossil fuels (Valera-Medina et al., 2018).

The global availability of various fuels for international shipping is forecasted as below in Figure-8. Out of 207 million metric tons of oil equivalent, 47 million metric tons of oil equivalent Ammonia, 48 million metric tons of oil equivalent biofuels may be available by 2050, whereas 96 million metric tons of oil equivalent fossil fuels may be available. Ammonia and Hydrogen may expect to be produced from renewable energy sources from 2030 onwards.

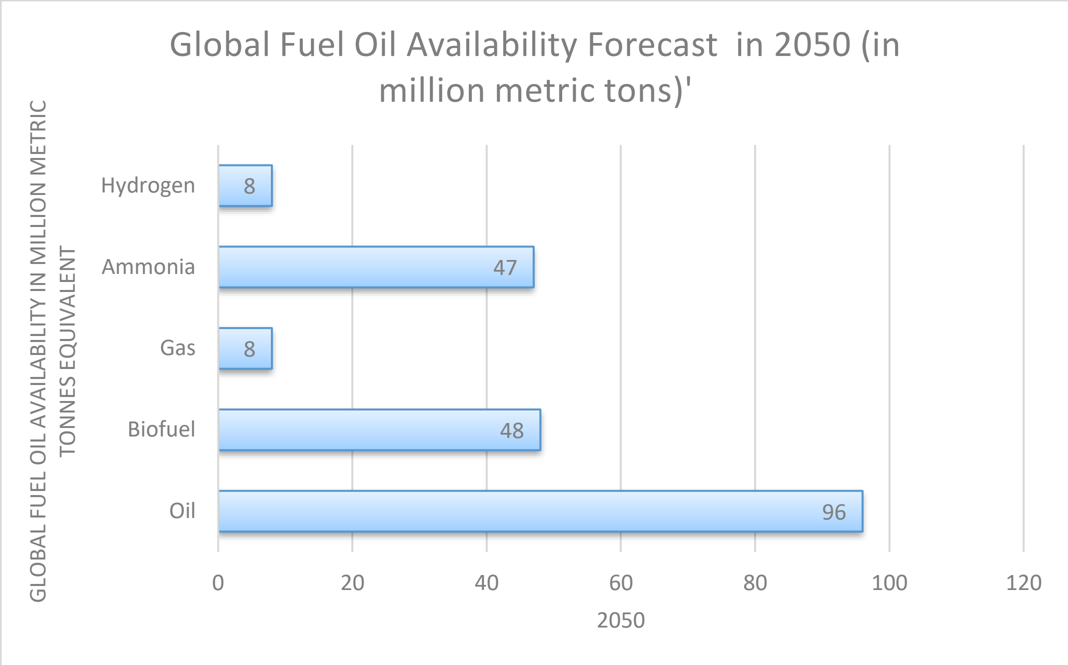

Figure 8 Global Fuel Availability forecast by 2050 in a million metric tons of oil equivalent

Created by author, Data sources for oil fuels from (Statista, 2022a), Clean Fuels (Ahad Al-Enazi a, Eric C. Okonkwo a, b, Yusuf Bicer a, 2019), (IRENA, 2021a), Ammonia (IRENA, 2022).

3.4 Life Cycle Assessment of Alternative Fuels for Zero Targets

About 56% of the world's consumption of liquid fuel oil comes from the transportation sector, and it is anticipated that this number will reach 132 EJ by the year 2040. (Capuano, 2018). A study has forecasted that 46% of the total type of fuels used, fossil fuels will be continued to be used (Statista, 2022a) till 2050.

To support a thorough and comprehensive analysis of the fuels' overall benefits, life cycle assessment (LCA), which examines the environmental impacts of a production system throughout its life cycle, can be used. Methane has 86 times and 36 times the global warming potential of $CO2$ over a 20-year horizon and a 100-year horizon, respectively (IPCC, 2013). Currently, LNG is used as a transition fuel till the other alternate fuels like Ammonia or Hydrogen are widely made available for shipping.

Production ease, shipowner economics, life cycle assessment, technical aspects, and safety considerations are all part of the equation. The below figure- 9 reflects the many aspects that may be considered for marine fuels to achieve sustainability by 2030, and hence by the year 2050, clean fuels will be used widely. Life cycle assessments, spill, and exhaust emissions may be significant when environmental aspects are taken as factors. Investment cost to buy alternative fuels may be considered in economic aspects. The use of main propulsion engines for alternative fuels, technology for feasible retrofit modifications from LNG to carbon-free fuels, the production of green Ammonia and the design of ships capable of using Ammonia as fuel and storage necessitate the development of infrastructure may affect technical aspects.

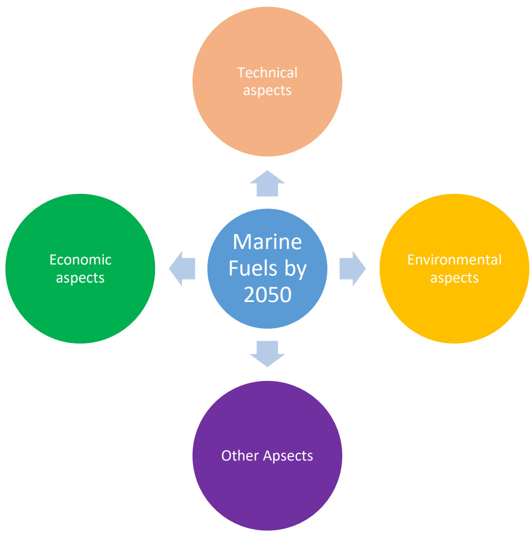

Figure 9 Aspects of Marine Fuels by 2050 for sustainability

Created by author by adapting from (Brynolf et al., 2014)

There is currently no marine engine on the market that can run on Ammonia, but several studies have suggested that Ammonia could be used as a shipping fuel in the future (Serra & Fancello, 2020). Ammonia production using renewable energy sources could result in a fuel that is both carbon neutral and long-lasting.

3.5 Energy Saving and Reduction Measures

Greenhouse gas emissions from power generation and propulsion on ships can be reduced by using clean, renewable energy sources like wind and solar. Between 0.2 and 12 per cent of CO_2 emissions can be slashed by onboard solar power generation, while wind-solar hybrid systems can save up to 40 per cent of fuel. (Bouman et al., 2017). Despite its potential to reduce GHG emissions, commercial shipping does not yet consider a viable alternative to conventional methods. Given that wind energy is more suitable for maritime transportation than on-land use, it is thought to be a better option than on-land wind energy use.

In comparison to traditional ship fuelling options, maritime wind propulsion can reduce fuel consumption and emissions (Talluri et al., 2016). The availability of energy at all times, the type of routes taken, and the feasibility of fitting wind energy-saving devices on all types of ships may influence the use of wind power. To reduce GHG emissions, it is possible to use wind energy as a supplement, but it is not a complete solution. It is possible to use a vertical axis wind turbine (VAWT) in conjunction with conventional propulsion in merchant ships to reduce emissions.

According to a recent study, the use of a wind-powered energy-saving device in conjunction with conventional propulsion could result in fuel savings of up to 16% (Talluri et al., 2016). Fuel consumption can be reduced by combining the use of energy storage with intelligent power management systems to achieve an optimal power split among various power generation sources (Nuchturee et al., 2020). To reach net zero GHG emissions by 2050, we'll need to use both renewable and non-carbon-emitting sources of energy.

4. Selection of Fuels for Zero GHG by 2050

4.1 Barriers to the adaption of Alternative Fuels

To select the best possible alternate fuel to achieve zero targets, one needs to assess the barriers that may be encountered by the shipowners or designers. The targets set are very ambitious, and if there are no immediate measures taken to switch to clean fuels, the world may miss the targets set as per Paris agreement for climate change. “Barriers are explanations for the reluctance to adopt cost-effective energy efficiency measures derived from mainstream economics, organisational economics, and organisational and behavioural theories” (Patrik Thollander1, 2012).

The main aspect that may arise when it is thought of barriers are technological availability in all regions, economic capabilities, regulatory measures, and safety aspects. A barrier might be characterised as a hypothetical mechanism that prevents investments in energy- and cost-efficient technology (S. Sorrell et al., 2004). Many zero-emission ships will have to be built by 2030, and all future orders for ships must include a "zero emission propulsion capability”. Similarly, zero-emission carbon-free fuels will have to be available for international shipping to achieve the targets. It is not an easy task to switch to clean fuels.

Cost viability will pose a major barrier to shipowners. New ships are to be built for the adaption of clean fuels, and with unpredictable choices of alternative fuel, the investment cost will be higher. According to a study (Cookson & Stirk, 2019) LNG is considered as a transition fuel and cannot be considered a sustainable fuel. Apart from the cost burden of switching to cleaner fuels, a huge investment is required for the production of clean fuels. The overall cost of switching to LNG with carbon capture storage installation would rise by 30%, while the overall cost of switching to biodiesel would rise by 90%.

Ship emissions will not be reduced any time soon, even though technological advancements have long been heralded as promising solutions to combat climate change. The barriers like cost and availability for early adopters in the shipping industry to pay a significant premium for unreliable investment returns will prevent the adoption of alternative fuels (Wan et al., 2018). The role of LNG in the mitigation of climate change is very limited and can be considered transitory (Cookson & Stirk, 2019). The need for other clean fuels is imminent, and technology should be available so that ship owners can place an order for new ships.

There is a growing demand for shore-based battery charging facilities due to the increasing electrification of new ships. It's still necessary for batteries to become more energy efficient and lighter despite major technological advances in battery capacity and efficiency for large ocean-going vessels. The use of Hydrogen as a carbon-free fuel is the best option. However, storage at high pressure poses a serious challenge and transportation of Hydrogen needs international regulations like the IGC code for gaseous product transportation.

4.2 Economic Viability for Zero Target

While many governments and non-governmental organisations are aiming for zero emissions, the economic viability of fuels must be taken into consideration. By 2030, ships, as well as fuels, must be ready to use. Production infrastructure is required in all parts of the world, and this costs a lot of money. It is imperative that viable options for financing capacity building and technology transfer be evaluated as soon as possible.

In a study conducted for cost assessment for various pathways for decarbonisation of the shipping industry, carbon capture storage arrives at the most economical viability (Law et al., 2021). Figure-10 illustrates the varied costs of alternative fuels for well to wake in comparison to heavy fuel oil when costs associated with their manufacture and use on ships are considered. Unless fuel producers can sell these very energy-intensive fuels at a lower price or pricing is enforced by law, they will be unwilling to produce them. The renewable energy costs are on the higher side as currently, they are not widely used, and production costs are very high. The cost of production of alternative fuels varies according to the availability of raw input. Optimal Hydrogen costs from Steam Methane Reforming (SMR) and CCS systems might fall to less than 1.20 US$/kg before 2025 in low gas price geographic areas (Law et al., 2021).

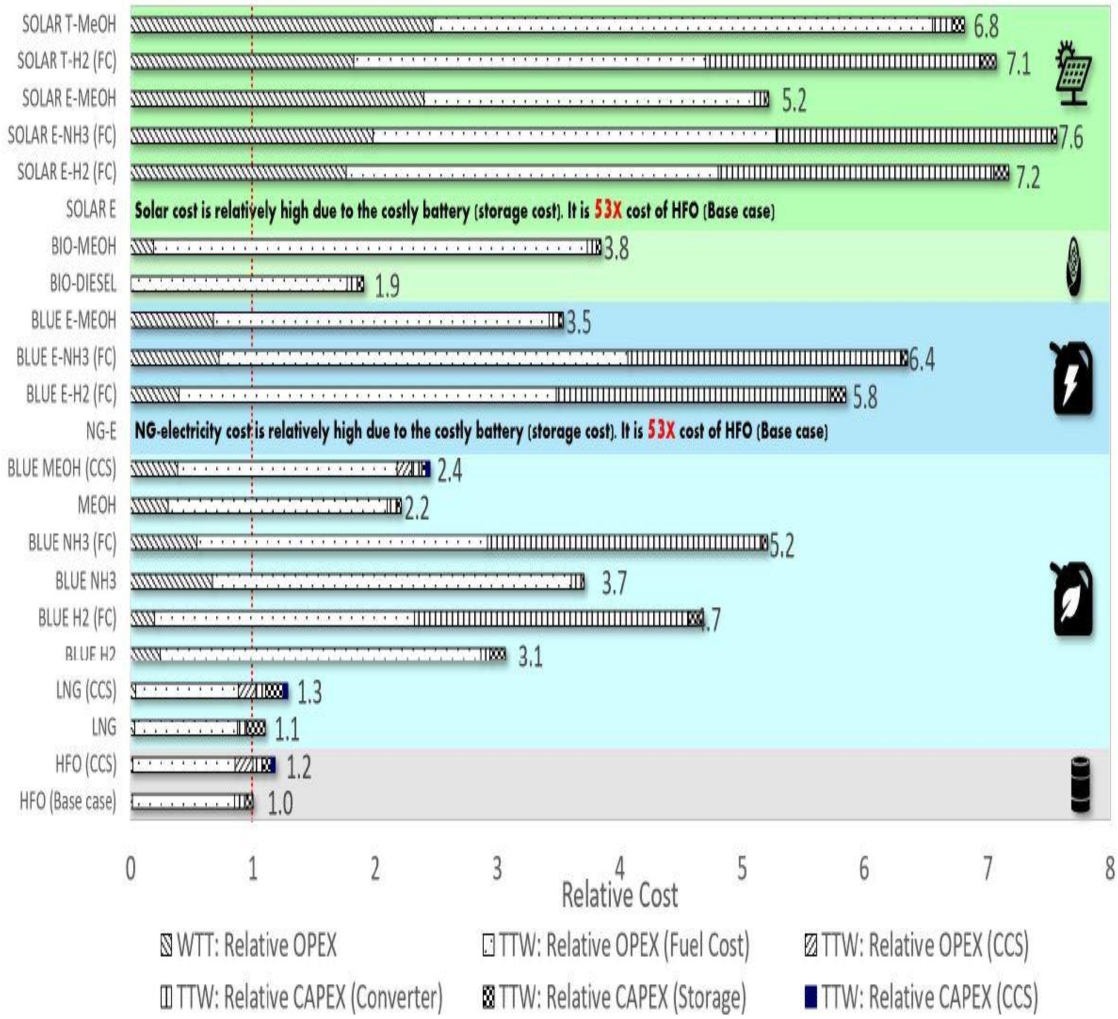

Figure 10 Well to Wake various fuel costs relative to HFO(base case) categorised as well to tank and tank to wake

Source (Law et al., 2021).

