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ALTERNATIVE FUEL EMISSIONS WITH REGARDS TO EUROPEAN UNION'S EMISSIONS TRADING SYSTEM AND FUELEU PROPOSAL

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ABSTRACT

The expansion of global commerce has highlighted the critical role that marine transportation networks play within logistics systems. Despite gains in ship efficiency, the growing reliance on marine traffic within the global logistics system has resulted in a significant increase in greenhouse gas (GHG) emissions from the maritime industry.

The objective of this thesis was to calculate the specific fuel consumption, total GHG emissions, and carbon intensity metrics of the alternative fuels. In particular, the purpose of this thesis is to evaluate the appropriateness of MeOH and NH_3 as alternative fuel choices within the context of the EU ETS and the upcoming FuelEU Maritime initiative.

Bulk carriers, oil tankers, and container ships, the types of vessels that emitted the most GHGs, were chosen for this thesis. The specific fuel consumptions were calculated based on the engine loading. The total GHG emissions were calculated with each fuel emission factor and the vessel's fuel consumption. Lastly, the carbon intensity metrics were calculated based on the voyage data.

The results of this thesis were compared to the IMO's fourth GHG reports for validation. The specific fuel consumption of alternative fuels was higher than that of conventional fuels, as the formers have lower energy density. With the lower energy density, the alternative fuels had to utilize conventional fuels as their pilot fuel to ignite and combust. However, the results still showed that there was a significant reduction in the total GHG emissions and carbon intensity.

Keywords: Alternative fuels, GHG Emissions, Maritime Emissions, EU Emissions Trading System, FuelEU Maritime.

CONTENTS

1 INTRODUCTION

The expansion of international trade has made marine transportation networks an essential component of logistics networks. 80% of all trade is moved by water, and the marine logistics network is what drives economic integration throughout the world (Wen et al. 2022). As a result, shipping — a fundamental requirement of global trade — has evolved into a useful lens for examining the whole economy. The greenhouse gas (GHG) emissions from the industry have consequently increased even though ships have become more efficient. According to the International Maritime Organization (IMO) Fourth GHG Study (2020, 5-7), global GHG emissions increased from 34,793 to 36,573 million tons from 2012 to 2018, representing a 5.12% increase.

One of the approaches to tackle this problem is utilizing alternative fuels. Conventional technologies are primarily fuelled by the extraction of fossil fuels, which has consequently resulted in significant environmental issues. It is necessary to use sustainable fuels and solutions more frequently to lessen the negative consequences of fossil fuels (Zamfirescu & Dincer 2008, 459. NH_3 is a potential storage medium that has reliable transportation and storage connections (Jeerh et al. 2021, 730). Furthermore, under liquid form at a temperature of 25 ℃ and a pressure of 10 atm, NH_3 has a larger energy density than liquid H_2, which has to be stored at lower temperatures and higher pressures to remain a liquid (Cengel & Boles 2014, 356). NH_3 offers a substitute fuel source to reduce harmful emissions to the environment during the energy-generating process because it is carbon-free and affordable (Siddiqui & Dincer 2018, 570).

In addition to having NH_3 as an alternative fuel, alcohols, or specifically methanol (MeOH), are another promising chemical for sustainable fuel. In typical engines, apart from conventional fuel, primary alcohols can be used as fuel with fewer modifications compared to those that use NH_3. These facilities generally obtain their syngas for the manufacture of MeOH from natural gas (Valera & Agarwal 2019, 10). Since MeOH is a fuel source in and of itself, producing it from renewable sources would help to lessen our dependency on fossil fuels in the energy and transportation sectors (Matzen & Demirel 2016, 1073–1075).

Besides utilizing technological advancement to reduce GHG emissions, one of the world's largest frameworks that requires intergovernmental effort in the fight against climate change is the Kyoto Protocol. It is a key component of the United Nations Framework Convention on Climate Change (UNFCCC) system. The UNFCCC regime also approved the Paris Agreement, adopted by parties in 2015 and entered into force in 2016 (UNFCCC 2016). By using carbon price policy tools, the reduction of GHG emissions is assessed to be one of the most economically effective methods for emissions reduction (Aldy 2015, 398). There are three main types of carbon pricing, which include cap-and-trade, carbon taxation, and the combination of both (Narassimhan et al. 2018, 980). The largest cap-and-trade scheme in the world and possibly the most significant market-based application to the climate challenge is the EU Emissions Trading System (ETS). In 2023, the system is currently in its fourth phase of operation with the target of reducing GHG emissions by 55% by 2023 (European Commission 2020c). In order to meet this target, the "Fit for 55" package was presented on 14 July 2021 (European Council 2021). In regard to the maritime industry, the FuelEU Maritime initiative, part of the "Fit for 55" package, was proposed to increase the demand for renewable and sustainable fuel.

As a result of the technological advancements in alternative fuels and the EU legal framework regarding maritime emissions, the purpose of this thesis is to examine the suitability of MeOH and NH_3 as alternative fuel options with regard to the EU ETS and FuelEU Maritime proposal. The literature review will provide an overview of current technologies in relation to the legal landscape. The results of this thesis will show the emissions factors and the carbon intensity from the alternative fuels under the current EU ETS and the future FuelEU Maritime proposal. The research questions for this thesis are:

- What is the specific fuel consumption of alternative fuels on current maritime engines?
- What is the total GHG emissions if the maritime vessels fleet switches to alternative fuels?
- What are the carbon intensity metrics for the maritime vessels fleet when it switches to alternative fuels?

2 COMPARISON BETWEEN ALTERNATIVE AND CONVENTIONAL FUEL

2.1 Physical and Chemical Properties

Because of the diverse fleets of vessels with different payloads and purposes, there are many types of fuels being used in the maritime industry. According to the IMO (2020, 5-7), Heavy Fuel Oil (HFO), Marine Gas Oil (MGO), and Liquified Natural Gas (LNG) were the most widely used fuels for maritime vessels because of their favourable chemical and physical properties (Table 1).

Table 1. Chemical and physical properties of conventional and alternative fuels, adapted from Kontoulis et al. (2018), Verhelst et al. (2019), Park et al. (2020), and Lee at al. (2017)

Property	HFO	MGO	LNG	MeOH	NH_3
Chemical formula	-	-	CH_4	CH_3OH	NH_3
Molecular weight (g/mol)	-	-	16	32	17
Density (kg/m^3)	989	882	428	790	681
Boiling point (℃)	813	547	-161.5	65	-33.3
Heat of vaporization (kJ/kg)	350	300	510	1100	1372
Lower heating value (MJ/kg)	39.49	41.06	48.6	20.09	18.64
Higher heating value (MJ/kg)	42.66	43.67	55.2	22.88	20.01
Volumetric energy content (MJ/m^3)	38050	36314	21405	15871	12693

All of the physical and chemical properties of the fuels in Table 1 were measured when these fuels were in liquid form. To begin with, HFO and MGO are the densest among the fuels examined in this thesis. They are the product of the crude oil refining process and HFO is slightly heavier than MGO because HFO mostly contains refinery residue and MGO has more refinery distillate (Abdul Jameel et al. 2019, 1052). Thus, HFO is classified as a residual fuel while MGO is classified as a distillate fuel. MeOH and NH_3, as expected, are not as dense as the oil fuel. These molecules are both polar which allows their liquid density to be quite heavy despite their small molecular weight. LNG, mostly containing CH_4, is the least dense fuel in this selection because of its small molecular weight and non-polarity.

Similarly, the boiling points of HFO and MGO are the highest of the fuels in the group because of their long hydrocarbon chain and molecular weight. On the other hand, LNG and NH_3 have the lowest boiling points because of their small molecular weight. The boiling point of NH_3 is significantly higher than LNG because NH_3 is a polar molecule while LNG mostly has non-polar molecules such as CH_4. Even though MeOH has a similar molecular weight to NH_3 and CH_4, it has a significantly higher boiling point because methanol is a polar molecule and is able to form hydrogen bonds from the hydroxyl group.

The heat of vaporization is the amount of energy needed for a liquid to become a gas. The energy added to the liquid has to overcome the intermolecular forces that are holding its liquid phase. MeOH and NH_3 have the highest heat of vaporization values due to their dipole-dipole force and hydrogen bond (with regard to MeOH). This means that they require the most energy to vaporise and will cool down their surroundings. The hydrocarbon fuels of HFO, MGO, and LNG have lower heat of vaporization values compared to those of methanol and ammonia because the hydrocarbon fuels have weaker intermolecular forces. Thus, the vaporization of these fuels would not cool down their surroundings as much.

The higher/lower heating values represent the amount of energy released when the fuel is burned. The higher heating value does not include the energy required to evaporate the water generated. The lower heating value does include the extra energy for water evaporation, which would reduce the final amount of energy extracted. Because C-H bonds store a high amount of energy, the hydrocarbon fuels have higher heating values compared to the alternative ones. Knowing the heating values and the density of the fuels, the volumetric energy content can be calculated. HFO and MGO have the highest energy content, which is important for the maritime industry because of the vessel size constraints. LNG has lower energy content compared to HFO and MGO because of its smaller density. Thus, alternative fuels have the lowest energy content because of their smaller heating values.

Because conventional fuels are a mixture of different types of hydrocarbons, analysing the elemental composition of these fuels will aid the understanding of their properties (Table 2).

Table 2. Elemental composition (%) of the conventional fuels, adapted from Zamiatina (2016) and Abdul Jameel et al. (2019)

Fuel	C	H	O	S	N
HFO	84.4	10.7	2.3	2.4	0.31
MGO	87.0	12.8	< 0.1	0.1	< 0.1
LNG	75.1	25.0	< 0.1	< 0.1	< 0.1

HFO and MGO have similar compositions because they are both products of the crude oil refinery process. HFO contains more residue and ashes from crude oil, which would explain the high sulphur and oxygen content. On the other hand, MGO is a more refined fuel because it is a distillate product at a lower temperature and has thus less residue compared to HFO. Lastly, LNG is different from the other conventional fuels in discussed this thesis because it is not from the crude oil refinery process. It contained mostly methane and small amounts of volatile hydrocarbons such as ethane, and butane.

2.2 Life Cycle Assessment

Constructing the life cycle assessment (LCA) would help researchers and government officials understand the environmental consequences, which include the global warming potential (GWP), ocean acidification, and eutrophication. LCA is an effective tool to be used in examining various emissions sources that are related to the life cycle of a type of fuel. In recent research, the emissions sources include processes such as raw material extraction, fuel production, transportation, bunkering, and utilization (Figure 1).

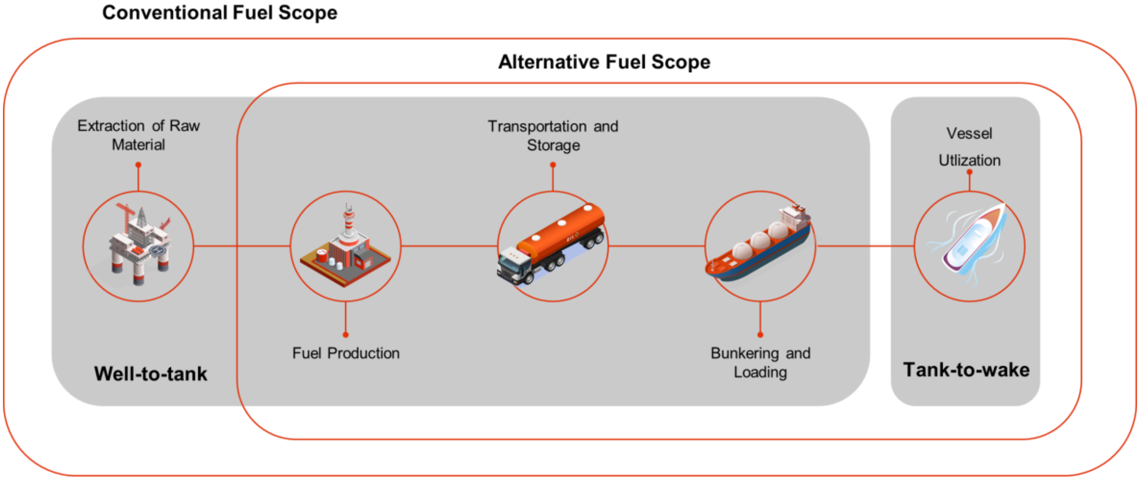

Figure 1. Overview of the LCA scope, adapted from Bengtsson et al. (2011) and Al-Breiki & Bicer (2021)

The LCA scope of both types of fuels in this thesis, conventional and alternative, can be divided into two consecutive groups. The first group is called Well-to-tank, which starts with extracting the raw material for conventional fuels and at fuel production for alternative fuels. The final process for the first group is bunkering and loading. In other words, the first group consists of procedures that prepare and process the fuels and transport the fuels to their final location. The second group, called Tank-to-wake, involves igniting the fuels to extract energy from them.

