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MARKET POTENTIAL OF ALTERNATIVE BIOFUELS

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Abstract

This thesis explores the potentials of the alternative biofuel market in the maritime industry. The outcome is based on three criteria which are feasibility, market evolutions and future projections. The findings reveal limited growth rates of biofuels in the past, which shows that there is room for improvement under certain conditions. Bio-diesel and bio-LNG show great potential in the short run, based on feasibility criteria, while bio-methanol and bio-ethanol show great potential in the long run depending on the development of production pathways. Market evolutions show a decrease in CO_2 emissions in the last couple of years. However, achieving the necessary volumes to prevent the tipping point of 1.5 °C remains very challenging. Despite uncertainties and challenges, the potential of alternative biofuels remains high, especially under certain conditions.

Keywords: sustainable energy, alternative biofuels, maritime industry, performance indicators, market evolution, future projections and CO_2 emissions.

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List of abbreviations

Abbreviation	*Definition*
°C	Degrees Celsius
EU	European Union
GHG	Greenhouse Gas
MBM	Market-based measures
EEXI	Existing Efficiency Energy Index
IRENA	International Renewable Energy Agency
IMO	International Maritime Organization
HFO	Heavy Fuel Oil
EEDI	Energy Efficiency Design Index
SEEMP	Ship Energy Efficiency Management Plan
CO2	Carbon Dioxide
GWP	Global Warming Potential
LNG	Liquified Natural Gas
HVO	Hydro-treated Vegetable Oil
FAME	Fatty Acid Methyl Ester
CII	Carbon Intensity Index
LCA	Life Cycle Assessment
WTW	Well-To-Wake
MGO	Marine Gas Oil
IMF	Internationally Monetary Funds

1. Introduction

This chapter aims to clarify various aspects of the research. The problem statement section will discuss the identified problems. The problem statement is accompanied by an explanation of the research objective and research questions. The next section will explain the thesis outline.

1.1 Problem statement

To provide a clear problem statement, this section will present background information on the topic. The background information will offer a broader understanding of the area of study and will help to identify the specific problem. When the problem is identified, it will be explained why the issue is relevant.

During the climate conference in Paris in 2015, nearly 200 nations shaped their climate plans around the tipping point of 1.5 °C. Currently, many climate experts believe, the outcome is inevitable, the global temperatures will exceed the threshold of 1.5 °C in comparison to pre-industrial levels. The tipping point of 1.5 °C is quickly approaching, the world has already warmed approximately 1.3 °C. Within a few years temperatures could exceed the target of 1.5 °C. According to scientists, the world is moving to a two °C hotter world. This represents a disrupted climate with more intense storms, higher sea levels, loss of biodiversity and more infectious diseases. During the Glasgow climate pact in 2021 long-term targets were set to keep warming below two °C. The biggest assumption made here is that nations promised to be net zero in 2050. Assuming for zero carbon emissions in 2050 is easy to say, however supporting them with short-term actions is very hard (Shivanna, 2022).

Decarbonization is a crucial strategy. This strategy involves a lot of adaptation, especially on low-carbon power and fuel sources. Various industries are trying to become more sustainable, the maritime sector is no exception. The maritime sector plays a crucial role in the global economy. Cargo ships transport four trillion dollars' worth of goods across the oceans. This equals approximately 80 percent of global trade volume (Ampah et al., 2021).

The maritime sector contributes almost four percent of total European Union (EU) Greenhouse Gas (GHG) emissions in 2018, which are pre-COVID levels. To cut the EU emissions with 55 percent in 2030 and reach net zero in 2050, the EU is working on proposals to reduce emissions from ships. The incentives to reduce emissions include both technical and operational measures that aim to improve vessel efficiency. Among the long-term global measures lie the market-based measures (MBMs). These MBMs can encourage and stimulate investments in energy efficiency and deployment of alternative biofuels. The implementation of a global MBM for the maritime industry poses complexities, consumes a lot of time and requires a need for consensus of the different interests. Alongside the global procedures, regional directives are being implemented to achieve local objectives. On European level, the EU directive decided to take immediate action to achieve targets. In 2019, the Green Deal was released, with the aim to achieve climate neutrality in 2050. The Existing Efficiency Energy Index (EEXI), which tries to improve energy efficiency of vessels via incentives, does support the Green Deal in achieving carbon neutrality in 2050 (Christodoulou et al., 2021). One of the best fulfilling pathways for the MBMs is a transition to alternative biofuels. However, the specific problem is whether the MBMs stimulate the adoption of alternative biofuels pathway sufficiently to prevent reaching the tipping point of 1.5 °C?

The relevance of the specific issue evolves around the tipping point of 1.5 °C. It is crucial to investigate whether MBMs like EEXI can prevent the tipping point of 1.5 °C. If not, governments and stakeholders need to shift the focus to other interventions to prevent devastating climate consequences.