Y-axis in Figure-10 shows the various alternative fuels. Fuels reflected in blue colour like Blue H_2, Blue NH_3,Blue MeOH etc are produced by capturing CO_2 emissions. Blue Ammonia (NH_3) fuel cost is 3.7 times as compared to heavy fuel oil. Light green colour reflects alternative fuels Biodiesel and Bio Methanol . Alternative fuels in green colour are produced using green energy and hence costs are relatively higher. The cost of Solar E- NH3 fuel cell is 7.6 times relatively cost to HFO.

Methanol conversion costs at least 2.22 timesof the conventional overall fuel cost while switching to Hydrogen or Ammonia produced via various pathways would raise the overall cost by at least 3.25, as opposed to these two alternatives. (Law et al., 2021). The cost of alternative fuel production ranges from 2 to 185 times that of HFO. A higher price or government regulation of pricing may compel fuel producers to produce these extremely energy-intensive fuels.

In regions like the European union cost of Hydrogen production is around 2.1 US$/Kg and is expected to fall to1.8 US$/kg by 2030 (Hydrogen Council, 2020).

Figure-11 reflects the relative costs of each fuel to energy content($/MJ) basis when compared to oil fuels which is considered as 0.014$/MJ. Green Ammonia production cost is 0.029 $/MJ when compared to oil fuel which is 0.014 $/MJ due to fact that they are not produced in large quantities and scarce available of green energy.

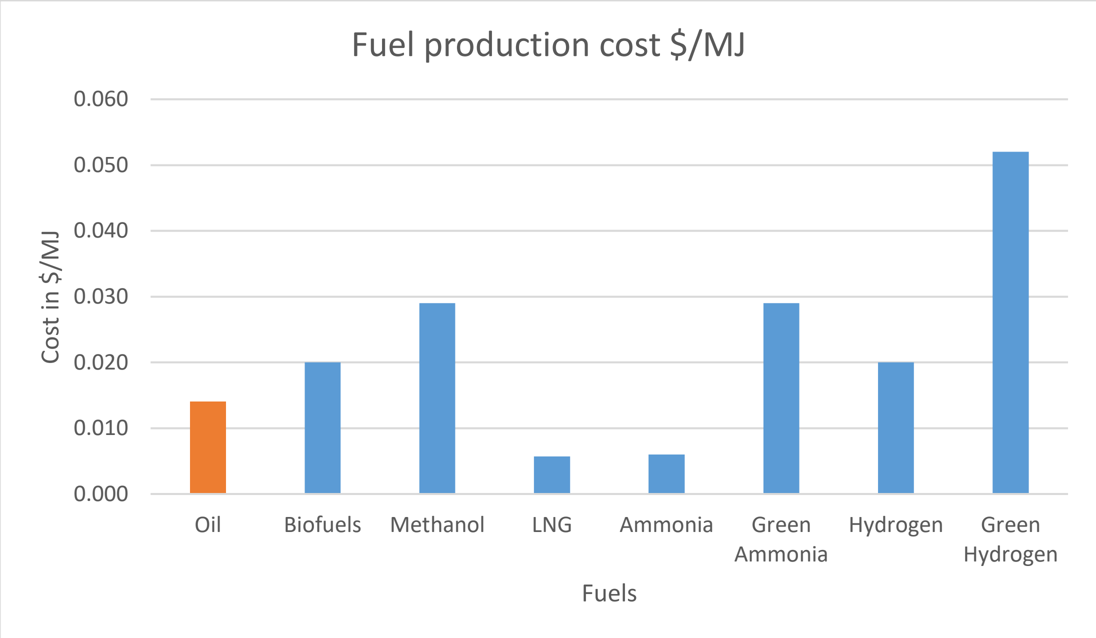

Figure 11 Comparison of cost of Alternative fuel production benchmarked to Oil fuel production cost

Created by author by adapting from (Wang & Wright, 2021).

With renewable Hydrogen generation, the costs of hydrogen production depend on economics and production scale, with the most important component being renewable energy inputs' price. Green Hydrogen production costs in the middle east might be as low as 1.6 US$/kg utilising solar energy, according to the International Energy Agency (IEA).

Figure-12 reflects an comparison analysis of the total cost incurred for the use of fuel cells in ships up to 2050. It has evolved that Hydrogen fuel cells are an option for ships with motor power requirements under 2 megawatts (MW), such as short sea passenger ferries or ferries with a capacity of fewer than 100 automobiles until 2030 (Hydrogen Council, 2020). When the power of more than 4 MW is required, Hydrogen fuel is recommended as compared to electricity because of the high cost, weight, and volume of the battery needed for ships of this size and fuel consumption.

When comparing Hydrogen fuel cells and Biodiesel as shown in Fig-12 for the total cost incurred with conventional diesel, it is observed that fuel cells in ro-ro pax vessels may have the least cost, and the next higher will be Biodiesel. After 2035, the cost of fuel cells and Hydrogen fuel may continue to fall due to anticipation of larger production and demand, allowing the Hydrogen fuel cell ship to become a viable alternative to conventional vessels.

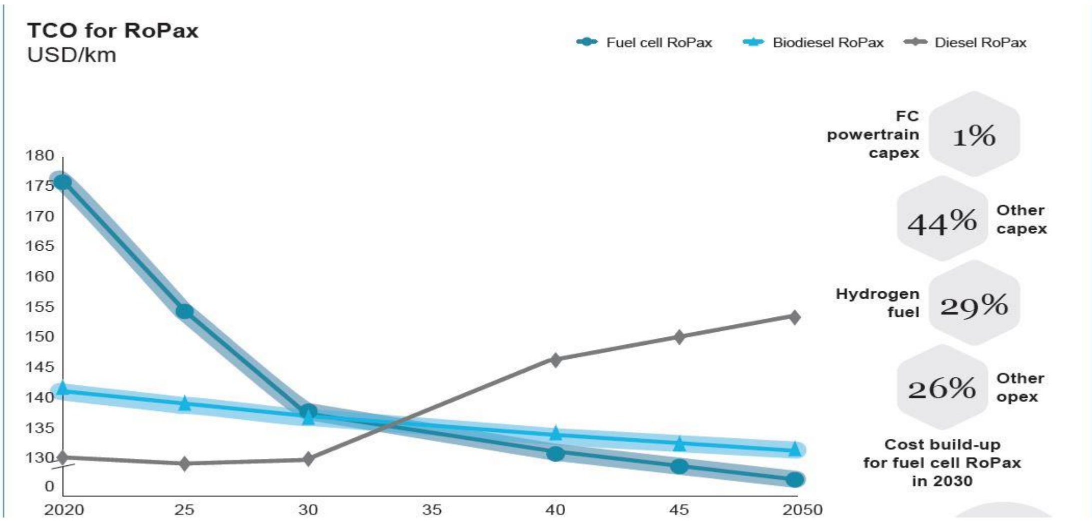

Figure 12 Comparison of total cost incurred for Fuel cell, Biodiesel and Diesel oil in Ro-Pax vessel

Source (Hydrogen Council, 2020).

For larger vessels, Ammonia is suitable as a fuel, and this approach often uses a modified engine like current technology and necessitates less overall change than using a fuel cell. The economic viability plays a crucial role in the selection of fuel which may be driven by the regulatory framework after the MEPC 80th session.

4.3 Seaborne Trade to World Trade by 2050 and its Impact

About 80% of international trade relies on maritime transportation, which includes dry bulk, crude oil, roll-on/roll-off, general cargo, and containers by volume. The growth in international trade will drive growth in seaborne trade. The demand for maritime trade will arise from the demand in international trade (Ma, 2020), and therefore it is anticipated that seaborne trade will grow by 2050.

Seaborne trade and international trade are interlinked and hence the consequent emissions. According to the 2021 UNCTAD report on the review of maritime transport, the total volume of seaborne trade for the year 2020 was 10.6 billion tons and is expected to grow. Total maritime trade is anticipated to expand by 2.4% yearly between 2022 and 2026, compared to 2.9% during the next two decades (UNCTAD, 2021).

Figure-13 shows a comparison between the two scenarios. Trade growth of high levels of social, technological, and human development are fostered by global trade and collaboration (scenario pathway-1) and trade growth in achieving environmental, and development goals through collective action on a global scale (scenario pathway-2) are compared. According to a study, the anticipated sustained total seaborne trade by 2050 may be 22 Gt when climate change policies are implemented (Müller-Casseres et al., 2021). In contrast, trade may grow up to 36 Gt in 2050 when a high growth rate is considered.

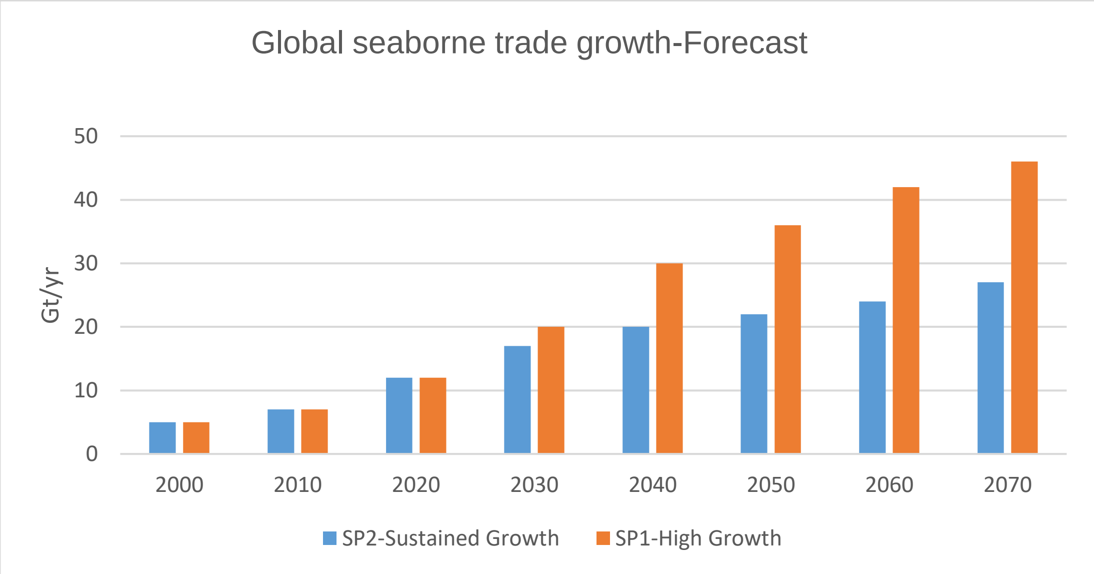

Figure 13 Forecast of global seaborne trade in sustainable and high growth scenarios

Created by Author by adapting from (Müller-Casseres et al., 2021). Data for both scenarios from (Müller-Casseres et al., 2021).

When considering the growth in seaborne trade, the forecasted greenhouse gas emission may rise to 1745 million tonnes by 2050, which is 1166 million tonnes more than the 2008 level (Chen et al., 2019). Chen et al. (2019) have used an allotropic model to predict the growth in global fleet size and hence have predicted the growth in GHG emissions in business-as-usual mode. His model has resulted in a rise in GHG emissions in 2050 to 150% to the 2008 level. In contrast, the fourth IMO GHG study report reflects that the emissions may rise to 90% to 130 % of the 2008 level. Figure-14 reflects the possible rise in emissions in different scenarios. There can be a 130% rise in GHG emissions if economic growth is higher and may be lower to 90 % if economic growth is lower and emissions reduction strategies are implemented.