2.2.1 Conventional Fuel Scope

To begin with, we may have a look at the origin of conventional fuels. All naturally occurring hydrocarbons in rocks are comprised of petroleum, which is made up of organic components that have been absorbed into sedimentary rocks. Over the course of geological time, these rocks' sinking and burial increase the temperature and pressure, which starts the maturation process for organic matter to become crude oil (Miller & Sorrell 2014). Because these conditions are needed in the formation of crude oil and short hydrocarbons, the raw material for conventional fuels is located deep underground. Thus, extracting the raw material requires drilling down through layers of rocks as well as injection of high-pressure fluids to force the crude oil up to the surface. The fuel production process of HFO and MGO is presented in Figure 2. The production includes multiple processing units before the fuels are suitable for usage.

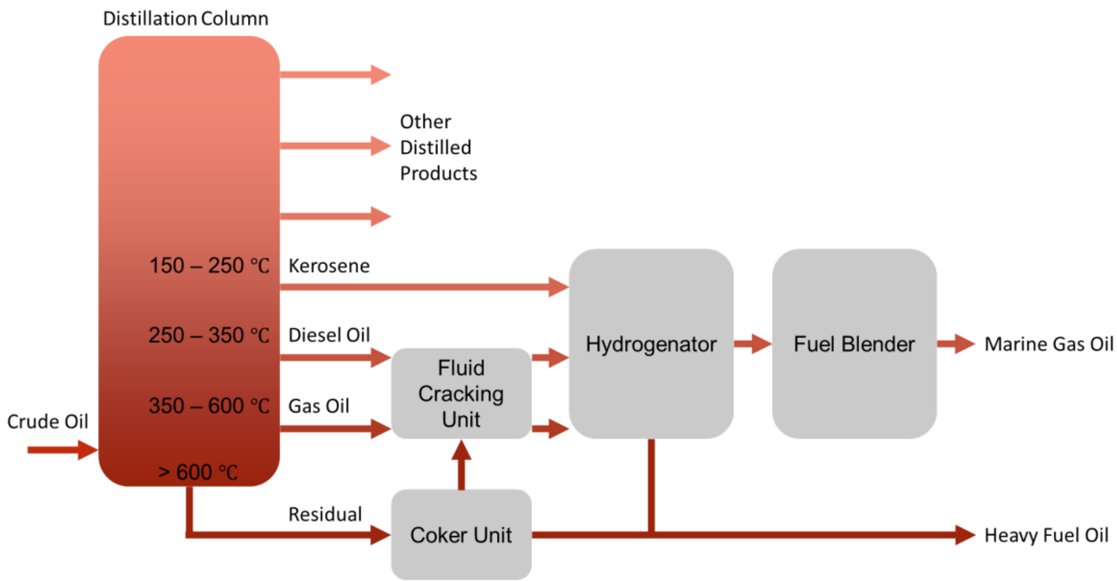

Figure 2. HFO and MGO fuel production, adapted from Rong et al. (2018)

The distillation column is the most important process of the crude oil refinery, in general, and of the HFO/MGO production, specifically. The column operates by separating substances based on their difference in boiling points. The extracted crude oil enters the bottom of the column and is heated to over 600 ℃. The residual products have the highest boiling points and thus would settle at the bottom of the column because they are not able to be boiled into higher stages. The residual products then pass through the Coker Unit, which separates some of the oils, which were not able to boil off into higher locations in the distillation column, from the solid petroleum coke. The Coker Unit also performs preliminary cracking reactions. Cracking reactions are those that break long chains of alkanes into shorter and/or branched alkanes, alkenes, and cycloalkanes. Gas oil and Diesel oil, which boil off at 250 – 600 ℃, enter the Fluid Cracking Unit along with cracked distillates from the Coker Unit. The Hydrogenator converts the alkenes and cycloalkanes from the Cracking Unit into alkanes before entering the Fuel Blender. This last unit blends the fuel to meet the industry specifications.

The fuel production process of LNG is presented in Figure 3. The production includes the pre-treatment of the raw feed and the liquidation afterward.

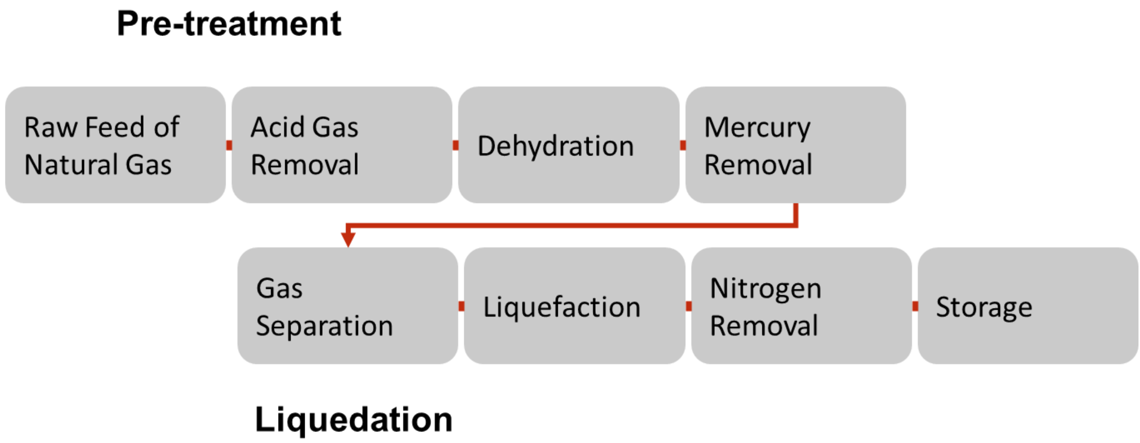

Figure 3. LNG fuel production, adapted from Ikealumba & Wu (2014)

The raw feed of natural gas contains impurities that need to be removed. These impurities include acid gas or H_2S and Hg, which are corrosive to the pipes, and water, which would clog the pipes when frozen. The liquidation process first starts with gas separation to increase the methane concentration by removing heavier hydrocarbons such as hexanes, pentanes and butanes. Traces amount of nitrogen would then be removed before LNG is moved to storage.

The next step in the LCA scope for conventional fuels is transportation and storage. The maritime routes for the transportation of these fuels are presented in Figure 4. These largest routes are classified into seven zones based on their locations.

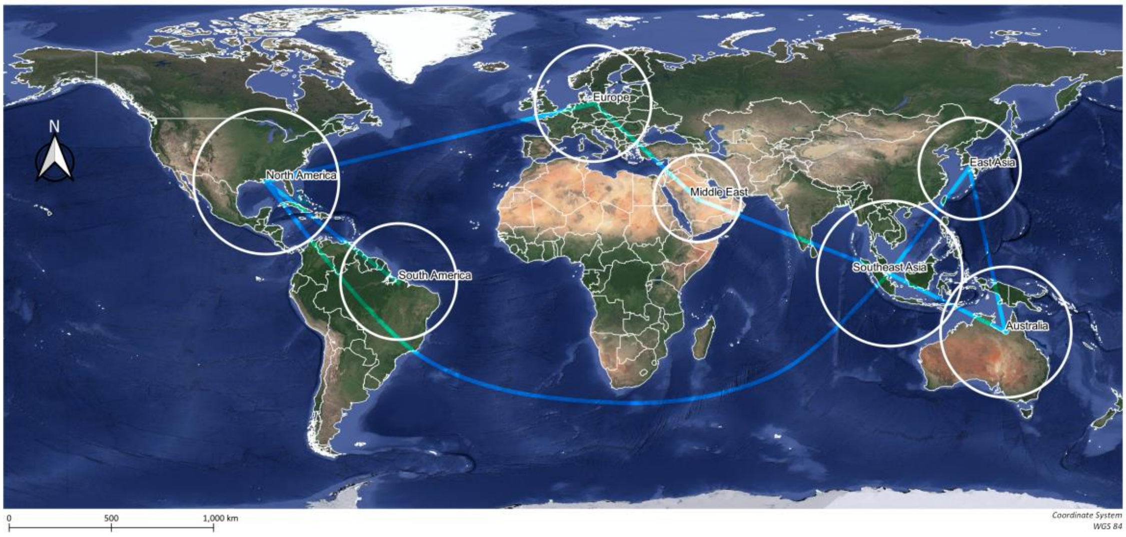

Figure 4. Conventional fuel maritime shipping routes, adapted from Peng et al. (2021) and Siddiqui & Verma (2013)

The Middle East region is the largest exporter of crude oil and its products. Because of its strategic geographic location, this region exports most of its conventional fuels to Europe and Asia Pacific. The European routes would require vessels to pass through the Suez Canal and the Gibraltar Strait while Asia Pacific routes would pass through the Malacca Strait and Singapore. The next largest trading region would be the Americas. North and South American conventional fuel trading remains quite localized due to their proximity to the large fossil fuel deposit in the Gulf of Mexico. The fuel shipping routes from North America to Southeast Asia are the newest to form because of newly active LNG power plants in Southeast Asia (Kieu 2023).

The last step in the “Well-to-tank” group in scope is bunkering and loading. This refers to how the vessels receive their fuel. Some vessels fill up their fuel storage tanks when they are docked at ports. However, there are vessels that fill up their tanks at sea and require other bunker ships to transport that fuel.

Lastly, vessel utilization refers to the combustion of the fuel to convert its chemical potential energy to mechanical or electrical energy for vessel usage. On large vessels, there might be multiple electrical generators that use a variety of fuels. In most LCA studies on maritime transportation, because the main engine propeller is the largest fuel consumer, the emissions calculation is based on the main engine fuel consumption.

2.2.2 Alternative Fuel Scope

The industrial production of NH_3 is based on the Haber-Bosch process (Appl 1982), named after the scientists Fritz Haber and Carl Bosch. The chemical reaction and its enthalpy are presented in Equation (1).

$$\begin{gathered} N_2 + 3H_2 \leftrightarrow \ 2NH_3 \\ \Delta H = -46.35\, kJ/mol \end{gathered} \tag{1}$$

In order to complete the process, H_2 and N_2 must react over an iron-based catalyst at temperatures close to 500 ℃ and pressures as high as 300 atm. Nowadays, the majority of NH_3 production facilities employ fused-iron catalysts that make use of a number of specifically created promoter substances (Humphreys et al. 2021). Because NH_3 production factories need high pressure and temperature in order to achieve the necessary yield, sizable energy input is essential for this fuel production. According to previous research, the majority of modern NH_3 synthesis catalysts used in the Haber-Bosch process operate at temperatures between 425 and 450 ℃ at pressures more than 100 atm to achieve conversion rates of around 10 - 15% (Liu 2011, 688). Because of how energy-intensive the production is, finding renewable energy sources presents many challenges. In addition, because H_2 is not readily available in nature, compared to N_2, which takes up 70% of the air, sustainable H_2 production methods also add complexity to the system. The production routes for NH_3 synthesis are presented in Figure 5.

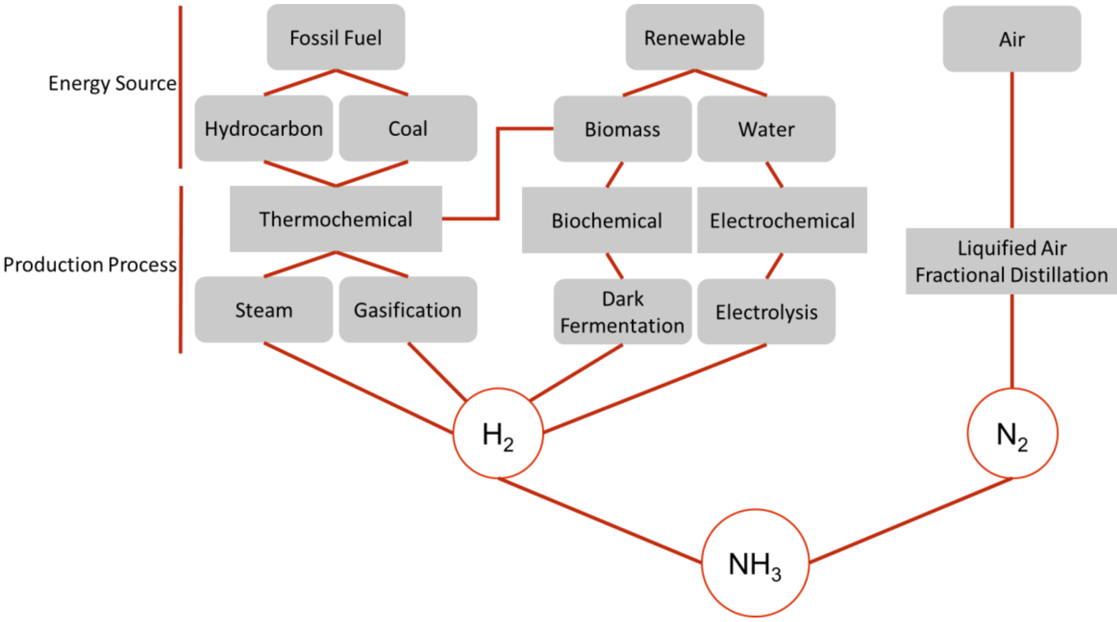

Figure 5. NH_3 production routes, adapted from Ghavam et al. (2021)

The N_2 production route for the Haber-Bosch process is quite simple. Air is taken in and cooled to -200 ℃ to liquify N_2, O_2, and CO_2. Then a fractional distillation is performed to separate the different components of air and capture the needed N_2.