1.2 Research objective

After explaining the problem statement in section 1.1 the goal and aim of this research will be introduced. This section emphasizes how achieving this objective will contribute to fill identified gaps in the literature.

The International Renewable Energy Agency (IRENA) is a global organization that promotes the widespread adaption and sustainable use of all forms of renewable energy sources. In 2021 they presented an outlook, the world energy transition outlook where they outline a vision to meet the goals of the Paris Agreement; limit the global temperature rise to 1.5 °C pre-industrial levels. The IRENA explores an approach for the maritime industry with an emission reduction of 80 percent in comparison to 2018 levels. This pathway is divided into four categories. During this research, the focus will be set on three distinct categories: effect on reduced demand, effect on improved energy efficiency and employment of advanced biofuels. The main focus during this research is on alternative maritime fuels made from bio-renewables, non-synthetic or electricity fuels. For this reason, this study ignores the fourth category: indirect use of clean electricity via synthetic fuels and feedstock. The effects of reduced demand and improved energy efficiency have a crucial impact on the alternative biofuel market. For that reason the mentioned indicators will be discussed in the next sections, to investigate if the tipping point can be prevented.

The objective of this research helps to identify if alternative biofuels are the right solution and the most feasible option in the context of MBMs and policy objectives. If not, governments and stakeholders need to shift the focus to other interventions which can help to reduce the carbon intensity.

1.3 Research questions

Based on the problem statement and research objective in sections 1.1 and 1.2 the primary research questions is formulated as follows: *What is the market potential of alternative biofuels regarding mandatory market incentives and policy objectives, with a focus on feasibility criteria, market evolution in the past, and future projections?* To clarify the main research question, it has been broken down into three sub-questions:

- *Which alternative biofuels meet specific sustainable and economic criteria to be considered as a feasible option in the maritime industry?*
- *How has the alternative biofuel market evolved in response to mandatory incentives in the past?*
- *How will the projected demand for alternative biofuels in the future be affected by policy goals, global economy indicators and the implementation mandatory incentives?*

1.4 Thesis outline

This study is organized in seven chapters. The literature review is first described in chapter 2, it situates the forthcoming research. It forms the foundation of the entire study and provides support for results presented in next chapters. Chapter 3 provides an explanation of the methodology with a specific focus on scope and parameters used. Chapter 4 presents descriptive statistics which show results of the analysis. This is followed by a discussion in chapter 5, where research findings, limitations and recommendations for further research are discussed. In the concluding chapters, chapter 6 and 7, the bibliography and appendix are discussed.

2. Literature review

This chapter will present a comprehensive overview of the existing important literature of alternative biofuels. The aim of this chapter is to review the literature and critically analyze the current knowledge in this field. The aim is to establish a theoretical framework which supports the data analysis of this study.

2.1 Current market

This section demonstrates how the current fuel market operates and what the important drivers are. Additionally, this section tells which policies are currently in place and how they manifest themselves.

The International Maritime Organization (IMO) has set strategies to reduce the carbon intensity of the maritime industry. The reason for these strategies are the increasing concerns for carbon dioxide emissions from the maritime industry. The transition to green maritime fuels is recognized as feasible option to reduce the emissions related to maritime vessels. One of the most important drivers for global energy demand is economic growth. The global economy is related to seaborne trade and crude oil prices, which are main drivers for fuel consumption in the maritime industry. Currently, fossil fuels dominate the sector, mainly Heavy Fuel Oil (HFO). The consumption of HFO resulted in an increased share of global maritime emissions to the level of almost four percent. The high share of emissions reduce the probability to attain key emission protocols like the Paris agreement. Therefore, the IMO has set more stringent regulations to address these issues. As discussed in section 1.2 the goal is to limit the global temperature rise to 1.5 pre-industrial levels. With retrofitting, there is a great opportunity for very low GHG emissions from shipping. One of the best pathways is a transition to alternative biofuels. Thus, the usage of alternative maritime biofuels has gained interest in recent years (Ampah et al., 2021).

Active policy that mandates the improvement of energy efficiency will enhance sustainability for a wider period of time (Ampah et al., 2021). Without any mandates, the ship-source GHG emissions are likely to increase up to 250 percent by 2050 compared to 2012 levels. In the Paris agreement goals, the shipping industry was not included specifically in the global emission reductions. In 2003, almost 200 countries signed the agenda of sustainable development. This agreement was the first step towards the goals outlined in the Paris agreement. The IMO introduced the Energy Efficiency Design Index (EEDI) for newly built ships to stimulate the most advanced technologies and engineering. The downside of this regulation is that it totally ignores the operational variations of ships that determine the total energy efficiency. Ignoring this important branch, which determinates the EEDI, could even result in slightly higher carbon dioxide (CO_2) emissions. Next to technical solutions, the operational solutions are implemented under Ship Energy Efficiency Management Plan (SEEMP). These solutions relate to energy management strategies like; slow steaming, enhance network routing and engine maintenance. The adaption phase can be very expensive for vessel owners. Consequently, clients will shift to low-cost carriers (Wan et al., 2018).