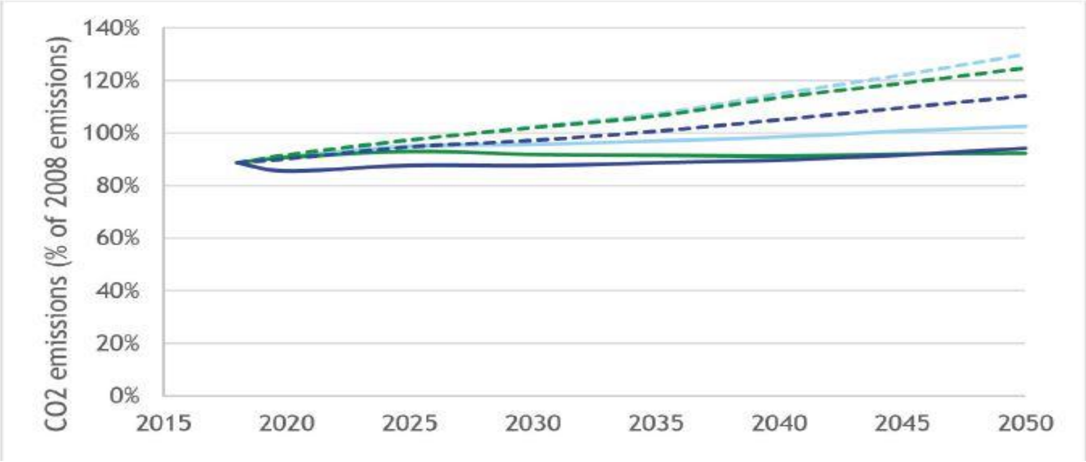

Figure 14 Projection of maritime ship CO_2 emissions as a percentage of 2008 level

Source (IMO, 2020a).

Considering the above facts, shipping has to adopt measures to reduce emissions. Adapting to change the fleet to the new ships, which have capabilities to adopt alternate fuels and incorporate renewable energy sources, could be the solution. Container fleet owners, bulk carriers, and tanker owners need to pay more attention to the decarbonisation aspect. Emission for different types of vessels for the year 2017 is shown in figure-15. Container ships emitted around 208 Mt of CO_2, followed by bulk carriers which emitted 175Mt of CO_2. Companies that own container ships and bulk carriers must act right away to adapt to decarbonisation or invest in new technologies as a contribution to GHG reduction pathways. Several studies have shown that the IMO GHG goals for 2030 are attainable, but no one knows if or how the goals for 2050 will be met, and achieving net-zero goals by 2050 is also not clear (ITF, 2018)

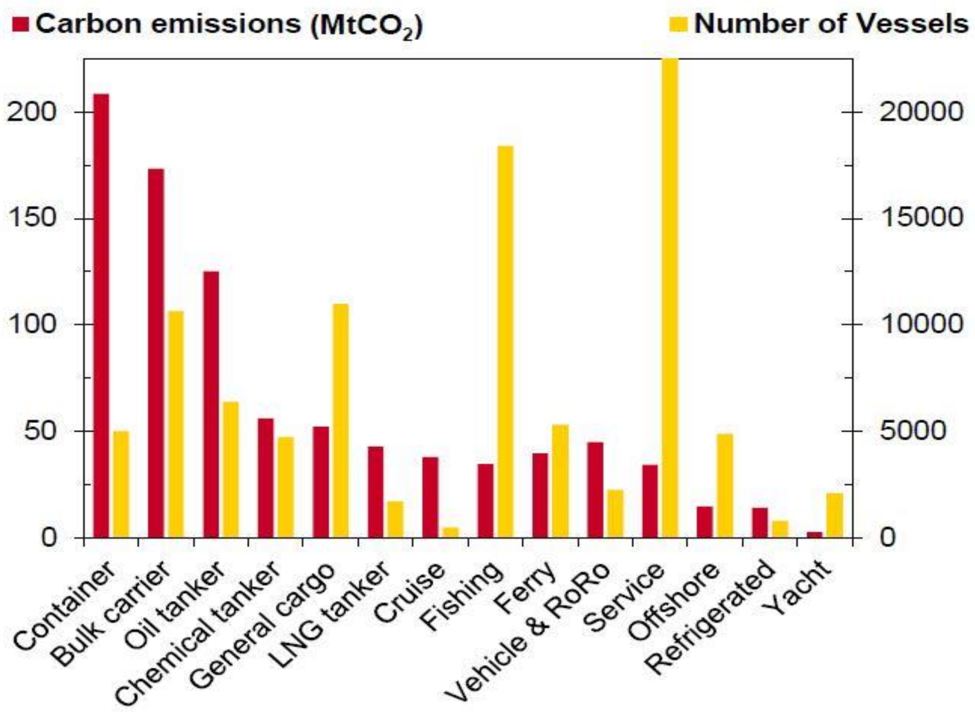

Figure 15 Number of vessels and their CO2 Emission as of 2017 for different types of vessels

Source (Balcombe et al., 2019).

4.5 Criteria for Selection

The goal of this study is to develop selection criteria based on data from a survey questionnaire and literature reviews. Criteria required has been evolved from the primary data analysis and database from literature. Figure-16 shows the criteria adopted in this study. Various existing measures and regulatory enforcement in place have been studied from the literature.

A survey questionnaire has been utilised and collected data were analysed. Evolved data was developed in the analytic hierarchy technique to get criteria weights. Criteria weights has been validated. The alternative fuels has been mapped with weight criteria, and the decision of selecting the alternative fuel has been made. Apart from the factors evolved from data analysis, behaviour measures for GHG reduction has been assessed.

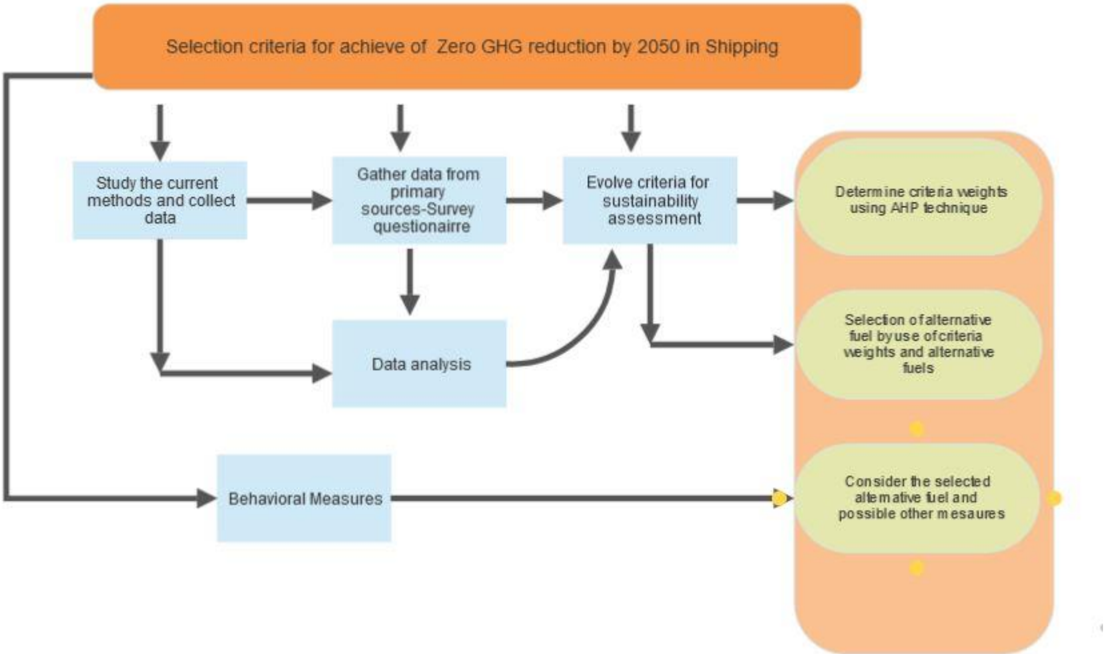

Figure 16 Selection Criteria for achieving zero greenhouse emissions in shipping

Created by author

5. Results and Discussion

5.1 Data Collection

It is necessary for the researcher to identify appropriate people for a survey study before distributing a research instrument (such as a self-assessment questionnaire (Bryman & Cramer, 2011). To gather primary data, the researcher used an internet-based survey questionnaire that was disseminated to relevant parties. This research's data collection process was outlined in Chapter 1.6.1. One of the distinctive features of qualitative research is the use of participant-reported questionnaires to gather data. It is the most direct and simple method of obtaining comprehensive and rich data for any study. Aiming for high quality and rigour in qualitative research is the same as in any research paradigm to minimise bias while increasing the accuracy and credibility of research results (Smith & McGannon, 2018).

The future of shipping towards climate neutrality depends on the decision made now by the stakeholders. An important factor in attaining the zero-target goals may be the views of many stakeholders, such as shipowners and designers and classification organisations, and regulators and seafarers themselves. Qualitative data was gathered using the questionnaire, which has been analysed further. One of the most important characteristics of a successful questionnaire is that it allows the researcher to obtain meaningful and accurate data from respondents (David W, 2003). Getting the responder to understand, articulate, and communicate his or her response to the researcher is a difficult procedure that necessitates a clear and unambiguous presentation of questions. Data collected from database sources, literature, and peer-reviewed papers relevant to this research has been analysed.

5.2 Data Analysis

Qualitative research frequently begins with data analysis as soon as the initial data are obtained, but this process continues and changes throughout the study (Burnard et al., 2008). All participants received a survey questionnaire in an internet form sent through an email.

The research effort utilised input of relevant stakeholders to develop criteria for zero emissions by 2050. Sailing chief engineers of ships and senior naval architects, as well as governmental and classification society officials and technical managers, were among the respondents.

All of the research was done in a confidential way to ensure that the identity of those who participated in the study remained anonymous. A software program was used to analyse the primary data collected, code the themes, and then analyse the results. The software enables the researcher to identify the prominent words derived from the respondent's reply, thereby analysing them qualitatively. An interactive word tree (Appendix-C) related to the questionnaire is created and analysed.

5.3 Alternative Fuels and Availability by 2030

LNG was the most widely available alternative fuel on ships for the current period. Methanol is the next readily available fuel. The analysis of the availability of alternative fuels has indicated that LNG will be the most widely available alternative fuel till 2030. As shown in Figure-17, out of the total alternative fuels available in shipping, 42% of Liquified natural gas, 31% of Methanol, 22% biofuel, 3% green methanol, and 1% of each Ammonia and Hydrogen are available as on 2022.

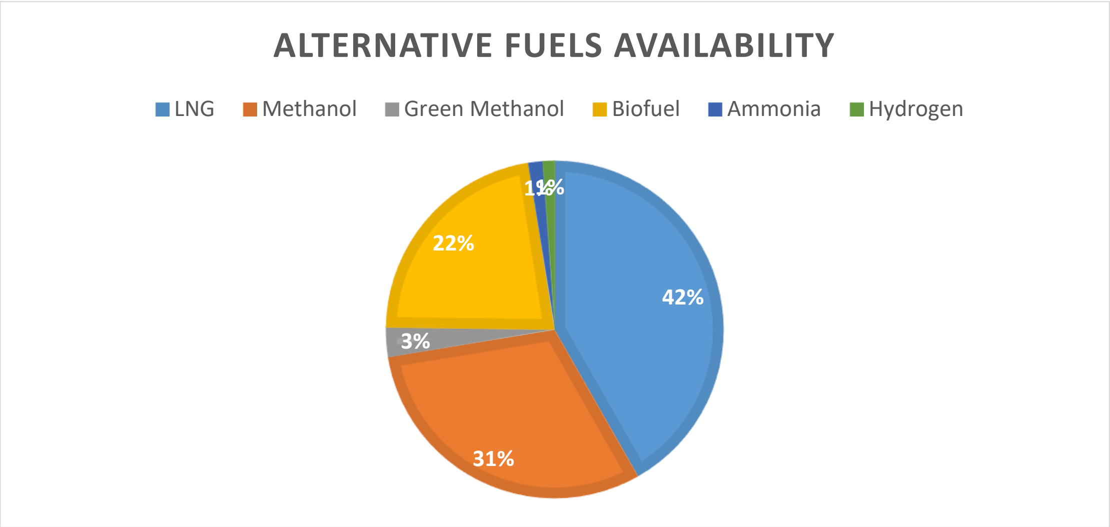

Figure 17 Different alternative fuels availability in 2022

Source Created by author

A growing number of vessels are utilising LNG as a source of propulsion (Serra & Fancello, 2020). There were 641 operating LNG vessels, including 45 floating storage regasification units (FSRU) and five floating storage units, at the end of April 2022. In 2021, the worldwide LNG fleet grew by 9.9% (IGU, 2022), indicating that LNG is widely available.

The International Energy Agency (IEA) estimates that by the year 2050, shipping will continue to use fossil fuels, about half of all the fuel types (Statista, 2022a). The following figure-18 predicts the use of fuels over the years from 2019 to 2070. By 2050 it is forecasted that 45% of fossil fuels, 22 % of biofuels, and 21% of Ammonia of the total fuels may be consumed.