On the other hand, producing H_2 is not as straightforward as there are multiple options with energy sources and processes. The energy sources are categorized into fossil fuel sources and renewable sources. As for the production processes, they are summarized in Table 3.

Table 3. Summary of H_2 production process, adapted from Dincer & Acar (2015), Ghavam et al. (2021), Kothari et al. (2017), and Liu et al. (2009)

Production Process	Description	Production Scale	Equation(s)	
Steam	CH_4 is heated up to 1100 ℃ with nickel (Ni) catalyst. The first reaction is the main reaction of this process. The second reaction, called water-gas-shift, is used to recover CO for further oxidation.	Large	$CH_4 + H_2O \rightarrow CO + 3H_2$ $CO + H_2O \rightarrow CO_2 + H_2$	(2)
Gasification	Coal is blown with O_2 and steam and formed a mixture of CO, CO_2, H_2, and H_2O. The water-gas-shift	Large	$C + O_2 + H_2O \rightarrow 3CO + H_2$ $CO + H_2O \rightarrow CO_2 + H_2$	(3)

Production Process	Description	Production Scale	Equation(s)
	reaction is also used to completely oxidized all byproducts.		
Dark Fermentation	Bacteria in the *Clostridium* genus are able convert sugars into simple organic acid with H_2 as a by-product.	Small	$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2$ (4)
Electrolysis	Water molecules are splits into their basic components with electricity	Large	$2H_2O \rightarrow O_2 + 2H_2$ (5)

Both the steam and gasification production processes are classified as thermochemical because of the high temperature needed for the reactions to occur. The steam process is the most widely used because of how inexpensive CH_4 is compared to other starting chemicals. In contrast, even though coal is even less expensive than CH_4, the gasification process is slowly being faded out because of how environmentally damaging this process can be (Wong 2017). Dark fermentation is a sustainable option to generate H_2 from biowaste. This process utilizes the bacteria energy conversion pathway to generate H_2 from glucose and other simple carbohydrates. CH_3COOH and other simple organic acids in the reactions can easily be treated to reduce this process's environmental impact (Kothari et al. 2017, 1217–1220). Lastly, electrolysis is considered the most sustainable and clean way to produce H_2 as it only requires water and electricity along with solid catalysts to speed up the reaction rate (Sebbahi et al. 2022, 143). So, by simply using electricity from sustainable sources, electrolysis can be a sustainable way of producing H_2.

The modern production of MeOH is based on Patent US4367206A invented by Pinto (1983) from Imperial Chemical Industries Ltd (ICI), now Johnson Matthey Plc. As shown in Equation (6), this reaction occurs in the presence of a copper-based catalyst. As carbon capture issues are gaining attention, new sustainable options for producing MeOH are under research. Equation (7) is proposed to generate MeOH from captured CO_2 with copper-based catalysts as well.

$$CO + 2H_2 \rightarrow 2CH_3OH \quad \Delta H = -100.46\, kJ/mol \tag{6}$$

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \quad \Delta H = -45.9\, kJ/mol \tag{7}$$

According to the patent description, reaction (6) is most efficient at 40 – 100 atm depending on the concentration of CO in the reactor. The temperature of the incoming gas should be between 50 and 150 ℃ and the copper-based catalyst should be heated to under 280 ℃. Reaction 6 also occurs in the same conditions but at a slower rate due to unfavourable kinetics. The production route for MeOH is quite similar to that of NH_3, as presented in Figure 6.

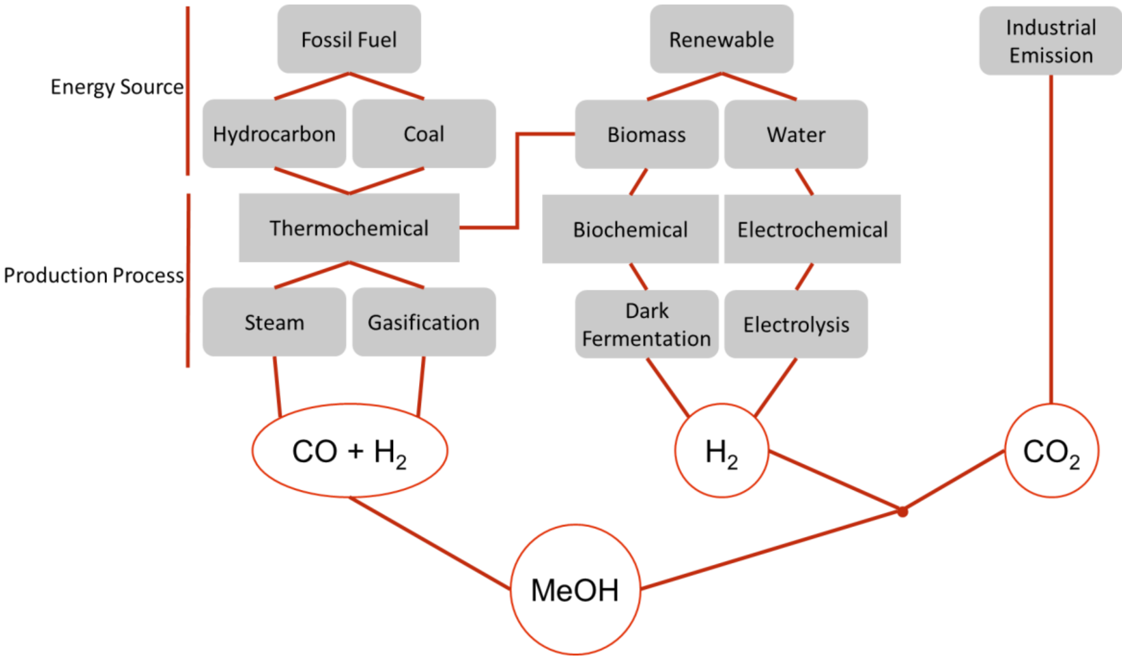

Figure 6. MeOH production routes, adapted from Dalena et al. (2018)

Currently, most of the MeOH production is still based on fossil fuels. The production relies on the CO and H_2 from the steam and gasification process as presented in Table 3. Thus, the environmental impact of this production route raises the same concern. However, a sustainable production route is being proposed for practical development. Instead of using CO as the carbon source, CO_2 is suggested to be a replacement which can be captured from industrial emissions. The H_2 in this new reaction (7) would come from renewable sources such as water and biomass as presented in Table 3. However, the conversion rate for this reaction is quite low for this method to be industrially viable. (Azhari et al. 2022.)

2.2.3 Life Cycle Assessment Emissions

The LCA results are presented in Table 4 for all of the fuels considered in this thesis. As discussed above, there are many pathways that can produce alternative fuels. The emissions for MeOH and NH_3 in the table were calculated based on the percentage of each production route.

Table 4. Life Cycle Assessment Summary, adapted from Bengtsson et al. (2011) for HFO, MGO and LNG, from Al-Breiki & Bicer (2021); Bicer & Dincer (2018); Chalaris et al. (2022) for MeOH and NH_3

	HFO	MGO	LNG	MeOH	NH_3
Well-to-tank					
Fuel consumption (MJ/t km)	0.04	0.08	0.07	-	-
Emissions (gCO_2-eq/t km)	4.20	4.50	5.90	12.15	45.00
Tank-to-wake					
Fuel consumption (MJ/t km)	0.49	0.50	0.52	-	-
Emissions (gCO_2-eq/t km)	39.00	37.00	33.00	35.80	3.60

During the Well-to-tank phase, conventional fuels have the lowest emissions compared to alternative fuels. Because of the large scale of production for conventional fuels, the emissions from the Well-to-tank phase benefit from the efficiency that comes with large-scale operations. In addition, the thermodynamics of the distillation and cracking processes have been optimized for the production of these fuels. However, it must be noted that the crude oil refinery process is not an environmentally friendly process despite the favourable emissions rate presented. The negative environmental impact as well as consuming non-renewable resources at such a high rate is not sustainable and has been damaging the earth’s environment. On the other hand, the emissions of MeOH and NH_3 for the Well-to-tank phase are significantly higher. As mentioned in the previous subsection, forming chemical bonds of these molecules requires much more energy. Thus, because the productions of these fuels still use fossil fuel as its energy source, the emissions for these fuels would remain high unless renewable energy sources and biological production methods are utilized more.

For the Tank-to-wake phase, all of the carbon-based fuels have similar emissions while NH_3 has the lowest emissions. Because of the low emissions rate, NH_3 is a promising sustainable fuel if its production can utilize more renewable energy sources.

3 LEGAL FRAMEWORK

3.1 European Union's Emissions Trading System

The largest GHG cap and trade scheme in the world is the EU ETS, established pursuant to Directive 2003/87/EC. The system, introduced in 2003 and operated since 2005, is a crucial pillar in the EU's campaign to reduce GHG emissions and global warming. It is one of the key strategies the EU is using to fight global warming and efficiently cut GHG emissions. Joined by 31 nations as of 2019, the system has more than 15,000 business entities, power plants, and other infrastructure covered (Anderson 2020). The ETS's most recent revision in 2020 for its fourth phase, would aid the more ambitious EU Green Deal objective of a 55% reduction in emissions inside the EU by 2030 compared to 1990 (European Commission 2020c). All of the mentioned legislation in this section is summarized in Table 5 and will be explained in detail throughout this section.

Table 5. Relevant legislation in regard to the ETS and maritime emissions

Name	Date	Notes
ETS Establishments and Guidelines		
Directive 2003/87/EC	13 Oct 2003	Establishing the ETS with basic monitoring and reporting criteria
Commission Implementing Regulation 2018/2066	18 Dec 2018	Following the IPCC (2006) report to establish GHG Inventory guidelines, updating monitoring and reporting criteria
National Allocation Plan		
Communication **COM (2003) 830**	07 Jan 2004	Guidance for setting the NAP
Communication **COM (2005) 703**	22 Dec 2005	Guidance for reporting the NAP
Commission Decision **2020/1722**	16 Nov 2020	Guidance for setting the Union-wide allowance
Market Stability Reserve		
Decision 2015/1814	06 Oct 2015	Establishing the MSR
Directive 2018/410	14 Mar 2018	Updating MSR to further reduce the EUAs in circulation
Maritime Emission Regulations		
Regulation 2015/757	29 Apr 2015	Monitoring and reporting GHG emissions for the maritime sector
Regulation 2023/957	10 May 2023	Including maritime transportation in the ETS

The emission cap, or the total amount of GHG that can be emitted, is set by the EU annually. The guidelines on calculating GHG emissions have been updated multiple times, with its newest revision presented in Commission Implementing Regulation 2018/2066. Companies must obtain a European Emission Allowance (EUA) for each tCO_2e they produce during a calendar year. One EUA entitles the company, or installation, to emit one tCO_2e. The guidelines for setting and reporting the total number of allocated EUA are in accordance with Communication COM (2003) 830 and Communication COM (2005) 703. According to these legislations, the initial distribution of the EUA is obtained through auction in addition to the secondary market for exchanging EUA. At the end of the year, companies have to surrender their EUAs in an equal amount to their GHG emissions. Fines are imposed on companies that have more GHG emissions than their obtained EUAs or any other non-compliance issues. The explanation of how the ETS operates is depicted in Figure 7.

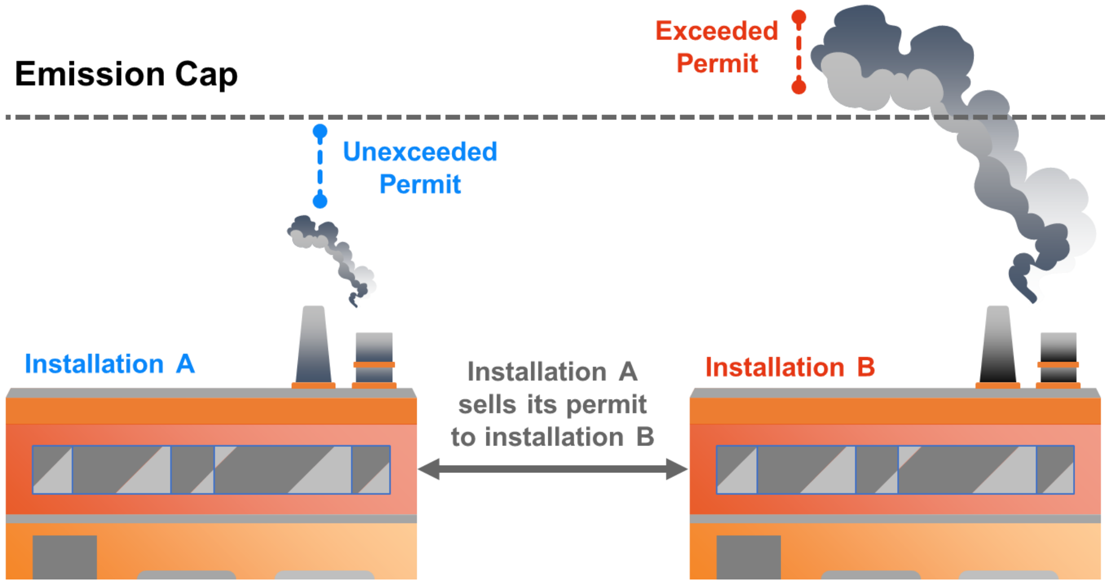

Figure 7. Depiction of the ETS

The mechanism behind the ETS is quite straightforward. Businesses will be required to make up for any excess CO_2 emissions they emit annually. Each tonne of CO_2e and GHG has a corresponding permit that businesses have to buy. The EUA's price and the emission cap each year since the ETS was launched can be seen in Figure 8.