For policy strategies, it is necessary to balance the interests, ensure that the mitigation strategy is sustainable and not at the expense of others. This study focuses on two specific mandates that try to ensure these criteria, the mandates will be discussed throughout the next section, 2.2. During this research, CO_2 is the main air pollutant. This is not surprising as the IMO mainly focuses on CO_2 as the main air pollutant when setting objectives. On top of that, CO_2 is the most significant GHG emitted by ships (Ampah et al., 2021).

Current literature observed that Liquefied Natural Gas (LNG) emerged as the most researched alternative to substitute conventional maritime fuels. This alternative maritime biofuel is the most suitable and cost-competitive and therefore quickly evolving. Besides LNG, other important alternative fuels are bio-diesel and bio-methanol. Although, the research into these fuels is not comparable with LNG, it is remarkable that the trend shows a shift towards biofuels. The explanation for this trend shift could be attributed to methane leakage. During the combustion of LNG, the powerful GHG methane is emitted, which is 120 times stronger in terms of Global Warming Potential (GWP) than average emissions. Therefore, LNG can not meet IMO objectives. On the other hand, bio-based alternative fuels offer future routes to decarbonize the maritime industry (Ampah et al., 2021).

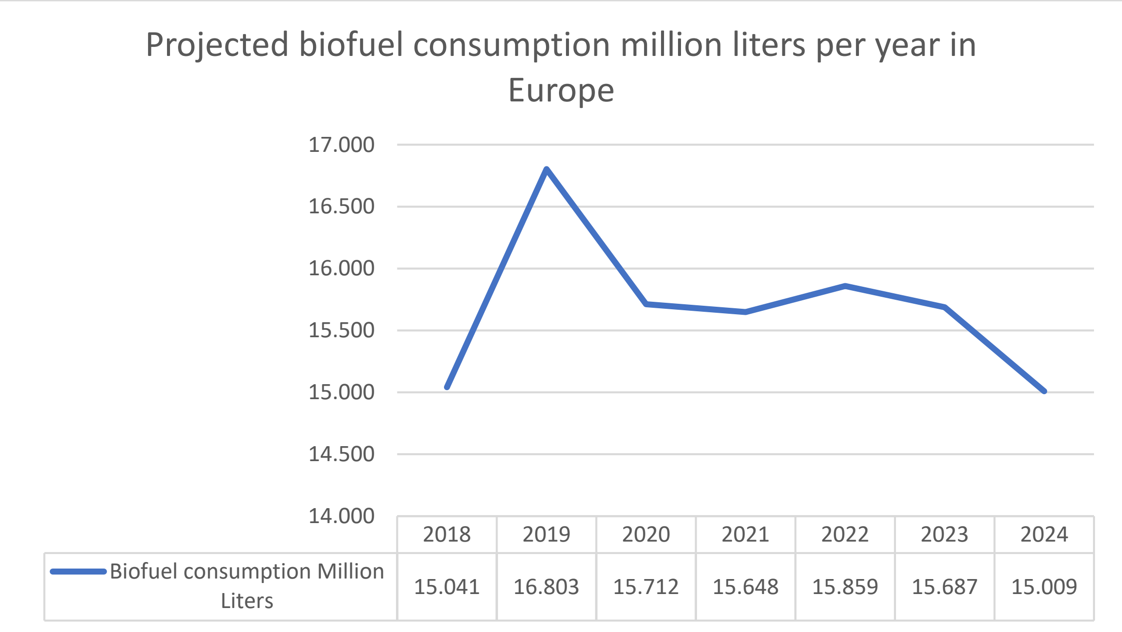


Figure 1 Biofuel consumption each year (IEA, 2022)

The pathway of biofuels is very promising. Currently, global biofuel consumption shows a contradictory image, pictured in figure 1. The biofuel consumption shows a negative projected trend. This trend has various reasons. The primary reasons are the COVID-19 crises and the Ukraine war. Additionally, biodiesels become less popular in the long run due to economic and environmental feasibility. Vessel owners will increasingly make the transition to other biofuels which are currently not competitive and underdeveloped (IEA, 2022).

2.2 Alternative biofuels

This section explains the potential alternative biofuels available on the current market. On top of that, the section provides an explanation of newly implemented policies that have a major impact on the maritime fuel market.