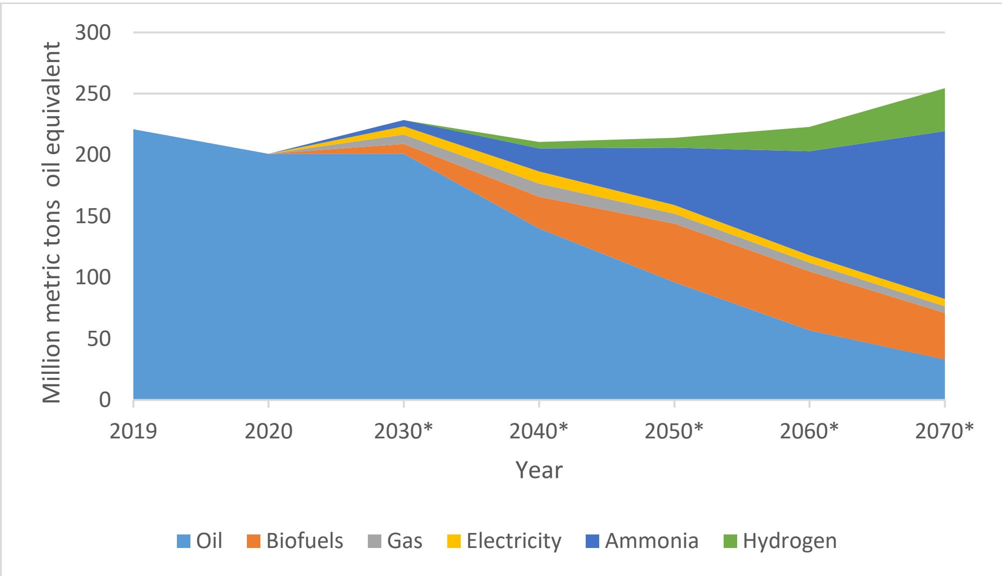

Figure 18 Prediction of use of fuels from 2020 to 2070 in International Shipping

Created by author by adapting from (Statista, 2022a)

Figure-19 shows the ranking of the alternative fuels for availability by 2030, as reflected in the responses. In the survey, 52 per cent of respondents indicated that LNG, 28 per cent Methanol, and 12 per cent biofuels may be available by 2030.

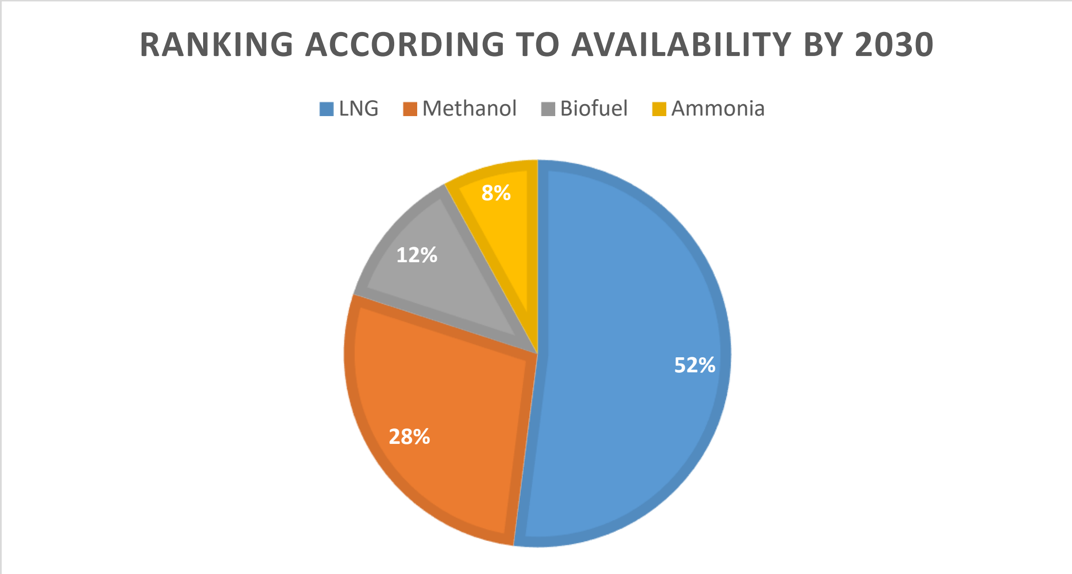

Figure 19 Ranking of Alternative fuels availability by 2030

Source Created by author

Participants, in general, have responded that LNG might be widely available by 2030. The GHG emissions from LNG propulsion are sceptical, and when considered from a life cycle assessment point of view, its potential for reduction of GHG is not beneficial (Balcombe et al., 2021). Methane slip in the upstream process and unburnt methane emitted from diesel engine exhaust may deter its use for complete decarbonisation. Biofuels are the best alternative fuels considering their negligible greenhouse gas emissions. Biodiesel production necessitates a substantial supply of biomass (Mohd Noor et al., 2018). Potential biodiesel requires feedstock like soyabean oil, sunflower, olive, rice bran etc., and these feedstocks are also required for human food consumption (Kolwzan et al., 2012).

5.4 Reduction of Greenhouse Gases

When considering ways to minimise greenhouse gas emissions, participants have considered "Technology, Renewable Sources, Availability, Production," and "Reduction potential," among others, the most influential factors.

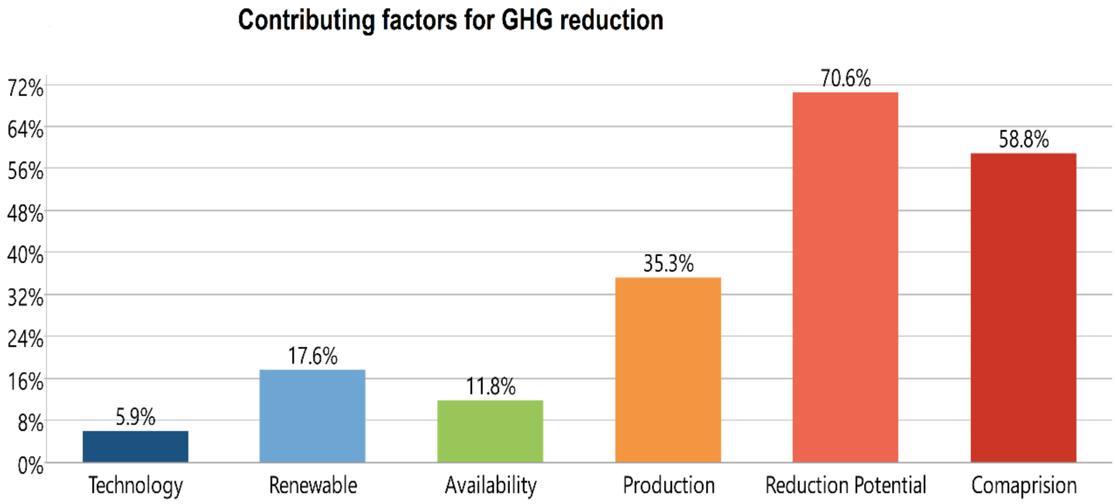

Figure 20 Percentage of Contributing factors for GHG reduction

Source Created by author

Figure-20 reflects that 70.6% of respondents have factored that the emission reduction potential of alternative fuels may be the decisive factor for the switch to alternative fuels.

One respondent has quoted as below for reduction potential,

"Methane is a potent GHG; 72 times more powerful than CO_2 in a 20-year perspective and 25 times as powerful from a 100-year perspective" Source Primary Data.

Scalability of production may also influence the use of alternative fuels. Respondents have indicated that the production scale could influence their decision. Fossil fuels will continue to be produced in abundance until 2050. The global supply of LNG is also considered adequate. The global LNG trade climbed by 4.5% in 2021, according to the International Gas Union's (IGU) 2022 report, reaching a total of 372.3 Million tonnes (International Gas Union [IGU], 2022).

However, 11.5 per cent of respondents have stated that the availability of a particular type of carbon-free fuel may be the most important factor. LNG may be accessible by 2030 depending on the availability situation, and biofuels may follow behind if they are not produced from traditional feedstock like palm oil etc., but instead sourced from Jatropha seeds etc. (Kolwzan et al., 2012).

Analysis of alternative fuel costs may be an important aspect for the adoption of new technologies. Majority of those polled said that cost comparison could be a deciding factor. Achieving zero GHG emissions by 2050 will need the use of renewable fuels such as green Ammonia and green Hydrogen.17.6% of those polled believe that renewable fuels can be utilised to attain net-zero emissions targets. Cleaner fuels are out of reach in today's scenario because of a lack of big renewable energy sources for their production.

5.9% of people who took the survey said that technology considerations could help them meet their goals. An Ammonia-based marine diesel engine fuel is still in the design phase. Maschinenfabriek Augsburg-Nurnberg (MAN) and Burmeister & Wain (B&W) expects to deploy the first marine diesel engine powered by Ammonia fuel in 2024 (Maschinenfabriek Augsburg-Nurnberg Burmeister & Wain [MAN B&W], 2021). The Haber–Bosch synthesis process is responsible for greater than 90% of the world's Ammonia production. The current process produces 1.5 to 2.5 tons of CO_2 for every ton of Ammonia produced. (Serra & Fancello, 2020). As a result, to even consider using Ammonia as a marine fuel, it must be produced using green technology.

5.4.1 The First Two Ranked Fuels' Effectiveness

LNG and Methanol are the top two alternative fuels available for adaption, as detailed in Ch. 5.3. Most respondents believed that if the first two rated fuels were used, it would be impossible to reduce greenhouse gas emissions to zero by 2050. One of them is quoted below,

"NO. Compared to 2008, 70% reduction of carbon dioxide emissions intensity by 2050." Source Primary data.

A reduction potential possibility in emissions if LNG and Methanol are used as a fuel is depicted in Figure-21. 47.62 per cent of those polled said that it's not possible to meet zero goals by 2050. The GHG reduction estimate in shipping for 2020 was roughly 21% of 2008 level (EU, 2021), predicting that a 30% reduction of greenhouse emissions may be achieved by 2030, but the path to zero targets by 2050 is not translucent.

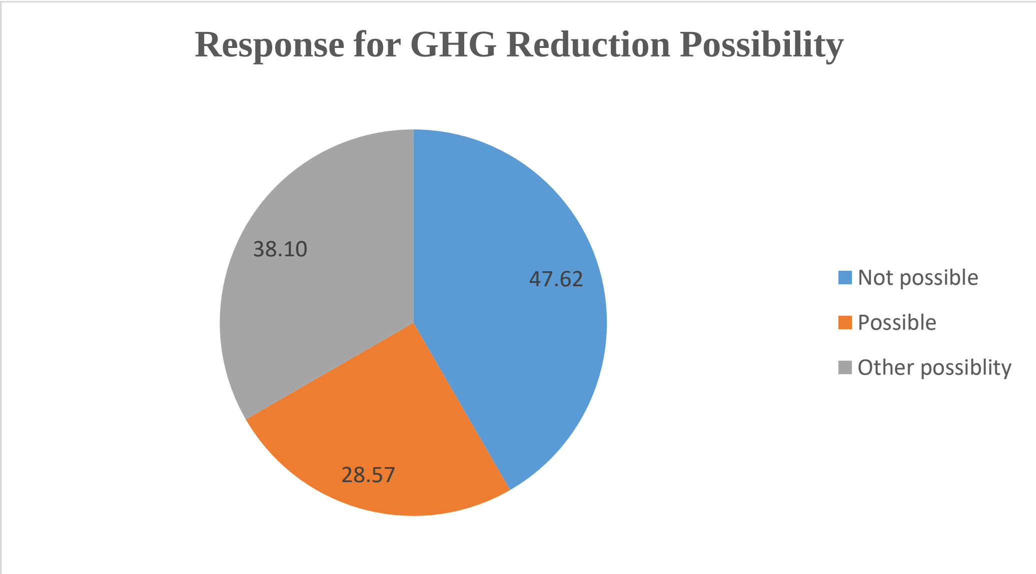

Figure 21 Response to GHG emissions reduction possibility if LNG and Methanol is used by 2050

Source Created by author

In a long-term projection up to 2050, the use of LNG may range from 8% to 25% of the total fuels, but the goal of achieving zero targets is impossible in this scenario. (Cookson & Stirk, 2019). Methane leaks from marine engines are a major contributor to the increased GHG level in the global warming potential of 100 years scenario (Brynolf et al., 2014). According to the Det Norske Veritas-Germanischer Lloyd (DNV-GL) report released in the year 2021 (DNV-GL, 2021), Methanol can be used on the existing ship's main engines and auxiliary engines with few modifications, but not as a long term measure.

5.5 Current Ways Followed for GHG Reduction

Operational approaches like speed reduction, the "just in time" concept and weather routing can also be used to reduce emissions. As shown in Figure 22, operational methods are the most common approach to reducing emissions of greenhouse gases employed in international shipping operations since 2011.