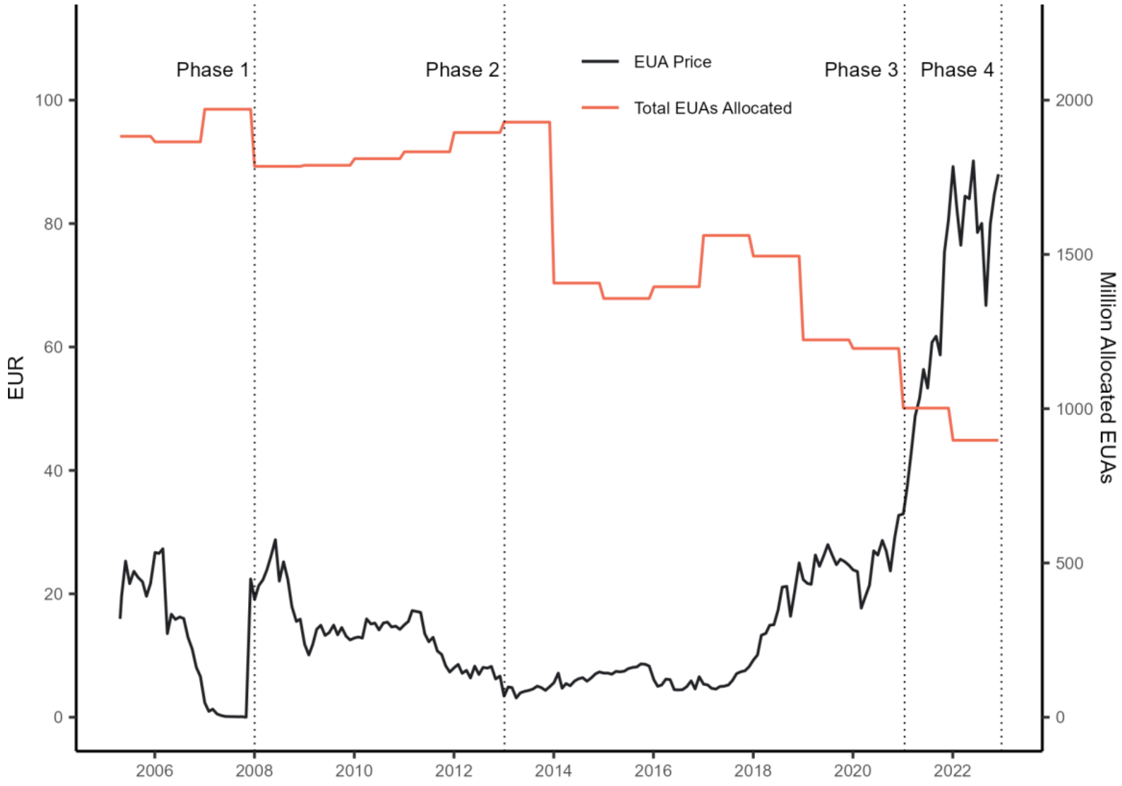

Figure 8. Historical price and number of allocated EUAs, dataset obtained from EEA (2023) and Trading Economics (2023)

The first two phases of the ETS had the highest number of EUAs allocated. The average annual number of EUAs allocated in the period was 1850 million EUAs and remained above 1700 million EUAs. The EUA price is determined by the supply and demand of the market. The EUA's price during this period was the lowest because of the large supply and low demand, averaging at €13.5/EUA. At the end of phase 1, the EUA's price dropped to near zero because the emission data was not reliable (European Commission 2020b). As a result, the total EUAs allocated were in surplus which caused the price to drastically reduce. Research by Lovcha et al. (2022) has shown that the major factors that influence the price variation during phases 1 and 2 were economic activity, natural gas, and other fossil fuel prices. In particular, positive demand shocks had a lasting impact on the EUA's price, while supply shocks had a more short-term impact on its price. Demand (or supply) shocks are defined as a sudden increase in demand (or supply). Thus, the fossil fuel markets were the best candidates to predict and investigate the EUA's price since they had the most impact on carbon price fluctuations. (Krokida et al. 2020, 10–11).

The next two phases, phases 3 and 4, saw considerable changes in EUA's price, allocation, as well as legislation surrounding the function of the ETS. The total number of EUAs has been decreasing annually, and in 2021, pursuant to Commission Decision 2020/1722, the annual allocation was capped at 1571 million EUAs with a linear reduction factor (LRF) of 1.74% in phase 3 and 2.2% in phase 4. In particular, only 897 million EUAs were allocated in 2020, which is less than half the number during phases 1 and 2. Since 2018, the EUA's price has been slowly increasing from €13.28/EUA in 02/2018 to €23.61/EUA in 03/2020, before the COVID-19 pandemic. The main factor behind this increase was the establishment of the Market Stability Reserve (MSR), pursuant to Decision 2015/1814. The MSR was created to reduce the number of surplus EUAs in circulation; therefore, based on the rule of supply and demand, the EUA's price would increase. According to Directive 2018/410, 24%, from 2019 to 2023, and 12%, from 2024 onwards, of the EUAs in circulation would be removed and placed in the MSR if there are more than 833 million of them in circulation. If there are less than 400 million EUAs in circulation, 100 million of them in the MSR will be released back into circulation. If there are less than 100 million EUAs in the MSR, all of the reserved EUAs will be released into circulation. As part of the "Fit for 55" package, the 24% rate was proposed to remain until 2030 in addition to more stringent rules to further reduce the number of EUAs in circulation.

Besides the new legislation, the price hike in 2021 and 2022 was also caused by the changes and disruptions in the energy sector. In 2021, the cold winter in combination with lower wind speed increased the demand for heating while reducing the renewable electricity output (Bruninx & Ovaere 2022, 1165). The EUA price further increased in 2022 as the higher natural gas price prompted more coal-fired power plants and other CO_2-intensive power generation (Ampudia et al. 2022).

As the number of EUA in circulation annually decreases, the EUA's price will be expected to continue rising. Businesses and investors have a strong incentive to make the switch to a sustainable future to tackle the high EUA's price. The urgency to address climate change is reflected in the high cost of carbon. Concerns have been voiced about how such high prices in the current economic and political situation may affect customers and businesses. Thus, finding a balance between meeting its climate commitments and maintaining a healthy economy will be crucial for the EU.

In regards to the maritime industry, from 2018, pursuant to Regulation 2015/757, vessels above 5000 gross tonnage (GT) are required to monitor, report, and verify (MRV) their CO_2 emission on a per-voyage basis and annual basis. Companies are required to submit their monitoring plans for all of their vessels carrying any EU registration. For the per-voyage basis, the following parameters are needed:

- Date and time of arrival and departure ports,
- Amount and emission factors of the spent fuels,
- CO_2 emission data,
- Voyage data (distance travelled, time at sea, etc.), and
- Carbon intensity parameters

In order to simplify the MRV process, vessels that have all of their voyages either start or end at EU ports are exempt from per-voyage basis monitoring during the reporting period. Moreover, vessels that have more than 300 voyages during the reporting period, are also exempt from this monitoring basis as well. For the annual basis monitoring, similar parameters as the previous monitoring basis are required in annual totality. In addition, the following parameters are needed:

- CO_2 emissions of voyages between EU ports,
- CO_2 emissions of voyages departing from EU ports, and
- CO_2 emissions of voyages arriving at EU ports.

In 2024, the maritime industry will be added to the EU ETS along with more MRV procedures, pursuant to Regulation 2023/957. Initially, only CO_2 emissions would be included in the GHG inventory calculation, pursuant to Regulation 2015/757 from 2018. Moving forward, CH_4 and N_2O emissions will be included from 2024 as companies prepare and submit their monitoring plan for these two types of GHGs. In addition, from 2025, vessels above 400 GT will be required to follow all MRV procedures. Thus, the high cost of EUA would boost financial incentives to reduce GHG emissions. Since the maritime industry would be subjected to the EU ETS, shipping firms that conduct business within the EU will need to obtain EUA in order to offset their GHG emissions. (European Parliament & Council of the European Union 2023b.)

3.2 "Fit for 55" Package

The "Fit for 55" package, which included an overhaul of the EU ETS, was the subject of a preliminary agreement between the European Commission, the European Parliament, and the Council of the EU on December 18, 2022. The package, aimed to update climate, energy, and transportation laws, will help the EU achieve its climate goals of attaining climate neutrality by 2050 and lowering net greenhouse gas emissions by at least 55% in 2030 compared to 1990 (European Commission 2020c). It is notable that the EU continues to push these targets in terms of climate mitigation despite rising energy prices and the recent political and economic instability.

The proposals suggested lowering the overall emission cap, as well as quickening the rate at which it would be lowered over time. The included industries should have a 62% reduction in emissions by 2030 compared to 2005. To provide the necessary long-term carbon price signal and motivation for that level of decarbonization, the number of allocated EUAs available across the Union must be decreased. From the proposals, the current LRF of 2.2% would be increased to 4.3% from 2024 to 2027. This sharp increase represents the Union's determination for its climate target. From 2027 to 2030, the LRF would be further increased to 4.4%. However, these factors can be subjected to adjustment based on the number of EUAs in circulation and in the MSR during their respective period. (European Parliament & Council of the European Union 2018a.)

To facilitate the increased LFR and safeguard the ETS from external conditions, the MSR still has an important role in the system in phase 4 as well as the "Fit for 55" package. In the new proposal, though the number of EUAs in circulation will remain at 833 million, the annual intake rate is 24% through 2030. The number of EUAs maintained in reserve will not be capped at the volume of the prior year's auctions. The proposal limits the total number of EUAs that may be maintained in the reserve to 400 million, with any excess EUAs being cancelled. Thus, by maintaining the high intake rate and invalidating excess EUAs, the number of EUAs in circulation will decrease annually.

Understanding that this system would put extra costs on businesses and manufacturers, free EUAs were allocated to industries that are sensitive to cost and can easily move their functions abroad to not be subject to the ETS. "Carbon leakage" describes the potential of businesses and manufacturers relocating their emission-intensive activities to countries with looser emission regulations due to the expenses associated with implementing the EU climate policy under the ETS. Their impact on global emissions would remain high, especially in energy-intensive industries as there may be a greater risk of carbon leakage.

The EU decided on a phase-in plan for the Carbon Border Adjustment Mechanism (CBAM), pursuant to Regulation 2023/956, to charge imported products based on their emissions in order to combat rising risks of carbon leakage in light of the EU's heightened climate ambition. The introduction of CBAM will correspond to the phase-out of the freely allocated EUAs to previously subsidized industries. The percentage of phase-in/out is presented in Figure 9.