When the fuel uses a renewable primary energy source like biomass, the fuel is classified as biofuel. Among the bio-based fuels, the current literature states that the following alternative maritime biofuels do have the most potential: bio-LNG, bio-diesel, bio-ethanol and bio-methanol. Each of the bio-based fuel properties will be discussed separately (Andersson et al., 2020).

2.2.1 Bio-LNG

LNG is increasingly used as a biofuel in the maritime industry as mentioned in section 2.1. However, fossil LNG remains a significant emitter of CO_2. To address this, renewable LNG, known as bio-LNG, is necessary to reduce emissions in the shipping sector (Mukherjee et al., 2023). Bio-LNG can be produced thermally through gasification or via anaerobic digestion. Feedstocks such as manure and energy crops are suitable for anaerobic digestion, while gasification can utilize woodchips (Siu Lee Lam et al., 2022). Bio-LNG is derived from the liquefaction of biomethane, the most cost-effective renewable gas that offers substantial CO_2 savings. Bio-LNG is increasingly used in the maritime industry. The bio variant of LNG emits significantly less CO_2 emissions (Siu Lee Lam et al., 2022).

2.2.2 Bio-diesel

Bio-diesel and petroleum diesel are very similar fuels. However, many additives can be added to bio-diesel which modify the properties (Ciolkosz, 2020). Bio-diesel are long chains of fatty acid oils derived from sources such as vegetable oils or animal fats. Pure bio-diesel which contains 100 percent fatty acid oils is often referred as B100 while B80 contains 80 percent bio-diesel and 20 percent petroleum diesel (Noor et al., 2018). Currently, Europe has the most developed market for bio-diesel. The growth rates in production have been 34 percent per year for over a decade. Eight member states do have facilities to produce bio-diesel (Radovanović, 2023).

There are two specific types of bio-diesel, hydro-treated vegetable oil (HVO) & fatty acid methyl ester (FAME). FAME is currently the most common bio-diesel in the world. This fuel can be produced via transesterification of fats and vegetable oils. This process transforms oil into very long chains using a liquid catalyst which creates FAME. The most common feedstocks for FAME are a source of lipid which could be animal fats, vegetable oils, waste cooking oils or microalgae (Amin, 2019). For HVO the same feedstocks are being used. However, the production pathway is different. Vegetable oils are hydro-treated which means that the oxygen will be removed which creates hydrocarbons molecules which are similar to diesel.

2.2.3 Bio-ethanol

Ethanol is a two carbons alcohol which is mostly produced from fermentation of sugars or derived from starch. For the production of ethanol, two main production pathways exist, which are thermochemical and biochemical routes. The first route, the biochemical, accounts for the vast majority of production globally. The advantage of this process is that any feedstock containing carbohydrates is suitable for this conversion technology. According to these processes bio-ethanol is classified in first, second, third and fourth generation fuels. First generation ethanol is produced from sugars or starch, the feedstock which is widely used is sugarcane or sugar beet. The largest producer of sugarcane-based ethanol is Brazil. Second generation bio-ethanol is produced via food crop waste. This production pathway is very attractive because it increases feedstock availability without the investment in additional land area. Moreover, it is compatible with circular economy principles. However, this production pathway is high power/energy consuming which makes it very costly. Currently, bio-ethanol is produced on a commercial scale in the United States, Europe, Brazil and China. In 2020, the fuel market accounted for approximately 80 percent of bio-ethanol use in Europe (’t Hart et al., 2023).

2.2.4 Bio-methanol

Similar to ethanol, methanol has undergone many tests in heavy duty vehicles which makes it an interesting fuel for the maritime sector. Methanol is an excellent replacement for diesel and the fuel may achieve good performances in diesel engines. The downside of these alcohol fuels is the low energy content. The required storage space for bio-methanol is twice as big as conventional fuels, while achieving the same energy output. The industrial synthesis of methanol was developed approximately 100 years ago. During that period the production of methanol was at very high temperatures and pressure. Methanol can be produced from fossils or renewable raw materials. In this section the renewable production pathway will be discussed (Andersson & Salazar, 2015). There are two types of sustainable feedstocks to produce bio-methanol, which are lignocellulosic biomass and glycerol. Lignocellulosic biomass are wood or forest residues. Glycerol is a by-product from bio-diesel production which can also be used for the production of bio-methanol. The first conversion pathway with the lignocellulosic biomass is via gasification as explained in earlier sections. The second pathway with glycerol as the primary feedstock is a simple low-pressure process. This pathway is less attractive because it is depending on the availability of bio-diesel production (van der Maas, 2020). Currently, only 25 percent of all the methanol in the world is bio-methanol. However, methanol is very suitable for additional sustainable measures in downstream applications. Nevertheless these processes require the development of a more integrated system (Shamsul et al., 2014).