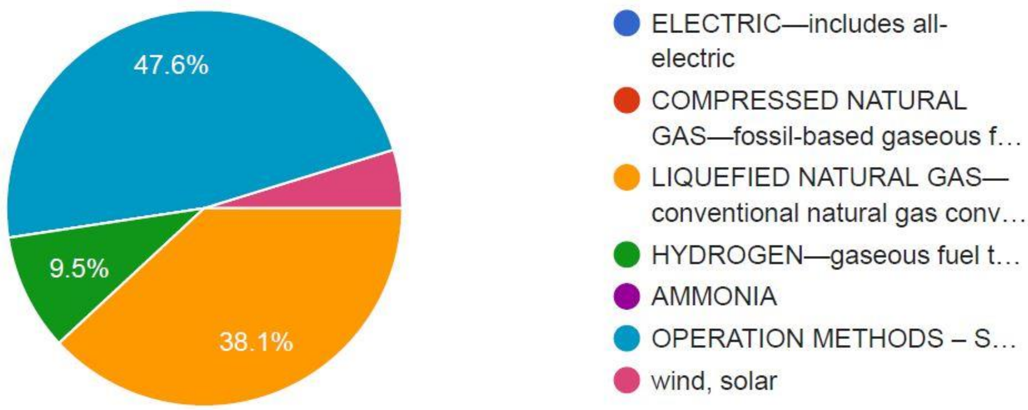

Figure 22 Current methods opted for GHG reduction in shipping

Source Created by author

The second most preferred is the use of LNG as an alternative fuel for GHG reduction. Many responders have chosen engine modifications or retrofits as a means of reducing GHG emissions. A retrofit/modification was chosen by 40 per cent of participants as opposed to alternative approaches, as shown in Fig-23. Duel fuel injection main propulsion engines are capable of burning LNG, Methanol and engine capable of burning Ammonia will be delivered in the year 2024 (MAN B&W, 2021).

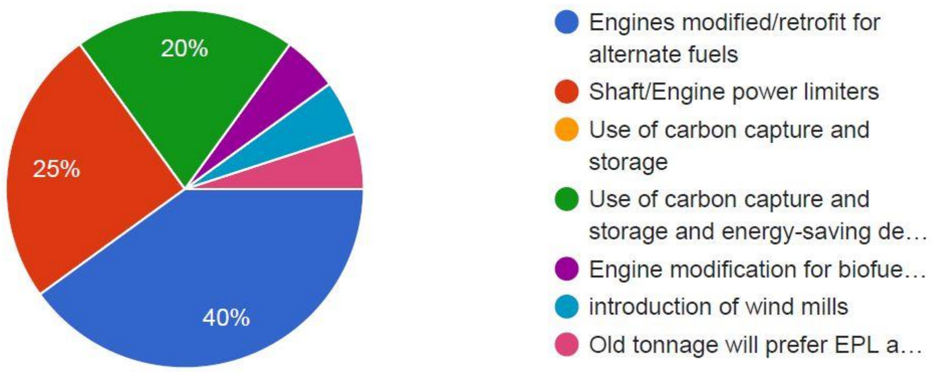

Figure 23 Retrofit methods for GHG reduction

Source Created by author

Although a large number of participants have responded that engine retrofit is the most likely to occur on existing ships, the engine retrofit in existing ships may not achieve zero targets by 2050. To accomplish zero objectives, new ships need to be built rather than engine modifications, as reflected in figure-24. Existing ships may be confronted with challenges such as the installation of new fuel storage tanks and the need for IMO to develop safety norms for Ammonia and Hydrogen fuels.

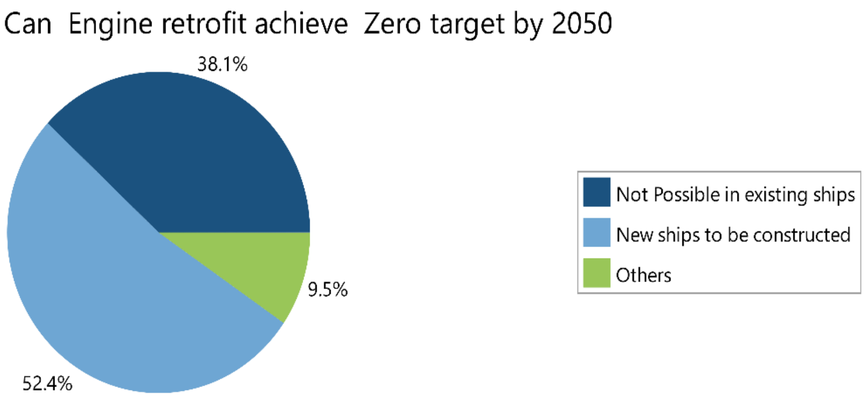

Figure 24 Possibility of engine retrofit for achieving zero target

Source Created by author

5.6 Regulatory Framework Effectiveness

The IMO has established a 2018 Initial strategy to cut GHG emissions by 50% by 2050. Fig-25 shows the response to the effectiveness of this strategy and aiming at the Paris agreement target goals of achieving less than 1.5°C. Most respondents had the opinion that IMO's Initial strategy may not achieve net-zero targets. One of the respondents emphasised as below,

"Yes. 2050 target can be met only when the shore industries ramp up the green fuel production to a level which meets shore, coastal and international shipping" Source Primary data

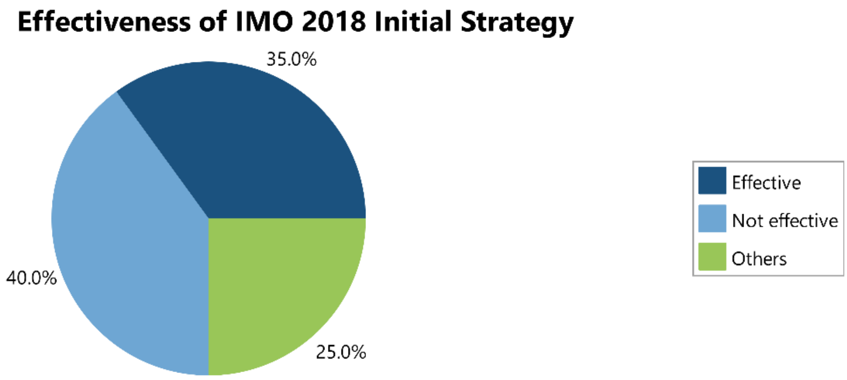

Figure-25 Response to the effectiveness of IMO 2018 Initial strategy

Source Created by author

The target to achieve zero GHG emissions will not be achieved by the standalone efforts of international shipping. Fourth IMO GHG study has indicated that the contribution of shipping to GHG emissions is 2.89% of the world's total GHG emissions. Net zero targets may be achieved if all the sectors use green fuels and methods in their life cycle. International shipping requires approximately fuel of 211 million tonnes of oil equivalent by 2050 (Statista, 2022a).

The current production of green fuels does not meet the demand for green alternative fuels (Wang & Wright, 2021). Most of the alternative fuels like LNG, Methanol, and Ammonia are not produced using green technology; however, it is expected to see a rise in green production after 2030. It is estimated that 71 per cent of the world's Ammonia facilities utilise natural gas, emitting on average 1.6-1.8 kilograms of CO_2 per tonne of Ammonia, and 22 per cent use coal (IRENA, 2022).

77th session of MEPC has adopted to revise 2018 Initial strategy anticipating that achieve of zero targets is necessitate of the hour (MEPC, 2021b). Regional measures like EU directives for GHG reduction may contribute as a catalyst to achieving zero targets. When asked whether regional measures will accelerate emissions reduction, the majority of respondents supported it. EU proposal of “Fit for 55” aims to achieve a 55 per cent reduction of greenhouse gas emissions by 2030 compared to the 1990 level. This measure will indirectly drive the non-European shipping stakeholders to adapt to stringent emission reduction measures. The European Commission is inclined to include the Emission trading system in shipping by 2023.

Several respondents believed that market-based measures may achieve the zero targets by 2050. Market-based measures encourage fuel-efficient ships and adopt measures like slow steaming methods in the short term and in the long term will encourage to adopt clean fuels or energy-saving devices (Psaraftis et al., 2021). In the 75th session of MEPC, few papers supported a proposal for market-based measures (Marshall, 2021).

There is a sweeping view from the respondents that the existing framework for the risk in the use of alternative fuels is not addressed. The regulatory framework for the address of risk associated with the use of alternative fuels has been implemented in the case of LNG and Methanol fuels. The International Gaseous Fuel (IGF) code addresses the technical provision of low flashpoint gaseous fuels. Technical provisions for alternative low-flashpoint fuels and energy arrangements such as fuel cell systems will be added to the IGF code as new chapters (DNV-GL, 2019). The safety norms for the use of Liquid Ammonia and Hydrogen as an onboard fuel ship have to be developed.

5.7 Economic Measures and Impact

Most of the respondents in this survey have confirmed that there will be a noticeable economic impact as compared to a very large impact. The implementation of GHG reduction measures may have a noticeable impact on a shipping company. The company would require large financial capital to buy new ships. A comparison of capital costs for installing alternative fuels in existing ships and new ships is shown in table -1. The cost of retrofitting is high as compared to the construction of new ships. The cost of new build four-stroke ICE engines for gas fuels is 387$/KW, whereas retrofitting costs around 818$/KW (Wang & Wright, 2021). Costs for fuel cells are extremely high as they are not commercialised in shipping in a larger way when compared to engines suitable for the use of fossil fuels.

Table 1 Cost comparison for alternative fuels fitment in new ships fitment and existing ships retrofit

Component	Retrofit Cost (US$/kW)	New Build Cost (US$/kW)
	Propulsion systems	
ICE Diesel, Biodiesel	-	240/460 [a]
ICE, Methanol	328	265/505 [a]
ICE, Ammonia		370/600 [a]
ICE, LNG, LBG, Hydrogen	900	387/850 [a]
Fuel cell, SOFC	-	4000–9000
Fuel cell, PEMFC	-	730–2860
Electrical and generator, LNG, LBG, Hydrogen	-	400
Electric motor	-	250
	Fuel storage system	
Gas supply system + tank, LNG, LBG (USD$/kg)	270–420	270–420
Gas supply system + high pressure tank (700 bar), Hydrogen (USD$/kg)		576–868
Battery, Nickel manganese cobalt oxide (NMC) (USD/kWh)	-	400–1000, and expected to fall to 124 in 2030
Battery, lithium–iron–phosphate (LPF) (USD/kWh)	-	210–1000, and expected to fall to 70 in 2030

[a] Four-stroke engine/two-stroke engine.

Note. From Comparative Review of Alternative Fuels for the Maritime Sector (Wang & Wright, 2021) Copyright 2021by MDPI

Storage tanks required for gas supply for LNG, LBG is the same for both existing tanks and new ships. Storage systems for batteries in new ships require around 1000 USD/kWh, and when compared to other fuels, it is higher side. Construction of new ships is an option that many respondents prefer and as detailed in para 5.2.3. Shipping companies require capital to acquire new ships. It is anticipated that there may be policies in future to support investment in zero emissions ships.

5.8 Impact of Shipping Growth Between 2022-2050

In response to the impact of the growth of international shipping and its effect on emission reduction, many respondents were sceptical. One of the respondents has said as below,

“Very difficult. Due to the non-availability of the data, it is difficult to estimate such an impact. The possible impact will be on fleet (number of ships globally), state (GDP, etc.) and stakeholders (inflation, supply, and demand deficit)” Source Primary data.

One respondent has stated that the growth of international shipping is anticipated; however, there will be a reduction in GHG emissions due to the factors of new sustainable ships that might be constructed.

Due to globalisation and continual demand for goods like oil, iron ore, gas, and manufactured products in emerging markets like Asia, growth in shipping is expected to occur (Ma, 2020). Figur-26 shows the year-to-year percentage change in growth between 2006 to 2022. Between 2013 to 2022, the percentage change in annual growth fluctuated between 4 to 2.8. It is anticipated that the annual rate of growth in international shipping may be between 2.4 per cent to 2.9 per cent (UNCTAD, 2021) for the years 2023-2026. The corresponding growth in GHG emissions attributed to growth in international shipping by the year 2050 may be 1.7 Gt CO2e (Chen et al., 2019).

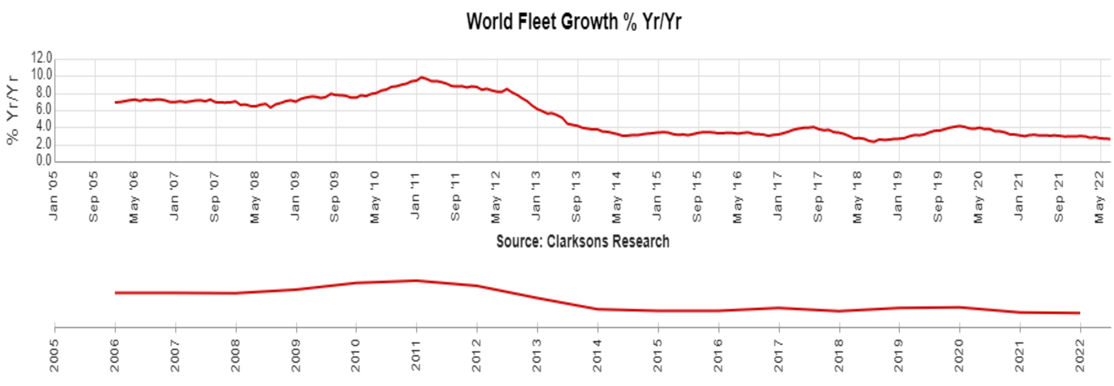

Figure 26 Year to Year world annual fleet growth rate

Source (Clarksons, 2022)

5.9 Sustainability assessment

Based on the criteria of alternative fuels and sub-criteria developed by a survey questionnaire, an assessment of fuel sustainability up to 2030 has been developed. This research has used an analytic hierarchy process technique to perform multicriteria decision analysis. Hansson et al. (2020) have used the analytic hierarchy process (AHP) to analyse stakeholder preferences in Sweden. An evaluation was made of the respective merits of several fuel sources based on their relative performance on ten criteria spanning economic, environmental, technical, and social elements.