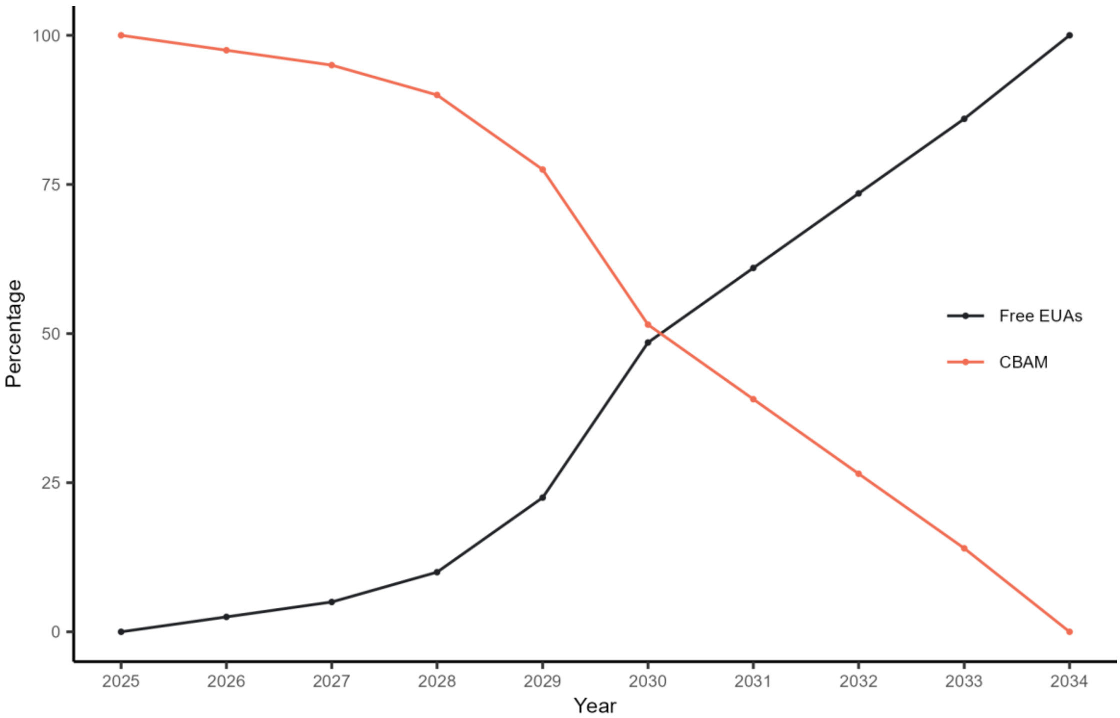

Figure 9. Percentage of phase-in CBAM and phase-out EUAs, data from Regulation 2023/956

The CBAM would only be applicable as a reporting requirement until the end of 2025. Starting from 2026, over a nine-year period, CBAM will be implemented for the impacted sectors under EU ETS, and free EUAs will gradually be phased out in conjunction with its implementation. From October 1, 2023, the transitional phase will begin, during which importers must adhere to a quarterly reporting requirement of their imported CBAM items and embedded GHG emissions. The CBAM will ensure that the carbon price of imports is equal to the carbon price of domestic production so that the climate objectives are not compromised.

In short, the “Fit for 55” package aimed to reduce the GHG emission in the EU by 55% with the many changes in the ETS, the MSR, and the introduction of CBAM. The ETS would have to reduce the emission cap at double the current rate. The MSR would maintain the 24% intake rate of the EUAs in circulation and cancelling any excess EUAs. So, the MSR is expected to absorb the shock from the rapid emission cap reduction. Businesses and manufacturers with high carbon intensity would see an increase in cost due to such actions and the EU might risk carbon leakage. To minimize carbon leakage, the new mechanism called CBAM was established to slowly phase out the free EUAs that these industries are having and impose CBAM on any imported goods starting in 2026.

3.3 FuelEU Maritime Proposal and the EU ETS in the Maritime Transportation

As part of the transportation sector reform of the “Fit for 55” package, Alternative Fuel Infrastructure (AFIR), ReFuelEU Aviation, and lastly, FuelEU Maritime are the three main legislative proposals to reduce GHG emissions for this sector. Articles in the FuelEU Maritime Proposal have been customized for the maritime industry to not only achieve the EU climate target but also facilitate a smooth transition when the new regulations come into effect. As the ETS will include the maritime industry, pursuant to Regulation 2023/957, the FuelEU Maritime proposal suggested targeting the emissions from vessels, which will gradually be included in the system (Table 6).

Table 6. Percentage of emission that will be included in the ETS based in the FuelEU Maritime proposal European Parliament & Council of the European Union (2023b)

	2024	2025	2026 onwards
Intra-EU Voyages	40%	70%	100%
Vessels at berth in EU ports	40%	70%	100%
Incoming/Outgoing Voyages	20%	35%	50%

Initially, according to Regulation 2015/757, vessels above 5000 GT will be included in the ETS scope. Afterward, Regulation 2023/957 amended in detail to which vessel size these regulations would apply. In regard to vessels above 400 GT, during intra-EU voyages (voyages that start and end at any EU ports) and vessels at berth in EU ports, 40% of these vessels' emissions will be included in the ETS, and this number will increase to 100% by 2026. As for vessels above 5000 GT, during their incoming or outgoing voyages (voyages that start or end at any EU ports), only 20% to 50% of the vessels' emissions will be included in the ETS, which is half the amount compared to other mentioned vessels' voyages and activity. CO_2, CH_4, and N_2O are all included in these regulations. The FuelEU Maritime proposal also set the GHG intensity reduction target compared to 2020 for the fuels as well (Table 7).

Table 7. GHG intensity (gCO_2e/MJ) reduction target of FuelEU Maritime proposal

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

From 2025 to 2035, the GHG intensity reduction will be less aggressive for this phase compared to the 2040 - 2050 phase. As noted in the Impact Assessment of the FuelEU Maritime proposal (2021), the research, development, and innovation (RDI) process will be quite time-consuming, in addition to the fact that the current technological level, along with the electrical infrastructure of many EU ports is not sufficient. Thus, the lower GHG intensity reduction for the first 10 years would allow RDI and infrastructure to be developed before the sharp reduction rate is applied. The Innovation Fund, established under Directive 2003/87/EC, has a major role in financing RDI activities on renewable and alternative fuels in the EU. Currently, the fund raises its capital via revenue from the auctioning of EUAs in the ETS. The FuelEU Maritime proposal suggested that monetary penalties for non-compliance be added to the fund as well. In addition, the Innovation Fund's scope should be expanded to include supporting the rapid development of renewable and low-carbon fuels for decarbonizing marine transportation, such as sustainable alternative fuels, energy-efficient ships and ports.

The FuelEU Maritime proposal promotes the usage of renewable and low-carbon fuels in the industry. In particular, to meet the EU climate target, the proposal suggests that these types of fuel represent 6% - 9% of the international maritime transport fuel mix in 2030 and 86% - 88% in 2050. In order to achieve such high usage of renewable and low-carbon fuels, many obstacles in the current market need to be tackled. Because of the current both low supply and demand for these types of fuel, policies to encourage the development and deployment of these fuels are necessary in the short and long term. To stimulate the supply and demand of these fuels, a reward system is added when calculating the GHG intensity of the vessels' fuel usage. In particular, the FuelEU Maritime proposal suggests the usage of renewable fuels of non-biological origin and recycled carbon fuels to have more rewards than conventional fuels. Renewable fuels of non-biological origin and recycled carbon fuels are renewable and low-carbon fuels with their feedstock listed in Part A and Part B in Annex IX of Directive 2018/2001. The reward system operates by having the energy density of these types of fuels doubled during GHG intensity calculation. Thus, this reward system, in the short term, should initiate the supply and demand of these fuels, and, in the long term, aim at closing the price gap between fossil fuels and these fuels.

In addition to encouraging the use of low-emission fuels, the FuelEU Maritime proposal also suggests that vessels at berth would use electricity from the EU ports rather than running their onboard auxiliary and boiler system. Vessels might opt out of connecting to an on-shore power if they have a zero-emission technology onboard during their time at berth. Because the emission factor from the electrical grid is lower, per MJ, than that generated from the onboard auxiliary and boiler system, having vessels connected to the onshore electricity would reduce their GHG emission during their time at berth.

However, as the electrical grids of different EU countries do not have the same emission factor, vessels might prioritise ports from countries with lower emission factors in their grid. To address this gap in infrastructure development, the EU Modernisation Fund will be used to boost the green infrastructure transition in low-income EU countries. In particular, with the revenue stream from the ETS, €7.5 billion has been invested to benefit ten EU countries, in addition to €2.4 billion from other sources to invest in 31 projects to reduce fossil fuel reliance. (European Commission 2023.)

To sum up, in the context of the maritime industry being incorporated in the ETS, the FuelEU Maritime proposal laid out multiple policies to meet the EU 55% GHG reduction target. The proposal suggests increasing the competitiveness of renewable and low-carbon fuels by the reward system that encourages the usage of these fuels and setting the GHG intensity for these fuels as well. In addition, the proposal also suggests utilizing the electrical grid during the time that the vessels are at berth. Infrastructure development funding for low-income EU countries is also prepared to push the green transition in their electricity grid.

4 METHOD

4.1 Types of vessels

For this thesis, bulk carriers, oil tankers, and container ships were the type of vessels chosen because they carry the most cargo by tonnage and have high emissions of GHG. The vessel type, along with their size categories and total of vessels in each fleet is presented in Table 8.

Table 8. Types of vessels considered in this thesis, size classification and number of ships, adapted from (IMO 2020)

Vessel Type	Size	Number of vessels
Bulk Carrier (dwt)	0-9,999	1446
	10,000-34,999	2014
	35,000-59,999	3391
	60,000-99,999	3409
	100,000-199,999	1242
	200,000+	516
Oil Tanker (dwt)	0-4,999	9692
	5,000-9,999	779
	10,000-19,999	235
	20,000-59,999	615
	60,000-79,999	429
	80,000-119,999	1029
	120,000-199,999	597
	200,000+	755
Container (TEU)	0-999	1027
	1,000-1,999	1271
	2,000-2,999	668
	3,000-4,999	815
	5,000-7,999	561
	8,000-11,999	623
	12,000-14,499	227

Bulk carriers are the vessels that transport the most cargo by tonnage. They are designed to transport cargo that cannot be stacked in normal containers. Some of these types of cargo include food grains, coals, and metal ore. Oil tankers are next on this list, considering how much crude oil and its products are used around the world. There are two types of oil tankers of which the crude oil tankers are usually in the larger size category than the product oil tankers. Container ships are the last type of vessel considered in this thesis. Unlike the others, container vessels are categorized by how many twenty-foot equivalent units (TEU) they can carry rather than the tonnage.

4.2 Emissions calculation

To begin with, the GHG emissions were calculated based on the amount of fuel consumption by the vessels and the emissions factor of the GHG based on the fuel type. The total emissions are calculated by Equation (8):

$$EM_i = EF_f FC_i \tag{8}$$

Where:	EM_i	GHG emissions	[g of GHG/h]
	EF_f	Emissions factor	[g of GHG/g of fuel]
	FC_i	Fuel consumption	[g of fuel/h]
	i	Vessel type	

The emissions factors of the fuels are presented in Table 9 along with the global warming potential (GWP) of the GHGs.

Table 9. The emissions factors (kg of GHG/ton of fuel) and the GHG global warming potential, adapted from Fridell et al. (2021) and Liu et al. (2022)

GHG	HFO	MGO	LNG	MeOH - MGO	NH_3 - Diesel	GWP
CO_2	3114	3206	2753	1576	204	1
CH_4	0.05	0.05	11.22	$5.44*10^{-2}$	$3.18*10^{-3}$	29.8
N_2O	0.18	0.18	0.10	$1.15*10^{-2}$	0.12	273

The emissions factors of conventional fuels were calculated by the IMO (2020). For MeOH and NH_3, because of their higher heat of evaporation (Table 1), in other words, vaporizing these fuels for engine ignition would reduce the surrounding temperature, a small addition of pilot fuel was needed to assist MeOH and NH_3 to combust. The emissions factors for MeOH were measured from the exhaust of a maritime engine with MGO as the pilot fuel (Fridell et al. 2021, 142). For NH_3, these factors were computationally determined by modeling a maritime engine with diesel as the pilot fuel (Liu et al. 2022; Nadimi et al. 2022, 2023).

Next, the vessel fuel consumption took into account the consumption of the main engine, the auxiliary engine, and the boiler. Thus, the total hourly fuel consumption FC_i was the sum of consumption from those systems as presented in Equation (9):

$$FC_i = FC_{ME,i} + FC_{AE,i} + FC_{BO,i} \tag{9}$$

Where:	$FC_{ME,i}$	Fuel consumption of the main engine	[g of fuel /h]
	$FC_{AE,i}$	Fuel consumption of the auxiliary engine	[g of fuel /h]
	$FC_{BO,i}$	Fuel consumption of the boiler	[g of fuel /h]

Afterward, the fuel consumption of the main engine was calculated based on the main engine's specific fuel consumption ($SFC_{ME,i}$) and the engine power demand (Equation (10)). The $SFC_{ME,i}$ has a quadratic relationship with the engine load and has the baseline specific fuel consumption (SFC_{base}) as its multiplier (IMO 2020), as presented in Equation (10) and (11):

$$FC_{ME,i} = SFC_{ME,i}W_{ME,i} \tag{10}$$

$$SFC_{ME,i} = SFC_{base}(0.455Load^2 - 0.710Load + 1.280) \tag{11}$$

Where:	$W_{ME,i}$	Main engine power demand	[kW]
	$SFC_{ME,i}$	Main engine specific fuel consumption	[g of fuel /kWh]
	SFC_{base}	Baseline specific fuel consumption	[g of fuel /kWh]
	$Load$	Engine load	[%]

The values for the SFC_{base} were based on the engine type and the fuel type, as presented in Table 10. These values for HFO, MGO, and LNG were measured by (Pavlenko et al. 2020). Similar values for MeOH and NH_3 were calculated by scaling the lower heating values of the alternative fuels in comparison to that of HFO and MGO. The maritime engines were classified by their number of strokes (four- and two-stroke), their speed (medium- and slow-speed), and their combustion pressure (High-pressure diesel fuel (HPDF) and Low-pressure diesel fuel (LPDF)).