2.2.5 Policy mandates

Since the beginning of 2023 new mandates are implemented to improve energy efficiency of vessels to reduce the overall CO_2 emissions in the maritime industry. One of the mandatory measures to reduce the total CO_2 emissions is the EEXI. The aim is to reduce the carbon intensity with 40 percent in 2030. The EEXI measure is relating to the technical design of a ship. Ships need to assess their own energy efficiency index known as attained EEXI. The attained EEXI will be compared with the required EEXI, a performance level set by the IMO regulations. Non-compliant ships need to find a way to comply with the required values. Vessel owners are facing a diabolical dilemma, do they retrofit or will the vessel retire in the near future. According Gao (2022), the average lifespan of a ship is usually 25 years. Ships between the age of 9 and 13 years are highly likely to retrofit. The most common approach to retrofit a ship are; reducing energy efficiency and-engine modifications for using alternative biofuels (Rutherford et al., 2020). A major component of the EEXI is the reduction of the Carbon intensity index (CII). Each ship has its own index, this will be categorized into labels from A to E. The label A pictures a superior index, while the label E shows a very bad index. A ship with a D-rating for three consecutive years, or E for one year, must submit an action plan to show how they will reduce their index to the required index of C. With the implementation of EEXI in 2023, all vessels with an E label are required to retrofit. Vessels that do not meet the threshold are far less likely to be financed or chartered. This with the reason that vessels with a bad label have higher operational costs and could issue fines. Vessels with a high average age are less likely to retrofit and more likely to retire.

3. Methodology

This chapter clarifies the methodology employed in this study to investigate the research objectives outlined in section 1.2. The goal of this chapter is to provide a clear overview of research methods and approaches used to analyze the data. By explaining the methodology the reader will gain insight into the purpose to explain the research questions.

Due to the implementation of EEXI a lot of shipowners are considering to assess maritime biofuels to fulfill sustainability goals. The decision for shipowners to switch to alternative biofuels is very challenging. To fulfill short- and long-term perspectives many criteria have to be considered. Figure 2 indicates all the important indicators to measure the performance of alternative biofuels (Andersson et al., 2020). The aim of this research is to focus on environmental and economic criteria, the orange and green squares, respectively.

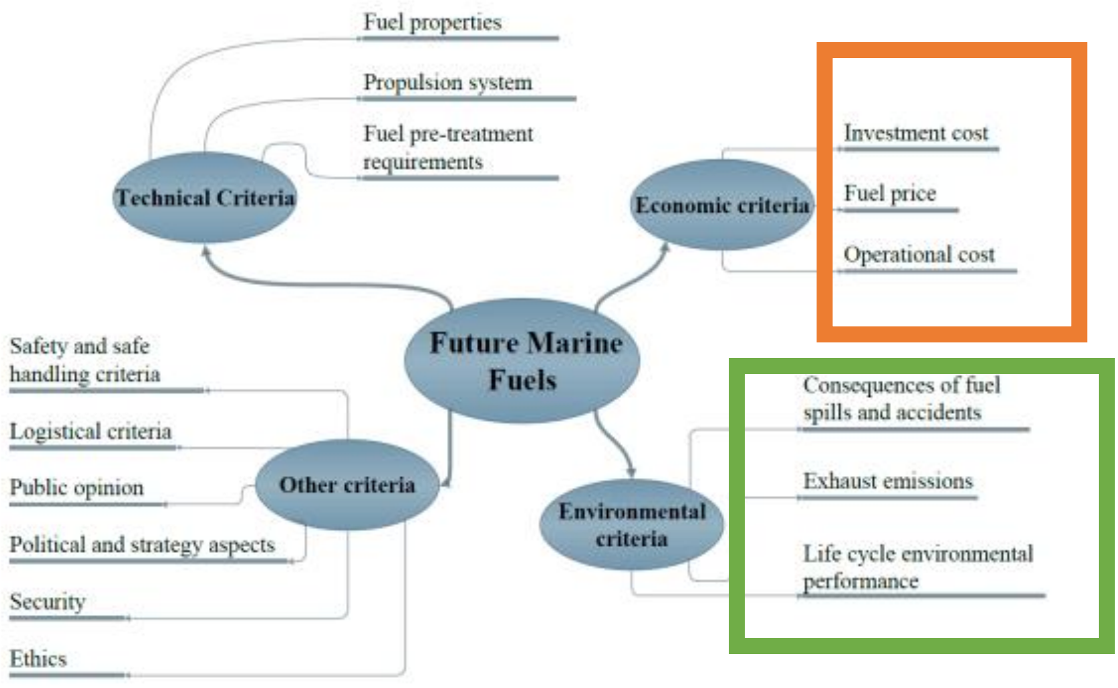


Figure 2 Future maritime biofuels suitability criteria (Andersson et al., 2020)

In the past the biofuel industry has largely been ignoring sustainability criteria which resulted into a lot of controversy. Some analysts showed that the biofuel development was environmentally harmful. However, many nations were promoting biofuels as the solution to the climate problems. Those biofuels do have significant startup risks. That is why this study will mainly focus on the integrated assessment of the sustainability of existing and future biofuels. The green square in figure 2 pictures all the important environmental criteria, which will be discussed (Solomon, 2010).