Fossil fuels, LNG, Methanol, green Ammonia, and green Hydrogen are among the alternative fuels selected in this study. Cost, emission reduction potential, regulatory efficacy, technology readiness, worldwide availability, and safety are the criteria derived from the primary data. The AHP technique compares the criteria among each other and scaled using table-2 (Saaty, 2008). The alternative marine fuels and the criteria for inclusion in the study are selected first. Data analysis from Chapter-5 and literature review was used to map the properties and performance of the alternative marine fuels in terms of the specified criteria. Pairwise comparison of the criteria is then carried out to evaluate their performance (Appendix-D) using the scales as per table-2. Normalised values are calculated for the scaled table as shown in Appendix-D.

The calculations are shown in Appendix-D, and calculated criteria weights reflected in Figure-27. The results reflected that 44 per cent weigh safety, 16 per cent weigh environmental reduction potential,15.7 per cent weigh cost, 13.1 per cent weigh regulation effectiveness, 5.9 per cent weigh technological readiness, and 4.4 per cent weigh global availability for sustainability criteria of alternative fuels.

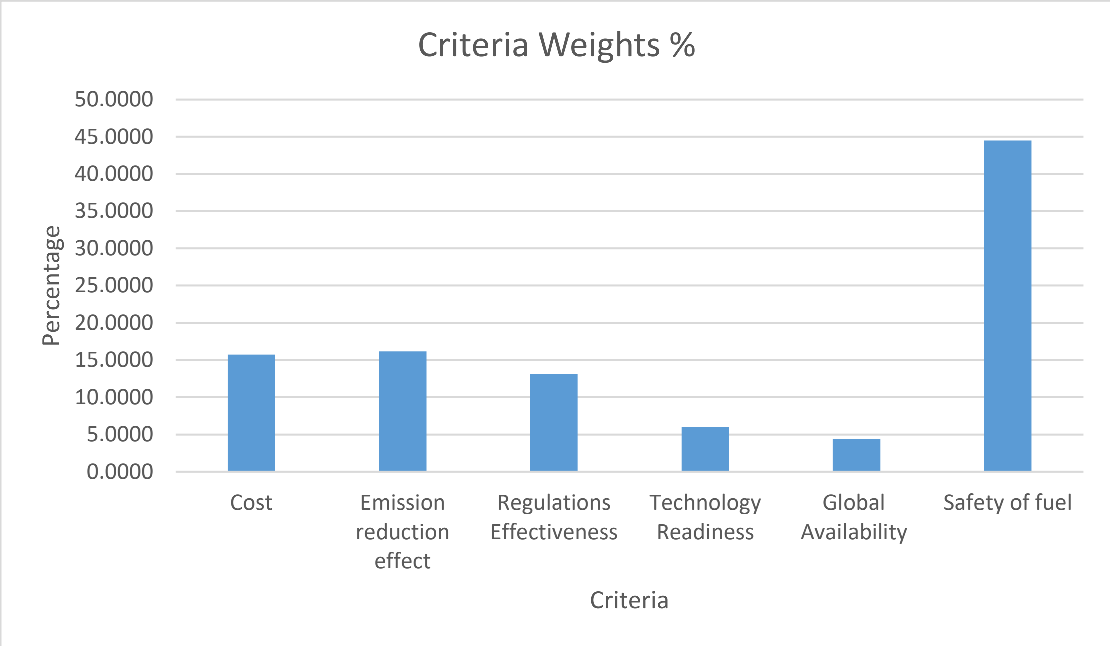

Figure 27 Criteria weights using AHP technique for Sustainability assessment of alternate fuels

Source Created by author

Fig-27 shows that safety, emission reduction potential and cost are the most preferred for the assessment of the sustainability of alternative fuels. These criteria weights will be utilised for the selection of alternative fuels.

Table 2 Scales in AHP for comparison

Scale	Description
1	Equal Importance
3	Moderate Importance
5	Strong Importance
7	Very Strong Importance
9	Extreme Strong Importance

Note. From Decision making with the Analytic Hierarchy Process (Saaty, 2008)

In order to identify the sustainability of the alternative fuels on the weight criteria factors calculated as above, an assessment value of various fuels for the criteria is made using the three scale method, (Law et al., 2021), compliance in between these may be scaled with the values 5,6,8,9. The assessment factors and scales are shown in table-3. Global LNG trade has reached 372.3 MT in the year 2021 (IGU, 2022). The availability of LNG as a fuel for shipping is expected to meet the demand by the year 2030 (DNV-GL, 2019). Production of Methanol for the year 2019 is 98 MT and is expected to be around 125 MT by 2025 (IRENA, 2021b) and may meet the demand in shipping by 2030.

The emission reduction potential of LNG and Methanol may be considered as low by the year 2030, considering its potential for methane engine slip and Life cycle assessment and when compared with Ammonia and Hydrogen (Balcombe et al., 2019).

Table 3 Assessment of Fuels for Sustainability by 2030

Factors	High Compliance Scale(10)	Reasonable Scale (7)	Not in Compliance Scale (4)
Cost	Low	Medium	High
Emission reduction Potential	High effect	Moderate	Negligible
Regulations Effectiveness(Stevens et al., 2015)	In force	Approved but not adopted	Not framed
Technology Readiness	Available and commercialised	Ready, not available to all	Under development
Global Availability (Statista, 2022a)	Global	In certain region	Not available
Safety of fuel	High Safe	Has some issues	No assessment and under research

Note. Created by Author

Table-4 shows the scaling of alternative fuels for the criteria selected, and scales are assigned to criteria using primary data analysis and data from the literature. Technology compliance for LNG and Methanol is reasonable as they need to be produced from renewable methods. Primary data analysis in Ch 5.2.4 has led to conclusive that regulatory effectiveness is reasonable as IMO's initial strategy may achieve the 50 % target. However, the 77th session of MEPC has concluded that there should be a revision of the initial strategy and aim at zero targets.

Table 4 Scale Assignment[1] for Alternative Fuels using Primary Data and Literature data

	Cost	Emission reduction Potential	Regulations Effectiveness	Technology Readiness	Global Availability	Safety of fuel
HFO with CCS	10	8	10	8	10	10
LNG	7	4	9	7	8	8
METHANOL	6	4	8	8	7	7
GREEN AMMONIA	4	10	7	7	7	7
GREEN HYDROGEN	4	10	7	7	6	7

Note. Created by Author

Safety aspects for use of heavy fuel oil is addressed in SOLAS regulation 4.2.1.1 of SOLAS II-2. Safety of LNG is addressed in SOLAS Ch-II-1 with the entry into force of the IGF code. Safety aspects of Ammonia and Hydrogen are yet to be addressed in the SOLAS convention. The selection of fuels for sustainability is made by multiplying the criteria weights calculated using the AHP technique to correspond to scaled values in table-4 and thereafter normalising its values. The technology

[1] Scale assignment for alternative fuels 4-Low, 7 Medium,10-Highest
Data Prima data analysis, Heavy Fuel oil (UNEP, 2021) and (British, 2022), LNG, (IGU, 2022), Methanol (IRENA, 2021b), Ammonia and Hydrogen (DNV-GL, 2019) Scale assignment for alternative fuels 4-Low, 7 Medium,10-Highest
Created by Author Intermediate scales 5,6,8,9 are used as applicable. Scales assignment method adopted by (Law et al., 2021)

required for Ammonia and Hydrogen as fuels may be reasonably available by 2030, provided that huge incentives may be provided for renewable production and hence considered reasonable.

Fig-28 shows the sustainability assessment of alternative fuels HFO with CCS, LNG, Methanol, green Ammonia, and green Hydrogen for the weight criteria of cost, emission reduction potential, regulation effect, technology readiness, and global availability, and safety. When cost factor is considered, green Ammonia and Hydrogen are higher compared to other fuels. The combined result shows that fossil fuels with carbon capture systems may dominate by the year 2030. However, the use of Green Ammonia may likely to commence before 2030; regulatory policies change toward climate change mitigation, subsidies in green technology investment and technology transfer may enable green Ammonia to take the lead by 2030. Hydrogen is the next best alternative fuel for selection. LNG and Methanol may not be used due to their GHG emission potential.

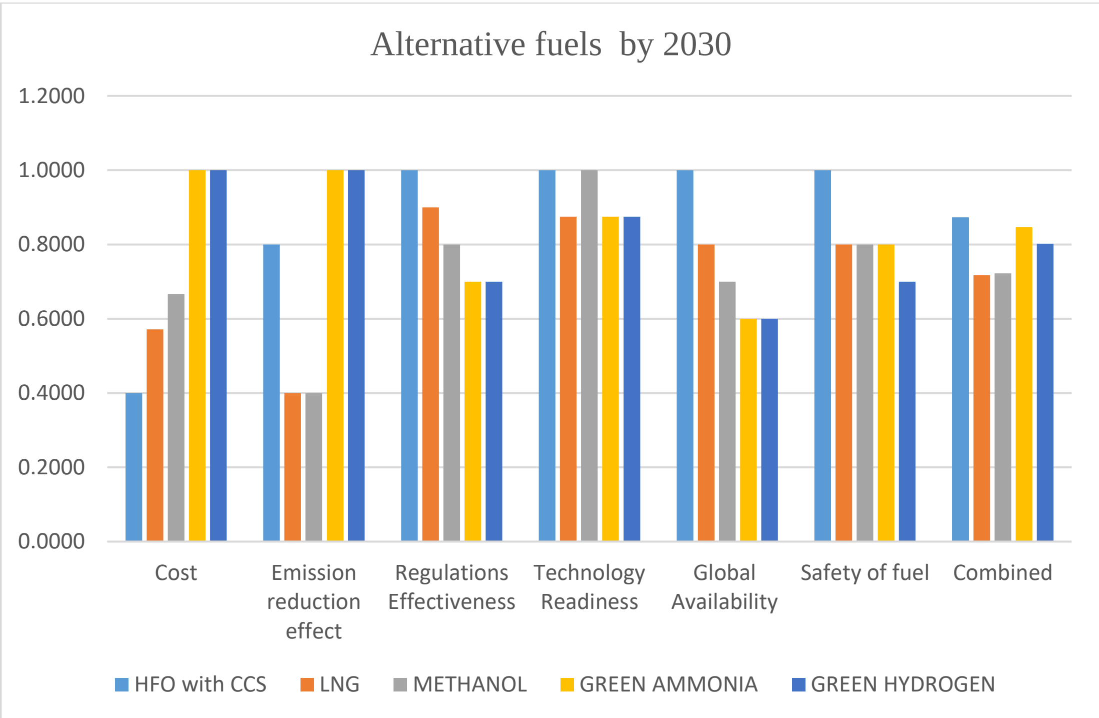

Figure 28 Alternative fuels sustainability assessment by 2030 using AHP technique and Normalised

Source Created by author

Data LNG (IGU, 2022), Methanol (IRENA, 2021b), Ammonia (AEA &IRENA, 2022), Safety (DNV-GL, 2019), Global Availability (Statista, 2022a), GHG Reduction potential (Balcombe et al., 2021), Regulations (Stevens et al., 2015) and primary data source.

5.10 Behaviour pattern and its potential for GHG emissions

Change in behaviour patterns is the key to achieving GHG emissions zero targets (IPCC, 2022). The increase in seaborne trade is directly related to the rise in emissions in the current scenario. There is a possibility of reducing emissions if the demand for seaborne trade growth is managed. Emissions reduction can be achieved by governmental interruption like laws, technological measures and by behaviour interruption. The extent to which this interruption may contribute to the emission reduction may not be possible to quantify. However, both interruptions may be the contributing factors to achieving zero targets (Nelson & Allwood, 2021).

Behavioural improvements are expected to lower energy-related activities by an average of 10% to 15% between now and 2050 (IEA, 2021). In shipping, behaviour improvements have to be anticipated by shipping companies and consumers. Key personnel in companies should encourage to invest in green ships. Business performance must be linked to long-term sustainability practices and their motivators (Yuen et al., 2017). While maintaining a decent profit level, a long-term investment plan and managing the required capital has to be made at the right time.