Table 10. SFC_{base} (g/kWh) of different fuels and engine types, adapted from Pavlenko et al. (2020)

Engine	HFO	MGO	LNG	MeOH[a]	MeOH[b]	NH_3[a]	NH_3[b]
LPDF, medium-speed, four-stroke	199.0	183.0	147.0	391.2	374.0	421.6	403.1
LPDF, slow-speed, two-stroke	198.0	182.0	142.9	389.2	372.0	419.5	400.9
HPDF, slow-speed, two-stroke	177.0	163.0	130.7	347.9	333.1	375.0	359.1
Slow-speed diesel, two-stroke	180.0	165.0	-	353.8	337.2	381.3	363.5
Medium-speed diesel four-stroke	188.0	173.0	-	369.5	353.6	398.3	381.1

a Converted based on HFO lower heating value
b Converted based on MGO lower heating value

Lastly, the fuel consumption of the auxiliary engine and the boiler were calculated according to their power demand and main engine specific fuel consumption, as presented in Equation (12):

$$FC_{AE|BO,i} = SFC_{base} W_{AE|BO,i} \tag{12}$$

Where: $W_{AE|BO,i}$ Auxiliary engine and boiler power demand [kW]

The power demand of the vessel auxiliary system and boiler depends on the current activity of the vessel. Four main activities were included in this thesis, including when the vessel is at berth, anchored, manoeuvring, or at sea. The auxiliary system and the boiler machinery include equipment such as pumps, compressors, and blowers. They are used to move fuel, chill refrigerated holds, feed air to the main engine's starting system, circulate fresh and saltwater for cooling systems, and power refrigeration equipment. For anchoring, manoeuvring, and cargo loading at berth, additional marine equipment includes cranes, capstans, windlasses, and winches. The power demands of these systems are presented in Appendix 1.

4.3 Carbon intensity calculation

The carbon intensity metrics of each type of vessel were evaluated by three criteria: Annual Efficiency Ratio ($AER_{i,k}$), Emissions per Distance Travel ($DIST_{i,k}$), and Emissions per Hour Underway ($TIME_{i,k}$). These criteria to access these vessels' performance are similar to those used by the IMO. The formulas for each metrics are presented in Equation (13), (14), and (15):

$$AER_{i,k} = \frac{m_{CO_2 i,k}}{\overline{dwt_{i,k}} * \overline{speed_{i,k}} * \overline{hour_{i,k}} * n_{i,k}} \tag{13}$$

$$DIST_{i,k} = \frac{m_{CO_2 i,k}}{\overline{speed_{i,k}} * \overline{hour_{i,k}} * n_{i,k}} \tag{14}$$

$$TIME_{i,k} = \frac{m_{CO_2 i,k}}{\overline{hour_{i,k}} * n_{i,k}} \tag{15}$$

Where:	$m_{CO_2 i,k}$	Total mass of $CO_{2\,eq}$ emissions	[g]
	$dwt_{i,k}$	Deadweight tonnage	[ton]
	$speed_{i,k}$	Cruising speed	[kn]
	$hour_{i,k}$	Time at sea	[h]
	n	Number of vessels	
	k	Type of vessel size	

The $m_{CO_2 i,k}$ values for each type of vessel and size were calculated with Equation (8) in the previous subsection. The other variables to calculate these metrics were tabulated in the IMO’s Fourth GHG Study (2020) and presented in Appendix 2.

5 RESULTS AND DISCUSSION

5.1 Data Validation

Because the data used in this thesis came from multiple published reports and articles, the data were tested against numbers from the IMO (2020) Fourth GHG Study for their reliability as baseline values. In particular, the total GHG emission, AER, DIST, and TIME values for each vessel type using conventional fuels (Table 8) were compared. To quantify the comparison, linear regressions were performed with the values from the IMO as the dependent variable while the values from this thesis were the independent variable. The result of the data validation can be seen in Figure 10.

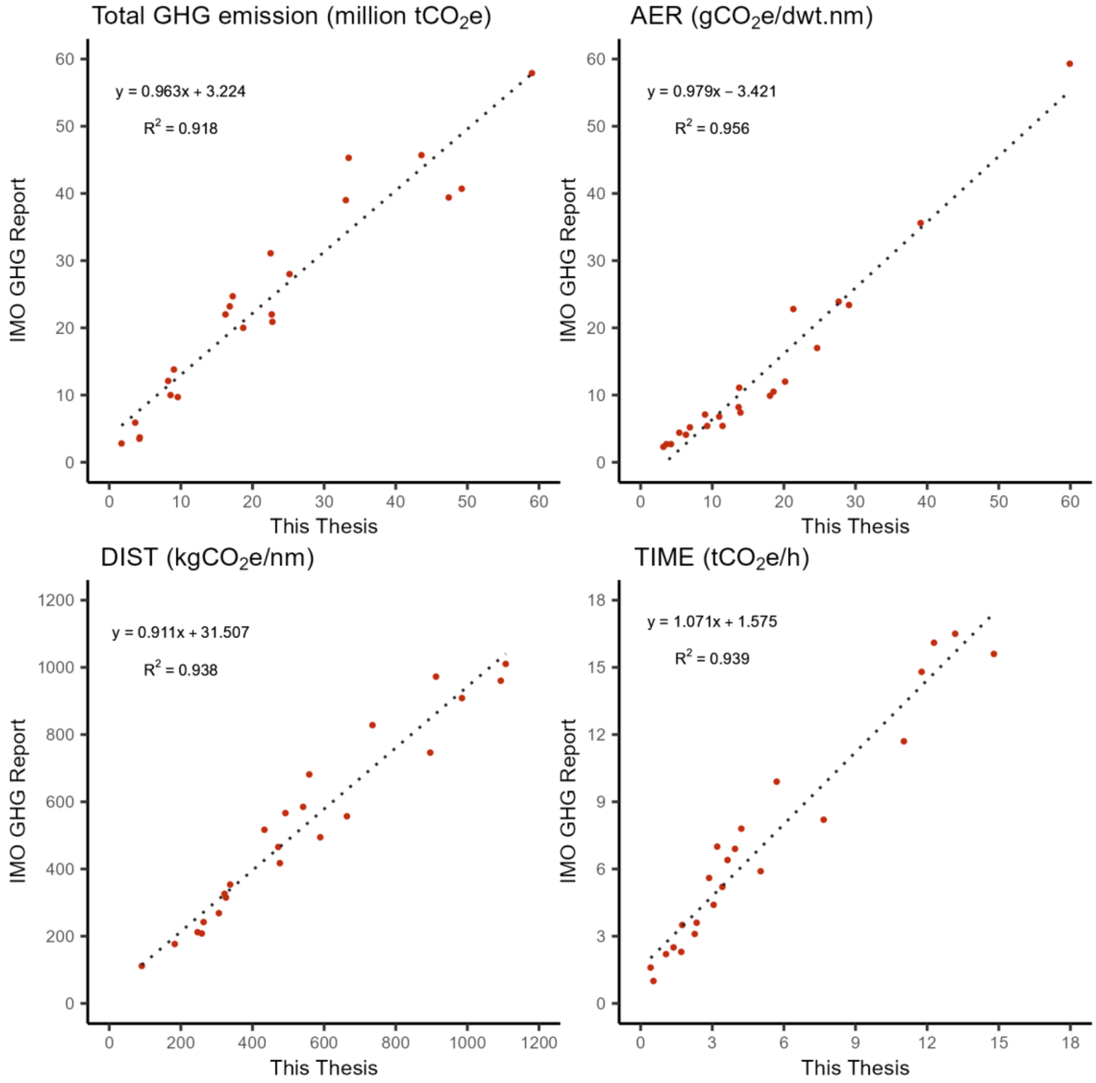

Figure 10. Correlation of multiple parameters between values from this thesis to values from the IMO (2020) Fourth GHG Study

Overall, the values of different parameters of this thesis had a good correlation with those of the IMO (2020) Fourth GHG Study. The total GHG emission and AER parameters showed the best correlations as the linear regressions of these parameters had their slopes within 1 ± 0.05 and $R^2 > 0.9$. Similarly, DIST and TIME parameters showed good correlations with the slopes of the linear regressions within 1 ± 0.1 and $R^2 > 0.9$. Thus, the baseline values for conventional fuels in this thesis could be considered accurate for their high correlation with values from the IMO (2020).

5.2 Specific fuel consumption

The SFC of an engine is a key factor in understanding how it would perform under different loadings. Knowing the SFCs is important because it would help guide businesses to select the most efficient engine based on the vessel and voyage characteristics. Thus, calculating the SFC would gauge the effect of alternative fuels on individual engine performance. Based on Equation (11) and Table 10 presented in section 4.2, the SFC for the slow- and medium-speed engines could be calculated at varying engine loads, as shown in Figure 11.

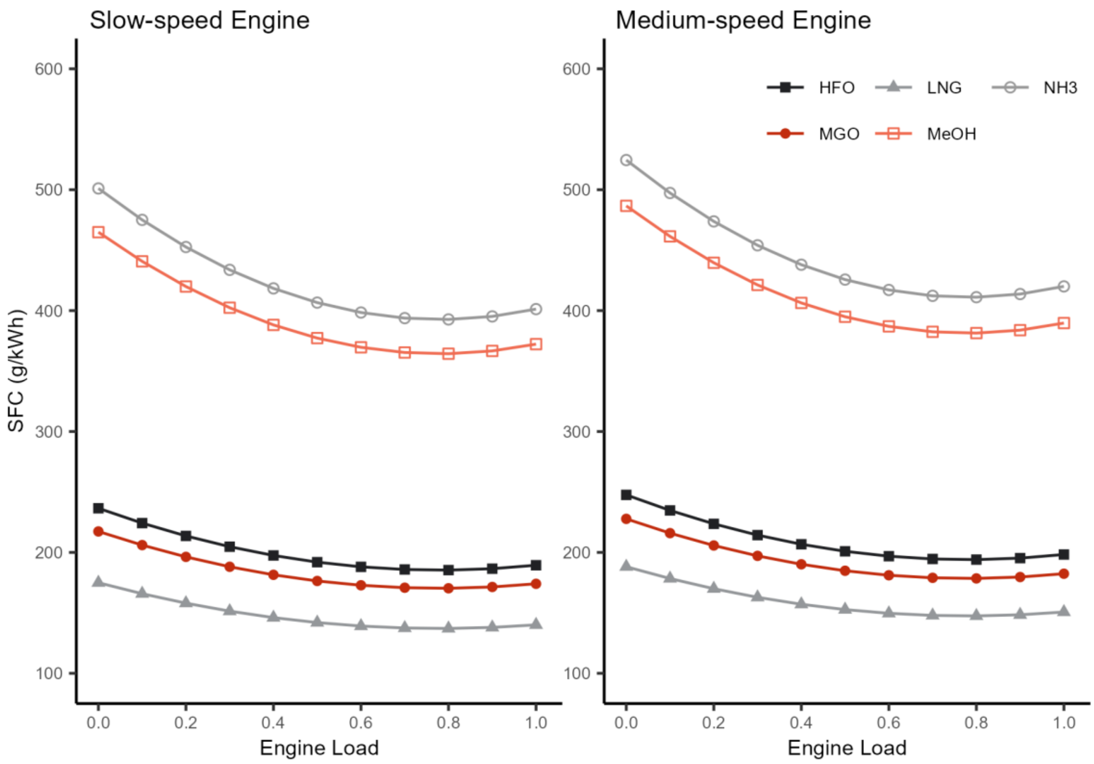

Figure 11. The specific fuel consumption (g/kWh) of Slow-speed engine and Medium-speed engine for different types of fuels

In general, the SFCs of the slow-speed engine were lower than that of the medium-speed engine. In particular, for conventional fuels, the SFCs for the slow-speed engine were all lower than that of the medium-speed engine at all engine loading. On average, the SFCs for slow-speed engines were 9.8 g/kWh lower when using conventional fuels. Previous research has shown that slow-speed engines could achieve lower SFCs, or higher efficiencies, because of the greater amount of torque that they could generate (Bordug et al. 2020, 822). On the other hand, for the alternative fuels, the SFCs of the slow-speed engine were only significantly lower than that of the medium-speed engine when the engine load was larger than 0.4. On average, the SFCs for medium-speed engines were 19.2 g/kWh higher when using alternative fuels.

Because of the high energy content that conventional fuels have, their SFCs for both types of engines were considerably lower than that of the alternative fuels. In particular, the SFCs of conventional fuels were half of the SFCs of alternative fuels. The SFCs for conventional fuels ranged from 130 to 250 g/kWh while the SFCs for alternative fuels ranged from 360 to 530 g/kWh. In other words, to generate the same amount of energy, vessels that use conventional fuels would only need to consume half the fuel weight compared to vessels that use the other types of fuels.