Petroleum spills are often associated with huge raptures of crude oil tankers which result in huge environmental issues. Biofuels are being used to minimize environmental impacts. However, the chemical and physical properties of biofuels are drastically different. The aim is to comprehensively record and evaluate the spill properties and associated risks of accidents involving various types of biofuels. (Kass et al., 2021).

Recently, global environmental problems have been caused by a rapidly rising level of CO_2 during fossil fuel combustion. Because of stringent regulations on CO_2 emissions, as discussed in earlier sections, research on alternative biofuels has accelerated. Among these approaches is reducing exhaust emissions and improving life cycle performances (Suh & Lee, 2016). The aim of the study is to monitor the CO_2 emissions of alternative biofuels for the entire supply chain. The emissions will be calculated via well-to-wake (WTW) emissions. Life cycle assessment (LCA) is a tool for analyzing this impact of a certain product at each stage of life cycle: raw material preparation, production processes, sales and transport and product disposal. The research will employ the LCA tool to assess the environmental impacts of biofuels throughout their life cycle. The findings aim to enhance our understanding of the environmental sustainability of biofuels. (Wahyono et al., 2022).

The shipping industry stakeholders say that cost plays a crucial role in determining viability and competitiveness of alternative biofuels. The economic competitiveness is essential to build support from stakeholders for development. Therefore, it is important to examine biofuels in terms of their techno-economic potential. Whereas, important economic indicators will be addressed, taking into consideration factors like investment cost, fuel price and operational cost. On top of that, the study of Solakivi et al., (2022) estimated future numbers. The calculations take new regulatory frameworks into account, like EEXI.

This study used the EMSA\THETIS-MRV dataset[1] from 2018 as the starting point for analysis. The dataset includes a wide range of parameters explaining maritime emissions like CO_2 as well as fuel consumption. By using statistical methods, the most recent dataset, EMSA\THETIS-MRV 2021, can be compared with the baseline year of 2018. This comparison can identify the progress made in emissions reduction in the context of achieving the IRENA pathway. However, the EMSA\THETIS-MRV dataset only focuses on member states of the EU. For this reason, the pathway of IRENA will be limited in this research to European waters. The second constraint of the dataset is that it only focusses on CO_2 in the context of emissions. So, in addition to this the pathway of IRENA in this research will be limited to CO_2. It is important to note that the EMSA\THETIS-MRV dataset uses a wide scope, including 15 different vessel types. In section 4.2, the scope used will be narrowed down. The main reason for choosing 2018 as the baseline year is relating to emission patterns. As the year 2018 is before the COVID-19 crises, the emissions during that year are representative for an economy which is fully operational. For the year 2021, this will not be the case, for that reason it is assumed that 2018 is the most representative dataset.

To process the EMSA\THETIS-MRV dataset, the statistical software package STATA has been employed. This program provided a set of tools to perform a statistical analysis. By using STATA, the large dataset could be handled and differences between 2018 and 2021 were compared using tables and graphs.

The impact of the three indicators of IRENA; reduced demand, improved energy efficiency and advanced biofuel utilization, will be assessed through various scenarios in this study. These scenarios will estimate the expected changes in CO_2 emissions in 2024 relative to the baseline year of 2018. The global economy is fundamental to predict the global container volume growth rates as discussed in section 2.1. As great uncertainty remains on the market recovery from COVID-19, there will be two scenarios; a base scenario and a low scenario. The risks about the market recovery are caused by tighter financial conditions and higher debt burdens, due to the increasing interest rates and high inflation. Second of all, crude oil prices. These prices per barrel have a big impact on the overall CO_2 emissions in the maritime industry. Again, the expected change in crude oil prices in 2024 is based on a base case and low case scenario for the crude oil price. In chapter four, the four possible outcomes will be presented resulting from the interaction of two variables each with two possible scenarios.

In order to estimate the total CO_2 emissions in 2024, it is crucial to estimate the correlation variables which are important for this study. The overall CO_2 emissions function as the dependent variable, whereas global trade volume and crude oil prices will function as the independent variables. For this

[1] https://mrv.emsa.europa.eu/#public/emission-report

study a log-log regression has been chosen for several reasons. The first one is interpretability, by taking a log-log regression, the coefficients represent an elasticity which makes the coefficients more meaningful during the interpretation. Second of all, transforming variables using a logarithmic scale help address issues of heteroscedasticity.