A change in consumer demand may change the demand in trade, and indirectly there may be a change in seaborne trade demand. According to the IEA report on the net zero 2050 forecast on CO_2 emissions, there can be an 8% reduction in emissions that may be attributed due to behavioural interruption (IEA, 2021). Figure-29 shows the possible reduction due to behavioural intervention in all sectors. 2.6 $GtCO_2$ is expected to get reduced due to behavioural intervention by 2050 in all sectors.

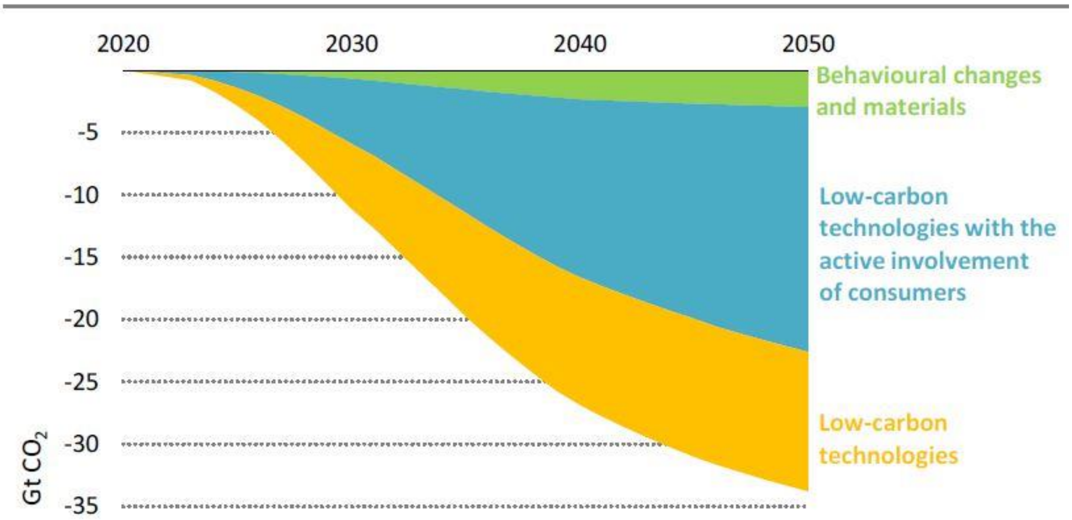

Figure 29 CO2 emissions reduction due to behavioural changes in all sectors when compared to other reduction measured

Source (IEA, 2021).

Figure-30 forecasts the emissions reduction if seaborne trade growth is managed at the rate of 2.2% annually combined with behavioural measures when implemented. According to the UNCTAD 2021 report, it is expected that the seaborne trade may grow 2.6% annually from 2023 (UNCTAD, 2021). If we forecast at the rate of 2.6% of growth rate, around 22.9 billion tons by volume may be expected by 2050. If the behaviour measures of 8% reduction (IEA, 2021) is effected, the cumulative emission reduction of CO_2 by 2050 is shown in figure-30. There can be a corresponding reduction in seaborne trade due to behavioural changes.

Figure-30 reflects the effect of additional CO_2 reduction to existing reduction measures already implemented. When we compare IMO 2018 initial strategy for GHG reduction, behavioural intervention may be expected to achieve of 78 per cent CO_2 reduction to the 2008 level in contrast of 70 percent reduction. The rest reduction of emissions may be achieved by the use of renewable Ammonia, Hydrogen, and renewable energy sources like wind-assisted rotors and solar panels on ships which may be available by 2030.

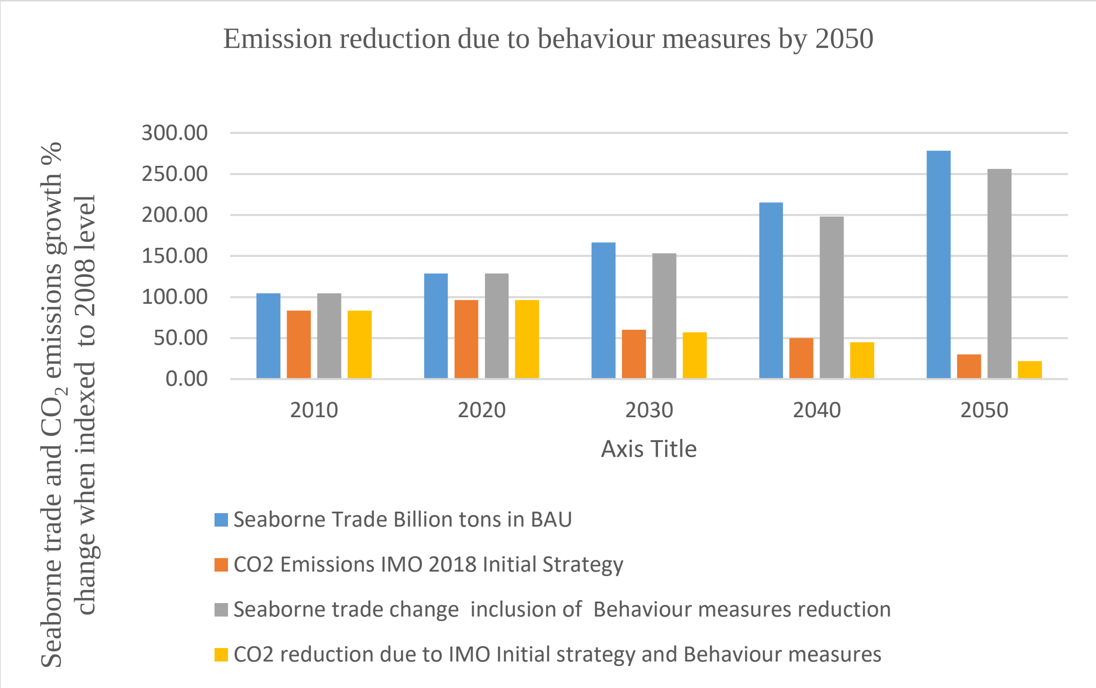

Figure 30 Emission reduction forecast when behavioural measures are adapted in conjunction with IMO 2018 Initial Strategy

Source Created by author

Seaborne trade and CO_2 emissions are indexed to the 2008 level by %. Data source for seaborne trade (UNCTAD, 2021). Data for CO_2 emissions (IMO, 2018). Forecast of behavioural reduction (IEA, 2021).

6. Summary and Conclusion

The increase in GHG emissions from shipping since the mid-19th century, has contributed to the increase in both global warming and air pollution. GHG emissions from shipping may be reduced by selection of zero carbon fuels and methods like renewable energy sources fitment, behavioural interventions. The sixth assessment report from the IPCC released in April 2022, has confirmed that there is an urgent need for substantial reductions in GHG emissions. All the economic sectors, including shipping, must reach net-zero GHG emissions by 2050 if we are to meet a 1.5-2° C climate target.

The study has identified that fossil fuels like heavy fuel oil, marine diesel oil will be available till 2050 or beyond that. LNG availability till 2050 does not pose a problem, however the production of LNG from conventional methods leads to CO_2 emissions and methane slip in downstream process of LNG usage and therefore may deter it's use. IMO's fourth GHG study has identified that methane emissions have substantially increased since third GHG study.

This study has found that the availability of Ammonia till 2040 is abundant for ship fuel purpose, yet its production procedure leads to CO_2 emissions. The necessity for production of Ammonia from green technologies emerges. The cost of producing green Ammonia is very high compared to fossil fuels production cost. Decarbonizing international shipping is technically possible with the use of green Ammonia, which is produced using renewable electricity that does not create greenhouse gases at any point in the product lifetime. Regulatory intervention, financial assistance, behavioural intervention my drive the production of green Ammonia in larger volumes by 2030.

The research has forecasted the global availability of various fuels by the 2050 for shipping industry. It is estimated that fuel of 207 million ton of oil equivalent may be required by 2050. As much as 47 million tons of oil equivalent of Ammonia and 48 million tons of oil equivalent of Biofuels might be available by 2050. Cleaner fuels may replace fossil fuels if the decarbonization drive from different stakeholders is successful.

Energy saving devices like fitment of vertical axis wind turbine, solar panels contribute to emissions reductions. New vessels must be fitted with these devices in order to achieve targets. The most promising avenues for achieve of zero targets is through the implementation of alternative energy measures. Sails, Kites, and Photovoltaic cells can be used to capture this additional energy in addition to switch to alternative fuels.

This study has focussed on the regulatory framework's effectiveness in GHG reduction. Apart from the efforts of IMO, regional measures like EU enforcement have pushed shipping to achieve zero targets by 2050. It is expected that in 2023, 80th session of Marine Environment Protection Committee may approve new strategy for GHG reduction aiming to achieve zero targets by 2050. Market based measures may be likely to be introduced by 2023 to achieve zero GHG targets by 2050. Twenty-five countries at COP26 agreed to create "green shipping corridors," or routes at sea with zero emissions by 2025.

There are a lot of barriers in the way of fuel selection for zero GHG goals. It has become clear that the IMO's initial strategy goal of a 50% reduction in GHG emissions by 2050 would not be enough to fulfil the targets of the United Nations' attempt to keep global warming within 1. 5°C.The cost to switch to alternative fuels is similarly high, and their availability is limited around the world. The production of green fuels calls for more green energy, ideally at a sensible price. Investment potential and risk, uncertainty on future regulatory measures, information and time constraints, technological limits, market challenges, and political impediments are the barriers that has to be overcome.

According to the results of this research, the safety and potential for emission reduction is the most important factor that has evolved in selecting an alternative fuel. LNG and Methanol do not lead to zero greenhouse gas emissions when considered full life cycle emissions Methanol and LNG produced from natural gas share a common source of energy and have the same global warming potential as that of HFO.

Cost, emission reduction potential, regulatory efficacy, technology readiness, worldwide availability, and safety are the factors that has evolved in this study for selection of alternative fuels. Analytic hierarchy process of multicriteria decision analysis has been applied to identify the most effective factor that may be applied for selection criteria. This process has identified that safety and emission reduction potential is the most prominent factor for consideration of selection criteria.

Sustainability assessment of the heavy fuel oil with CCS, LNG, Methanol, green Ammonia, green Hydrogen for the criteria factors has been carried out. In order to reach zero-emissions targets by 2050, the results have indicated that the shipping industry must switch to green Ammonia by 2030. New ships for use of Ammonia as fuel must be considered by 2030. Most of shipping industry has chosen LNG as alternative fuel and placed order for new ships, however, to achieve zero targets switch to Ammonia as fuel is the best option.

A set of criteria has been established using AHP for selection process as an objective. New vessels must be fitted with the selected alternative fuel i.e. Ammonia by the year 2030. The weight criteria established are “Safety of Fuel”, “Emission reduction potential”, “Cost”, “Regulations effectiveness”, “Technology readiness”, and “Global availability”. It's also important to install energy-saving equipment’s in newly built ships. Behavioural intervention is essential for the shipping industry if it is required to control the growth of seaborne trade. To reach the 2050 goal of zero greenhouse gas emissions, the combined approaches will need to be put into place.

As a result of this study, zero CO_2 and GHG emissions by 2050 is feasible with the adoption of Ammonia as fuel and combination of several separate solutions. By 2030, the shipping industry will need to have adopted the use of Ammonia as a fuel and equipped their vessels with energy-saving equipment. The implementation of behavioural intervention may contribute to reduction of emissions for zero targets.

Ammonia has been identified as most suitable alternative fuel by 2030. Further research is required aiming at production of green Ammonia other than renewable energy sources. Research on cost effectiveness of ship design with Ammonia as fuel and fitment of energy saving devices needs to be carried out. It is also expected that the new IMO regulatory strategy for GHG reduction will have more realistic approaches and will promote financial aid for technological development to produce green Ammonia and financial assistance for new shipbuilding.

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Appendix-A Survey Questionnaire

Questionnaire

1. What are various alternate fuels available for use on ships, list at least five fuels that you know that may be used onboard and rank them according to the availability in all parts of the world by the year 2030?

2. If you choose the first three fuels as listed above, can you explain how the greenhouse gas emissions from ships may be reduced (300 words or more)?

   2(a)Will it be possible to reduce greenhouse gas emissions to zero level by 2050 if you choose the first two fuels as listed in question no.1?

3. Which of the following alternative fuels/methods is widely used on ships for greenhouse gas emission reduction?
   - ELECTRIC—includes all-electric
   - COMPRESSED NATURAL GAS—fossil-based gaseous fuel, mostly comprised of methane.
   - LIQUEFIED NATURAL GAS—conventional natural gas converted to liquid form through cooling.
   - HYDROGEN—gaseous fuel typically used in the fuel cell or direct combustion
   - AMMONIA
   - OPERATION METHODS – Speed reduction
   - ___________________ (Others)

4. Can you highlight the three most influential obstacles that may be encountered while the use of alternate fuels as listed above in lieu of fossil fuels onboard ships?

5. Are you familiar with IMO's 2018 initial strategy for greenhouse gas reduction, if yes will it be effective in the reduction of emission targets by 2050 to zero level?

   5(a) If familiar with IMO 2018 initial strategy, will the other measures like the European Union or other groups will accelerate along with IMO initial strategy to achieve zero targets by 2050?