In addition, with the SFCs as a quadratic function of the engine load, the slopes of the SFC curves from the alternative fuel were larger than the slopes from the conventional fuels. In other words, changes in engine load would have a greater effect on the SFCs of engines that use alternative fuels than those that use conventional fuels. Increasing the engine load from 0.1 to 0.8, the engines with alternative fuels would have their SFC reduced by 80 g/kWh while those with conventional fuels would only have a 32 g/kWh reduction in SFC. Thus, to remain efficient, engines with alternative fuels need to operate that higher engine load.

5.3 Total GHG Emissions

Besides calculating the SFC values to estimate the effect of alternative fuels on singular engine performance, the total GHG emissions for different types of vessels were also calculated to gauge the effect of these fuels on the maritime industry. The total annual GHG emissions were calculated by replacing physical properties values and the SFCs of the conventional fuels with either MeOH or NH_3 for different types of vessels (Figure 12). The values presented below were calculated based on Equation (8).

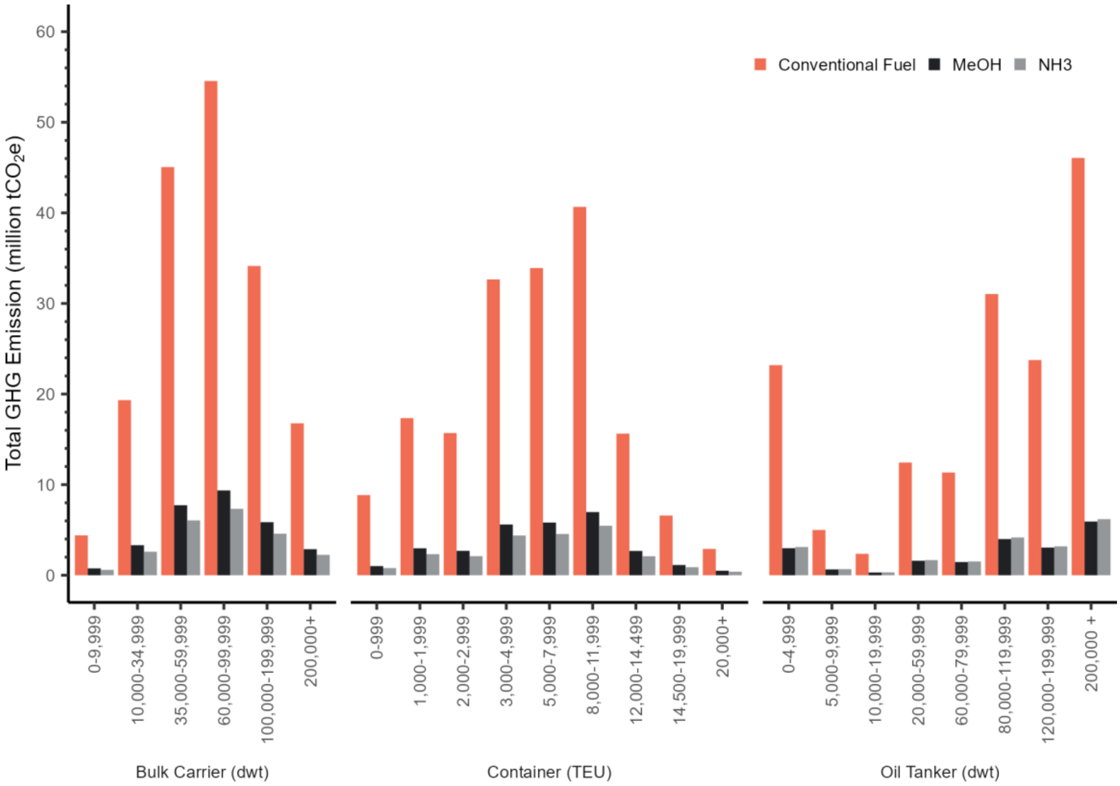

Figure 12. Total annual GHG emissions (million tCO_2e) for various ship types and sizes

For the bulk carrier vessels, the highest GHG emissions were from vessels in the 35,000 – 199,999 dwt sizes. These vessels emitted, in total, 128.7 million tCO_2e annually. The large amount of GHG emitted from these vessel groups can be attributed to fleet size, with over 8,000 vessels being recorded by the IMO. Because the average engine load of bulk carrier vessels of different sizes was similar (from 0.5 to 0.6), the total GHG emissions of each vessel size correlate with the total number of vessels. In total, bulk carrier vessels emitted 193.4 million tCO_2e annually.

For container vessels, those with sizes ranging between 2,000 – 11,999 TEU had the largest GHG emissions. The total emissions of container vessels with these sizes emitted 158.9 million tCO_2e annually and the total GHG emission of container vessels, in general, summed up to 248.6 million tCO_2e annually. Despite emitting more than 70% of the GHG emissions, the number of container vessels, that is between 2,000 and 11,999 TEU, only added up to 50% of the total container fleet. This is due to the fact that vessels with these sizes operate at a lower engine load. In particular, they operated, on average, 0.33 to 0.4 engine load, while other container vessels operated, on average, 0.41 to 0.56 engine load.

Unlike the emission trend of the mentioned vessel types which had their medium size vessels emitting the most GHG, for oil tankers, the smallest and largest size groups had the most GHG emission. Oil tankers smaller than 4,999 dwt and those larger than 80,000 dwt emitted 90.1 million tCO_2e annually and the total GHG emissions from all oil tankers accounted for 158.9 million tCO_2e annually. There are over 9,500 oil tankers that are 4,999 dwt or less, which is 68% of the total number of oil tankers, contributing to the high amount of GHG emitted from this group of oil tankers. On the other hand, despite the number of oil tankers larger than 80,000 dwt only accounting for 17% of the oil tanker fleet, these larger oil tankers travelled, on average, 23,000 nm more than the others. Thus, their fuel consumption would be significantly higher, which would lead to higher GHG emissions.

When the three vessel types examined in this thesis reverted to alternative fuels as their energy source, there was a significant reduction in GHG emissions for all groups. In particular, by switching to MeOH, GHG emissions could be reduced by 84% while an 86% GHG emissions reduction could be seen when switching to NH_3. Using MeOH as an alternative fuel, CO_2 would be the main GHG being emitted (99.7% in weight of the total GHG emissions mass) as there is a carbon atom in the MeOH molecule. On the other hand, for NH_3, though CO_2 remained the largest GHG being emitted (86.46% in weight of the total GHG emissions mass), a considerable amount of N_2O would also be emitted (13.25% in weight of the total GHG emissions mass). In conventional fuels, N2 would be the substrate to generate N_2O through the high temperature and pressure in the engine. However, because NH_3 combusts at a lower temperature, N2 would not be the main substrate, but rather NH_3 itself as it is kinetically in favour to generating N_2O as a side reaction. (Liu et al. 2022; Nadimi et al. 2022, 2023.) Thus, the environmental impacts of N_2O must be noted when considering NH_3 as an alternative fuel for the maritime industry.

Despite using alternative fuels that would have vessels emit much less GHG, another aspect, fuel consumption, should be taken into consideration as well. The total fuel consumption of three types of vessels using conventional and alternative fuels is presented in Figure 13.

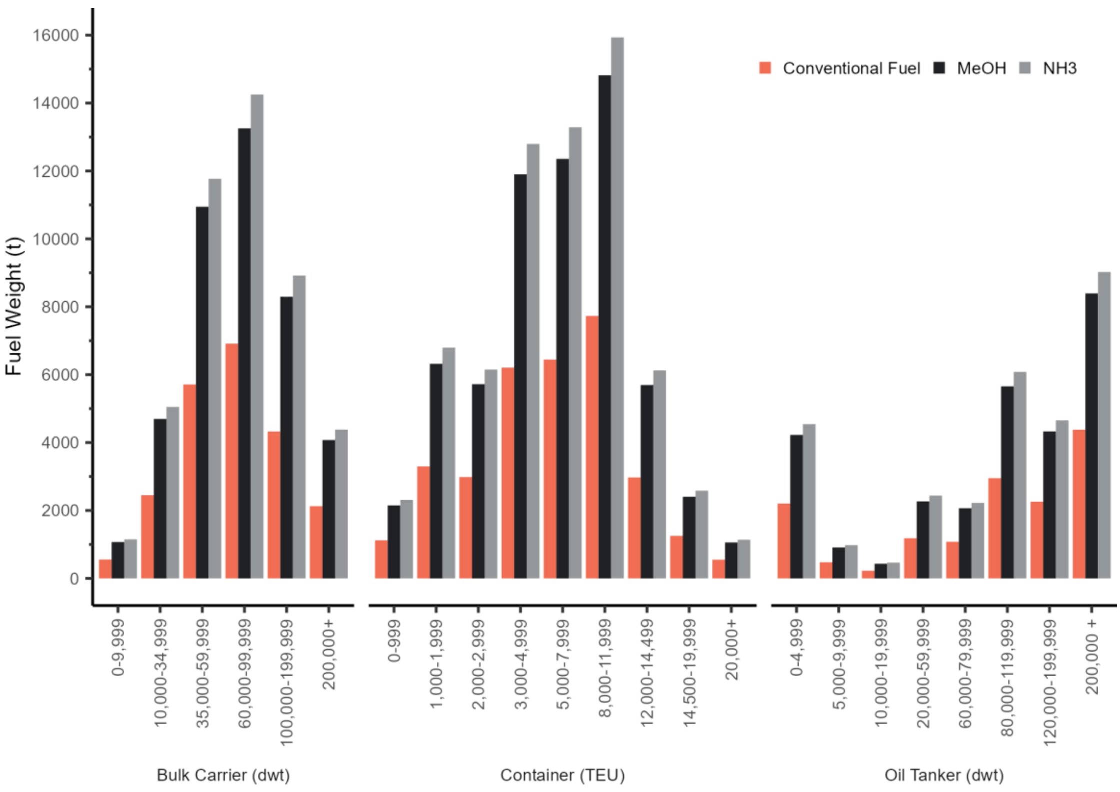

Figure 13. Total fuel weight (t) consumption for various ship types and sizes

Because of the lower heating value of the alternative compared to the conventional ones, generating the same amount of energy would require the vessel engine to consume more alternative fuels. In particular, vessels would need to consume 48% more fuel by weight when using MeOH and 52% when using NH_3. In other words, to travel similar distances, vessels using alternative fuels need to carry double the amount of fuel compared to their usual amount. Even though the total amount of GHG emitted would be reduced, the total amount of fuel consumption would increase. Thus, either vessel fuel tanks or voyage distances need to be modified in order to accommodate the usage of alternative fuels.

5.4 Carbon intensity

Following the calculation of the total GHG emissions to understand the impact of alternative fuels on the vessel fleet as a whole, calculating the carbon intensity would give insight into the performance of each vessel group when switching these fuels. As presented in section 4.3, the criteria being accessed for this thesis are AER, DIST, and TIME. Shown in Table 11 is the comparison of these metrics for conventional fuels against MeOH and NH_3.

Table 11. Carbon intensity metrics of conventional fuels and alternative fuels

Ship Type	Size	AER ($gCO_2e/dwt.nm$)			DIST ($kgCO_2e/nm$)			TIME (tCO_2e/h)		
		Conventional Fuel	MeOH	NH_3	Conventional Fuel	MeOH	NH_3	Conventional Fuel	MeOH	NH_3
Bulk Carrier (dwt)	0 - 9,999	27.39	16.31	2.61	116.83	69.55	55.73	0.69	0.41	0.66
	10,000 - 34,999	17.91	7.11	1.14	316.85	188.64	15.12	2.19	1.30	0.21
	35,000 - 59,999	11.94	4.74	7.59	393.38	234.21	18.77	2.91	1.73	0.28
	60,000 - 99,999	8.13	3.23	0.52	418.73	249.30	19.98	3.01	1.79	0.29
	100,000 - 199,999	5.45	2.16	3.46	606.52	361.10	28.94	4.40	2.62	0.42
	200,000+	4.08	1.62	2.60	695.72	414.21	33.19	5.08	3.02	0.48
Oil Tanker (dwt)	0 - 4,999	76.99	18.33	3.92	235.04	55.97	5.98	0.54	0.32	0.07
	5,000 - 9,999	50.23	19.94	4.26	338.58	134.38	14.36	1.37	0.81	0.17
	10,000 - 19,999	35.53	14.10	3.01	433.79	206.61	22.07	2.24	1.33	0.28
	20,000 - 59,999	17.68	7.02	1.50	757.17	300.53	32.11	3.68	2.19	0.47
	60,000 - 79,999	11.56	4.59	0.98	556.77	331.48	35.42	4.12	2.45	0.52
	80,000 - 119,999	8.84	3.51	0.75	632.12	376.34	40.21	4.68	2.78	0.60
	120,000 - 199,999	6.93	2.75	0.59	717.76	427.33	45.66	5.42	3.23	0.69
	200,000+	4.63	1.84	0.39	944.55	562.35	60.08	7.32	4.36	0.93
Container (TEU)	0 - 999	37.38	9.89	15.85	332.17	87.89	70.43	1.77	0.70	1.13
	1,000 - 1,999	31.66	8.38	13.43	413.60	164.16	131.54	3.93	1.56	2.50
	2,000 - 2,999	25.91	6.86	10.99	612.20	242.99	194.71	6.46	2.56	4.11
	3,000 - 4,999	23.84	6.31	10.11	852.79	338.48	271.23	9.85	3.91	6.27
	5,000 - 7,999	23.21	6.14	9.84	1151.74	457.14	366.31	14.17	5.62	9.01
	8,000 - 11,999	17.57	4.65	7.45	1265.44	502.27	402.47	15.12	6.00	9.62
	12,000 - 14,499	14.10	3.73	5.98	1422.52	564.62	452.43	16.93	6.72	10.77
	14,500 - 19,999	14.70	3.89	6.23	1172.38	620.44	497.16	15.79	6.27	10.04
	20,000+	-	-	-	1404.82	743.45	595.73	19.01	7.55	12.09

In general, there is a considerable reduction for all metrics across all groups of vessels. Depending on the metric, a reduction of 40% to 90% can be seen when vessels use alternative fuels. As the vessel size increases, the AER metric would decrease while DIST and TIME would increase. So, vessel sizes and their related characteristics are important factors that affect the performance of a vessel.