As a result of the implementation of mandatory incentives to reduce CO_2 emissions, it is likely that vessel owners will improve their energy efficiency. In order to calculate the improvements in energy efficiency, certain assumptions have been made for this study. According to the study of Rutherford et al. (2020), the mandatory EEXI policy will result in an overall CO_2 reduction of 1.3 percent in 2030 in comparison to the baseline. For the purpose of the research, it will be assumed that by 2024, exactly half of this reduction will be achieved. This assumption is based on the fact that in 2024, the time frame to achieve the goal will be exactly halfway, between 2018 and 2030. Second of all, throughout this study, it is assumed that vessels with the CII label A, B and C will not retrofit. As these vessels are eco-friendly, there is no need to reduce their EEXI and CII. Vessels with the carbon label of D or E are likely to retrofit. With the implementation of EEXI in 2023, all vessels with an E label are required to retrofit within the next year. According to the study of Kim et al. (2023), it is predicted that in 2023, vessels with an E label account for 19 percent of the total fleet population. It will be assumed that in 2024, through retrofitting or retirement of inefficient vessels, there will be a 0.65% decrease in the overall CO_2 emissions of the vessels with the index of E. The study of Kim et al. (2023) calculated the CII as represented in expression 3.

$$CII_{Ship} = \frac{M}{W} \quad (3)$$

$$M = Fuel\ oil * Conversion\ rate\ in\ the\ fuel\ oil$$

$$W = Ship\ capacity * Total\ transport\ distance$$

4. Results

This chapter provides the findings of the study, a collection and interpretation of literature and gives a comprehensive analysis of the data collected. The goal of this chapter is to depict the results in an organized manner to give answer to the research objectives and questions. This will give new insights into patterns and trends into the field of alternative biofuels.

4.1 Feasibility of alternative biofuels

The following section shows which alternative biofuels will have a dominant share within the near and distant future. The results are based on the environmental and economic criteria outlined in figure 2.

4.1.1 Environmental performance

The environmental indicators that will be discussed in this chapter are; fuel spills & safety and the life cycle performance for each alternative biofuel. The main performance indicator for the environmental performances are CO_2eq emissions in this study. A carbon dioxide equivalent, CO_2eq, is a measure to compare various GHGs on the basis of their GWP.

4.1.1.1 Bio-LNG

Fuel spills & safety

Bio-LNG has minimal environmental impacts in the event of a spill. While it creates a white cloud upon exposure to the atmosphere, the low solubility and fast degradation of methane results in low toxicity and rapid dissipation. However, the high flammability of bio-LNG poses a fire hazard, and detecting spills can be challenging (Kass et al., 2021).

Life cycle performance

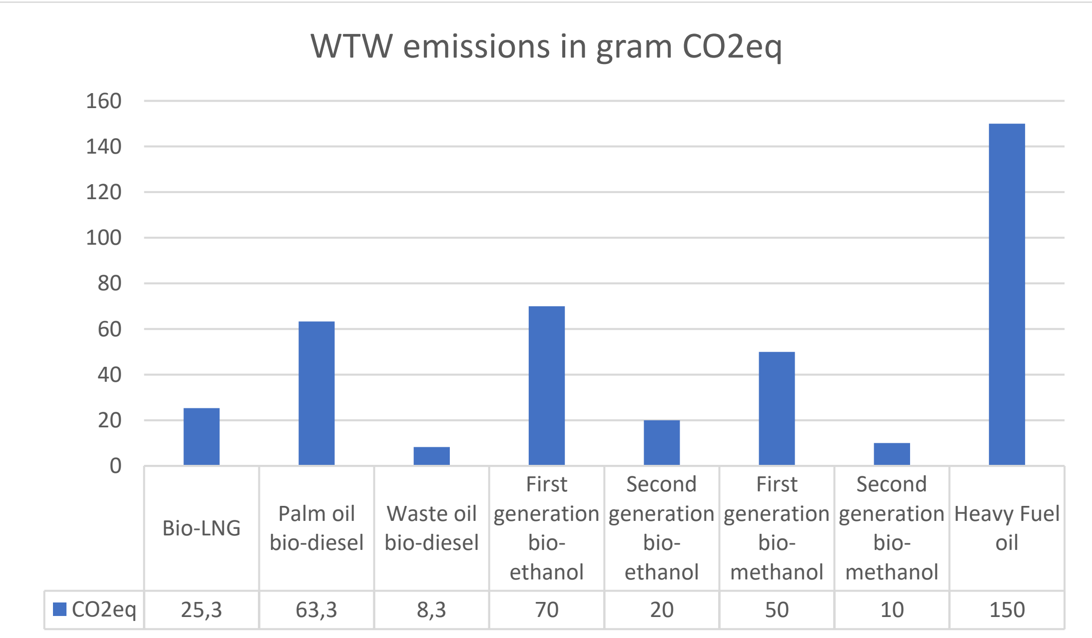


Figure 3 Well-to-wake CO_2 emissions for alternative biofuels (Gerritse & Harmsen, 2023) ('t Hart et al., 2023)