6. How do the existing regulatory frameworks address the risk associated with the use of alternate fuels on ships?

7. Rank the economic impact to a shipping company for the implementation of greenhouse gas reduction measures?
   a. No economic impact
   b. Somewhat Impact
   c. Very less Impact
   d. Marginal impact
   e. Noticeable impact
   f. Considerable impact
   g. Large economic impact
   h. Very large impact
   i. Extremely large impact
   j. Don't Know

8. Will the market-based measures like the emission trading system or any other method will achieve zero targets by 2050?

   a. Yes
   b. No
   c. _____________(Others)

   8(b) If yes, then how much benefit will be the market-based measures in achieve of zero targets by 2050
   i. Much more beneficial
   ii. More beneficial
   iii. Neither more nor less beneficial
   iv. Less beneficial
   v. No beneficial
   vi. _____________(Others)

9. What can be the most likely retrofit that may happen on existing ships for greenhouse gas reductions considering cost investment?
   a. Engines modified/retrofit for alternate fuels
   b. Shaft/Engine power limiters
   c. Use of carbon capture and storage
   d. Use of carbon capture and storage and energy-saving devices
   e. _____________(any other methods)

   9(a) Will the above-selected retrofit mechanism achieves the zero GHG targets for existing ships, or else new ships have to be constructed?

10. Finally, provide your own estimate of impact of growth of international shipping on greenhouse gas emissions between 2022-2050 ?

Appendix-B EEDI Phase Amended in MEPC 75

Reduction factors (in percentage) for the EEDI relative to the EEDI reference line

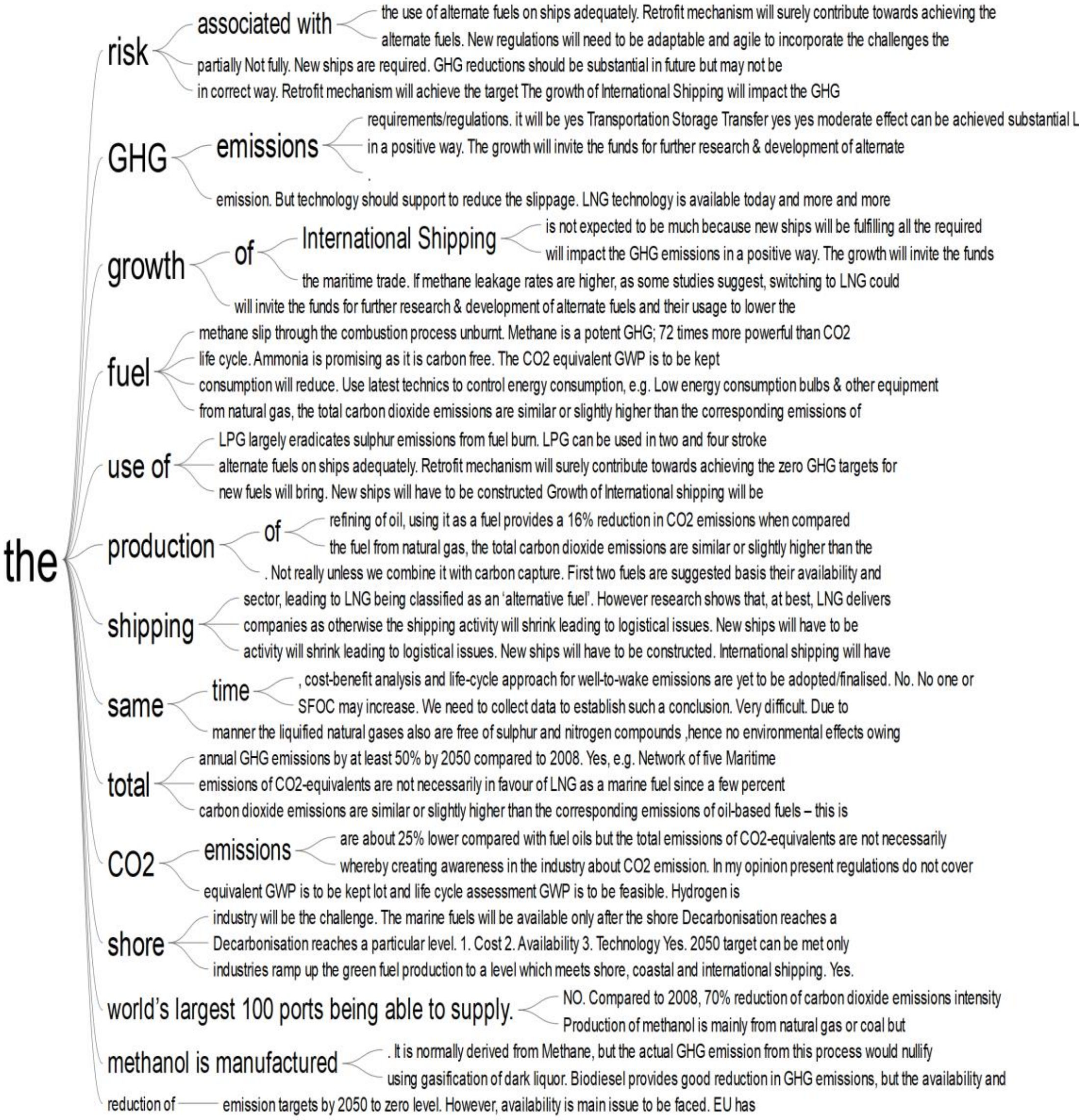
Ship Type	Size	Phase 0 1 Jan 2013 – 31 Dec 2014	Phase 1 1 Jan 2015 – 31 Dec 2019	Phase 2 1 Jan 2020 – 31 Mar 2022	Phase 2 1 Jan 2020 – 31 Dec 2024	Phase 3 1 Apr 2022 and onwards	Phase 3 1 Jan 2025 and onwards
	10,000 and above but less than 15,000 DWT	n/a	0-10*	0-20*		15-30*	
General Cargo ships	15,000 DWT and above	0	10	15		30	
	3,000 and above but less than 15,000 DWT	n/a	0-10*	0-15*		0-30*	
Refrigerated cargo carrier	5,000 DWT and above	0	10		15		30
	3,000 and above but less than 5,000 DWT	n/a	0-10*		0-15*		0-30*
Combination carrier	20,000 DWT and above	0	10		20		30
	4,000 and above but less than 20,000 DWT	n/a	0-10*		0-20*		0-30*
LNG carrier***	10,000 DWT and above	n/a	10**	20		30	
Ro-ro cargo ship (vehicle carrier)***	10,000 DWT and above	n/a	5**		15		30
Ro-ro cargo ship***	2,000 DWT and above	n/a	5**		20		30
	1,000 and above but less than 2,000 DWT	n/a	0-5*,**		0-20*		0-30*
Ro-ro passenger ship***	1,000 DWT and above	n/a	5**		20		30
	250 and above but less than 1,000 DWT	n/a	0-5*,**		0-20*		0-30*
Cruise passenger ship*** having non-conventional propulsion	85,000 GT and above	n/a	5**	20		30	
	25,000 and above but less than 85,000 GT	n/a	0-5*,**	0-20*		0-30*	

* Reduction factor to be linearly interpolated between the two values dependent upon ship size. The lower value of the reduction factor is to be applied to the smaller ship size.

** Phase 1 commences for those ships on 1 September 2015.

*** Reduction factor applies to those ships delivered on or after 1 September 2019, as defined in

Appendix-C Interactive tree Extracted from Data



Appendix-D Analytic Hierarchy Process Assessment Sheet

ASSESSMENT OF SUSTAINABILITY OF ALTERNATIVE FUELS BY THE USE OF ANALYTIC HIERARCHY PROCESS (AHP)

CRITERIA ▶	Cost	Emission reduction effect	Regulations Effectiveness	Technology Readiness	Global Availability	Safety of fuel
Cost	1.0000	2.0000	2.0000	2.0000	2.0000	0.2500
Emission reduction effect	0.5000	1.0000	3.0000	3.0000	3.0000	0.3333
Regulations Effectiveness	0.5000	0.3333	1.0000	4.0000	5.0000	0.2500
Technology Readiness	0.5000	0.3333	0.2500	1.0000	2.0000	0.1429
Global Availability	0.5000	0.3333	0.2000	0.5000	1.0000	0.1111
Safety of fuel	4.0000	3.0000	4.0000	7.0000	9.0000	1.0000
	7.00	7.00	10.45	17.50	22.00	2.09

STEP 1 CALCULATION OF NORMALISED VALUE

CRITERIA ▶	Cost	Emission reduction effect	Regulations Effectiveness	Technology Readiness	Global Availability	Safety of fuel
Cost	0.1429	0.2857	0.1914	0.1143	0.0909	0.1198
Emission reduction effect	0.0714	0.1429	0.2871	0.1714	0.1364	0.1597
Regulations Effectiveness	0.0714	0.0476	0.0957	0.2286	0.2273	0.1198
Technology Readiness	0.0714	0.0476	0.0239	0.0571	0.0909	0.0684
Global Availability	0.0714	0.0476	0.0191	0.0286	0.0455	0.0532
Safety of fuel	0.5714	0.4286	0.3828	0.4000	0.4091	0.4791
	1.00	1.00	1.00	1.00	1.00	1.00

STEP 2-CALCULATION OF CRITERIA WEIGHTS

CRITERIA ▶	Cost	Emission reduction effect	Regulations Effectiveness	Technology Readiness	Global Availability	Safety of fuel	Criteria Weights
Cost	0.1429	0.2857	0.1914	0.1143	0.0909	0.1198	0.1575
Emission reduction effect	0.0714	0.1429	0.2871	0.1714	0.1364	0.1597	0.1615
Regulations Effectiveness	0.0714	0.0476	0.0957	0.2286	0.2273	0.1198	0.1317
Technology Readiness	0.0714	0.0476	0.0239	0.0571	0.0909	0.0684	0.0599
Global Availability	0.0714	0.0476	0.0191	0.0286	0.0455	0.0532	0.0442
Safety of fuel	0.5714	0.4286	0.3828	0.4000	0.4091	0.4791	0.4452

STEP 3- CALCULATION OF CONSISTEN

CRITERIA WEIGHTS	0.1575	0.1615	0.1317	0.0599	0.0442	0.4452			
CRITERIA ▶	Cost	Emission reduction effect	Regulations Effectiveness	Technology Readiness	Global Availability	Safety of fuel	Weighted sum value	Criteria weights	Ratio
Cost	0.1575	0.3230	0.2635	0.1198	0.0885	0.1113	1.0635	0.1575	6.7528
Emission reduction effect	0.0787	0.1615	0.3952	0.1797	0.1327	0.1484	1.0962	0.1615	6.7889
Regulations Effectiveness	0.0787	0.0538	0.1317	0.2396	0.2212	0.1113	0.8364	0.1317	6.3498
Technology Readiness	0.0787	0.0538	0.0329	0.0599	0.0885	0.0636	0.3775	0.0599	6.3008
Global Availability	0.0787	0.0538	0.0263	0.0300	0.0442	0.0495	0.2826	0.0442	6.3872
Safety of fuel	0.6300	0.4844	0.5269	0.4194	0.3982	0.4452	2.9040	0.4452	6.5235

ƛ max =	6.52	(AVERAGE(L36:L41))	
Consistency Index =	ƛ max-n/ n-	0.1034	
Consistency Ratio	Consistency index/ Random index		0.0834
(Random index for six criteria is 1.24)			

Since the consistency ratio is less than 0.10, selection criteria are validated.

SUSTAINABILITY ASSESSMENT USING WEIGHT CRITERIA

Criteria weight ▶	0.1575	0.1615	0.1317	0.0599	0.0442	0.4452
CRITERIA ▶	Cost	Emission reduction effect	Regulations Effectiveness	Technology Readiness	Global Availability	Safety of fuel
HFO with CCS	10.0000	8.0000	10.0000	8.0000	10.0000	10.0000
LNG	7.0000	4.0000	9.0000	7.0000	8.0000	8.0000
METHANOL	6.0000	4.0000	8.0000	8.0000	7.0000	8.0000
GREEN AMMONIA	4.0000	10.0000	7.0000	7.0000	6.0000	8.0000
GREEN HYDROGEN	4.0000	10.0000	7.0000	7.0000	6.0000	7.0000

NORMALISED VALUES

CRITERIA ▶	Cost	Emission reduction effect	Regulations Effectiveness	Technology Readiness	Global Availability	Safety of fuel	Combined
HFO with CCS	0.4000	0.8000	1.0000	1.0000	1.0000	1.0000	0.87
LNG	0.5714	0.4000	0.9000	0.8750	0.8000	0.8000	0.72
METHANOL	0.6667	0.4000	0.8000	1.0000	0.7000	0.8000	0.72
GREEN AMMONIA	1.0000	1.0000	0.7000	0.8750	0.6000	0.8000	0.85
GREEN HYDROGEN	1.0000	1.0000	0.7000	0.8750	0.6000	0.7000	0.80

		Rank
HFO with CCS	87.32	1.00
LNG	71.71	5.00
METHANOL	72.20	4.00
GREEN AMMONIA	84.63	2.00
GREEN HYDROGEN	80.17	3.00