Based on the variables in Equations (13), (14), and (15) that were used to calculate these metrics, analysing the features of different types of vessels can explain the trend observed in Table 11. For bulk carrier and oil tanker, these vessels carry the most cargo by weight in the maritime industry and their time at sea and distances travelled increase with their size. In particular, as shown in Appendix 2, the largest group of bulk carrier vessels spent 117 more days at sea than its smallest group. Similarly, the largest group of oil tankers spent 80 more days at sea compared to its smallest group. Thus, the difference in 3 to 4 months annually at sea is the main variable that affects these metrics.

On the contrary, container vessels spent, on average, 238 days at sea annually with similar time at sea between groups. However, container vessels have a higher cruising speed compared to bulk carriers and oil tankers. While bulk carrier and oil tanker vessels travel between 12 – 16 kn, container vessels usually travel between 20 – 25 kn. Moreover, container vessels between 2,000 – 11,999 TEU had the fastest cruising speed, traveling 23 – 25 kn. So, the speed of container vessels is the main factor that affects the metrics described in this section.

5.5 Discussion

Besides quantifying the effect of alternative fuels on the maritime industry emissions, this thesis also analysed the current legislative system regarding the EU ETS and the “Fit for 55” package along with its FuelEU Maritime proposal. The FuelEU Maritime proposal is part of the “Fit for 55” package for the transportation sector. With the maritime industry being incorporated into the ETS, the proposal was set to facilitate this transition with the border aim of a 55% GHG reduction. The proposal suggested slowly decreasing the GHG emissions from vessels based on the type of voyage that a vessel had taken (European Parliament & Council of the European Union 2023b). In addition, the carbon intensity was also a target of the proposal with a 6% reduction by 2030. One of the main points of the proposal was suggesting that vessels be connected to the port electrical grid at berth to take advantage of the lower GHG emissions from the grid. In addition, funding for RDI and infrastructure investments would be sourced from revenues from the ETS.

As the result of this thesis has shown, there was a large reduction in GHG emissions when the current vessel fleet switched to alternative fuel. In particular, the medium-size bulk carrier and container vessels along with the small and large-size oil tanker vessels would benefit the most when changing their fuel type as they are the category of vessels that emitted the most GHG. In addition, under the FuelEU Maritime proposal, vessels are required to use on-shore electricity or emission-free energy sources when at berth and anchoring, the GHG emissions during those processes would be further reduced. Moreover, the use of alternative fuels also showed that the current vessels could meet the carbon intensity reduction target as well. So, the use of alternative fuels in the maritime industry would help the EU’s emissions target become more probable.

With the present political and economic environment, the EUAs in circulation would continue to decrease while the EUAs’ price would follow the opposite (Kothari et al. 2017; Lovcha et al. 2022). In order to absorb price shocks, the MSR was created to remove or release EUAs in circulation. In addition to controlling the EUAs’ price, the MSR was also tasked to permanently remove EUAs to incentivise businesses to have good environmental practices.

As the EU's commitment to be carbon neutral in 2050, the "Fit for 55" package was proposed to update the ETS and introduce new legislation to regulate GHG emissions (European Commission 2020c). The proposal suggested imposing harsher GHG reduction efforts by increasing the LRF to 4.4% and maintaining the MSR high intake rate of 24% until 2030. The "Fit for 55" package also proposes CBAM as a mechanism to combat carbon leakage from cost and emissions-sensitive industries.

Using the average EUA price in 2022, €80/EUA, the cost of purchasing EUA for conventional fuel would range from €250 - €260/ton of fuel (€18,500 – €23,100/MWh), while the price would be €127/ton of fuel (€22,600/MWh) for MeOH and €19/ton of fuel (€3,600/MWh) for NH_3. Even though the cost per ton of fuel is lower for alternative fuels, after adjusting for their energy content, the cost of using MeOH remained in the similar range as the conventional fuels while the cost of using NH_3 is much lower.

However, these cost estimations remained speculative due to many reasons. First, because of hedging and speculative trading from businesses, the EUA price would not be stabilized in the short term (Perino et al. 2022, 342). As the MSR would remove and cancel a large number of EUAs, the low number of allowances in circulation would increase the EUA's price (Gerlagh et al. 2022). So, the high volatility along with the shortage in EUA would mean that the EUA price would fluctuate and the exact cost and cost saving of using alternative fuel would be hard to predict.

Adding to the complexity of calculating the cost saving of alternative fuel is that the FuelEU Maritime proposal required the GHG emissions and carbon intensity to include the LCA of both conventional and alternative fuels. The purpose of this inclusion would encourage businesses to use not only alternative fuels but also sourcing these fuels from sustainable sources as listed in Part A and Part B in Annex IX of Directive 2018/2001. Because the result of this thesis did not include the emission during the production process of the alternative fuels, the final cost of alternative fuels might be higher than what was stated above.

One limitation of this thesis is the lack of data on the current vessel fleets. Because of the proprietary information, most of the data regarding the characteristics of the fleet relied on the summary from the IMO (2020) Fourth GHG Study, journal articles as well as public commercial reports. So, the lack of precise data was the main source of the discrepancy found in this thesis. However, this thesis included section 5.1 which verified that the data used for this thesis correlated with values from the IMO (2020) report.

6 CONCLUSIONS

In this thesis, multiple parameters for bulk carriers, oil tankers, and container vessels using conventional fuels were compared against alternative fuels. The result of this thesis found that there was a large discrepancy between the key performance factors when examining vessels using conventional and alternative fuels. Because of the difference in the energy content and the emission factors, the engine performance, along with the GHG emissions, and carbon intensity of vessels using these types of fuels varies significantly. In particular, the SFCs of engines using conventional fuels were much lower than those using alternative ones. In other words, engines that use alternative fuels have to consume much more energy to generate the same amount of energy compared to conventional fuels.

Moreover, the total GHG emissions showed significant reductions if the current vessel fleet switched to alternative fuels. The emission factors of the alternative fuels were lower due to their lower carbon content in the case of MeOH and no carbon in the case of NH_3. However, previous research has noted that these fuels need a pilot fuel with high energy density to trigger the ignition and combustion reactions within the engine. So, a small amount of MGO or diesel was needed in the fuel mixture. (Fridell et al. 2021; Liu et al. 2022; Nadimi et al. 2022, 2023).

In addition, the carbon intensity metrics (AER, DIST, and TIME) were calculated based on the data from the current vessel fleet specifications. Utilizing alternative fuels, these metrics showed great improvement for all vessel sizes. The improvement depends on the characteristics of the vessels as well as the type of journeys they took. Variables such as cargo weight, engine load, and speed affected these metrics.

As noted by Foretich et al. (2021) and Al-Enazi et al. (2021), the implementation of alternative fuels in the maritime industry is still in the early to middle stages. The articles showed only a few engines have been installed on smaller vessels of the fleet and many studies were still performed in laboratories. Technical and financial challenges need to be tackled before alternative fuels can be fully integrated into the current fleet. Thus, to accurately quantify the impact of alternative fuels on the maritime industry, more practical experiments on various sizes of vessels are required.

Some issues raised by this thesis also required more research as well. For NH_3, having an increased level of N_2O as a byproduct of the combustion reaction might also raise some concerns about using this fuel. As N_2O is known to trigger negative environmental impact besides global warming (Scheer et al. 2020, 72), using NH_3 as a fuel, even though it emits much less GHG, research into mitigation measures to reduce the amount of N_2O should be promoted. In addition, because the fuel consumption of alternative fuels was predicted to be much higher than conventional fuel, the vessel's design might need modification in order to carry more fuel for the same voyage.

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APPENDIX

Appendix 1. Power consumption requirements from auxiliary boiler and auxiliary engine (IMO 2020)

Ship Type	Size	Auxiliary Boiler Power Output (kW)				Auxiliary Engine Power Output (kW)			
		At berth	Anchored	Manoeuvring	At Sea	At berth	Anchored	Manoeuvring	At Sea
Bulk carrier (dwt)	0 - 9,999	70	70	60	0	110	180	500	190
	10,000 - 34,999	70	70	60	0	110	180	500	190
	35,000 - 59,999	130	130	120	0	150	250	680	260
	60,000 - 99,999	260	260	240	0	240	400	1,100	410
	100,000 - 199,999	260	260	240	0	240	400	1,100	410
	200,000+	260	260	240	0	240	400	1,100	410
Oil tanker (dwt)	0 - 4,999	500	100	100	0	250	250	375	250
	5,000 - 9,999	750	150	150	0	370	375	560	375
	10,000 - 19,999	1,250	250	250	0	690	500	580	490
	20,000 - 59,999	2,700	270	270	300	720	520	600	510
	60,000 - 79,999	3,250	360	360	280	620	490	770	560
	80,000 - 119,999	4,000	400	400	280	800	640	910	690
	120,000 - 199,999	6,500	500	500	300	2,500	770	1,300	860
	200,000+	7,000	600	600	300	2,500	770	1,300	860
Container (TEU)	0 - 999	250	250	240	0	370	450	790	410
	1,000 - 1,999	340	340	310	0	820	910	1,750	900
	2,000 - 2,999	460	450	430	0	610	910	1,900	920
	3,000 - 4,999	480	480	430	0	1,100	1350	2,500	1,400
	5,000 - 7,999	590	580	550	0	1,000	1,400	2,800	1,450
	8,000 - 11,999	620	620	540	0	1,150	1,600	2,900	1,800
	12,000 - 14,499	630	630	630	0	1,300	1,800	3,250	2,050
	14,500 - 19,999	630	630	630	0	1,400	1,950	3,600	2,300
	20,000+	700	700	700	0	1,400	1,950	3,600	2,300

Appendix 2. Data and statistics on different vessel (IMO 2020)

Ship Type	Size	Average Load	Average Main Engine Power (kW)	Average DWT (tons)	Average Speed (kn)	Average Distance Sailed (nm)	Days at Sea
Bulk carrier (dwt)	0 - 9,999	0.52	1796	4265	12	40449	178
	10,000 - 34,999	0.60	5941	26544	14	47407	177
	35,000 - 59,999	0.57	8177	49436	15	50781	184
	60,000 - 99,999	0.54	9748	77287	14	59118	214
	100,000-199,999	0.50	16741	167032	15	67978	252
	200,000+	0.56	20094	255525	15	73223	258
Oil tanker (dwt)	0 - 4,999	0.46	966	3053	11	29220	135
	5,000 - 9,999	0.49	2761	6740	12	31816	142
	10,000 - 19,999	0.54	4417	14650	13	32892	136
	20,000 - 59,999	0.51	8975	42832	15	45492	166
	60,000 - 79,999	0.53	11837	72249	15	55066	194
	80,000 - 119,999	0.48	13319	107314	15	53429	195
	120,000 - 199,999	0.48	17446	155325	15	61254	222
	200,000+	0.48	27159	306071	16	72529	252
Container (TEU)	0 - 999	0.48	5077	8887	16	55998	196
	1,000 - 1,999	0.46	12083	19595	19	68141	210
	2,000 - 2,999	0.39	20630	35435	21	75381	220
	3,000 - 4,999	0.33	34559	53662	23	87456	246
	5,000 - 7,999	0.34	52566	74426	25	97500	258
	8,000 - 11,999	0.40	57901	108058	24	102600	261
	12,000 - 14,499	0.41	61231	151357	24	96501	246
	14,500 - 19,999	0.56	60202	159496	20	99770	250
	20,000+	0.51	60210	-	20	82534	210