During the combustion of bio-LNG, the vessel is almost carbon neutral, the tank-to-wake – CO_2 is not relevant. On the other hand, the other GHGs have a significant share. Methane slip is a phenomenon that occurs during the combustion of bio-LNG, resulting in the release of harmful emissions. However, the aim of this study is to focus on CO_2 emissions, that is why methane slip is excluded from consideration. The total WTW CO_2eq emissions for bio-LNG equals 25.3 grams, the emissions are primarily generated during the production process (Gerritse & Harmsen, 2023).

4.1.1.2 Bio-diesel

Fuel spills & safety

Bio-diesel, commonly blended with HFO or diesel, offers advantages such as stability, lower viscosity, and being lighter than water. It forms slicks of varying thickness, resulting in faster degradation than regular diesel, particularly in warmer water. Notably, bio-diesel has low flammability and toxicity, and spills are easily detectable, minimizing environmental impact (Kass et al., 2021).

Life cycle performance

Due to the renewable nature of bio-diesel, the fuel will generate barely any emissions during combustion. Therefore, the tank-to-wake emissions for CO_2 are not relevant to discuss. The study of Bonomi et al., (2018) suggests that there is a big variance in life cycle performance for HVO & FAME. This variance is the result of many different combinations of the production of HVO and FAME in the context of feedstocks and production-processes. Figure 3 shows the differences between estimated g CO_2eq/MJ for different feedstocks. The disparity between bio-diesel derived from waste oils and palm oil is substantial. Currently, most of the HVO and FAME are produced from palm oil. However, the production process of bio-diesel from waste oils is increasingly being utilized. The well-to-wake emissions for palm oil bio-diesel amount to 63.3 grams, whereas waste oil bio-diesel registers significantly lower, at just 8.3 grams (Gerritse & Harmsen, 2023). However, it is anticipated that the WTW emissions of bio-diesel will likely be higher than estimated. Currently, many vessels that utilize bio-diesel, do not employ pure bio-diesel but instead use a blend known as B80, consisting of 20 percent petroleum and 80 percent bio-diesel. This blending practice can lead to higher CO_2 emissions in the tank-to-wake phase of the fuel life cycle.

4.1.1.3 Bio-ethanol

Fuel spills & safety

Ethanol as a fuel for road transport is well developed. However, ethanol as a maritime fuel is hardly developed. If we compare bio-ethanol to other alternative maritime fuels it is less toxic. Ethanol is highly volatile which means it will evaporate over time if left in the open. Ethanol is completely soluble in water. When ethanol is released to surface water the substance will float. Because of the high solubility this substance will disappear very quickly. More serious concerns are about the risks of fire. Ethanol is highly flammable. These fires can be very harmful for the ecosystem and ship crew. On top of that, the spills are very hard to detect which makes it even more difficult for the ship crew (Kass et al., 2021).

Life cycle performance

The ethanol combustion emits around 10 percent less CO_2 in comparison to diesel with the same efficiency. Historically, LCA studies for first generation bio-ethanol point towards the agricultural phase as the most polluted one. Figure 3 shows that the total well-to-wake emissions for first generation bio-ethanol equals to 70 grams of CO_2eq. The situation is different for second generation bio-ethanol, different chemicals and inputs are introduced which give rise to industrial pollutants. However, the feedstock choice has the biggest influence on the emissions. Therefore, current availability of feedstock, considering existing economic, social and environmental figures is relevant while assessing ethanol production technologies ('t Hart et al., 2023). However, in the context of combustion emissions and more advanced agricultural phases, the second generation bio-ethanol fuels are more favorable. The total well-to-wake emissions are 20 grams of CO_2eq.

4.1.1.4 Bio-methanol

Fuel spills & safety

Bio-methanol spill behavior will be very similar to bio-ethanol. However, methanol is more volatile, which means the substance will evaporate more quickly. Because of very rapid degradation, a large spill will only have large impacts near the release point. A very high concentration of methanol can be very toxic. However because the fuel is very volatile the concentration will dilute quickly over time which makes it less dangerous. So in other words, large bio-methanol spills will degrade faster compared to possible clean up. The big difference between methanol and ethanol is that for methanol only a small fraction of highly flammable vapors will rise. On top of that these vapors dissipate quickly into the atmosphere. Like ethanol, methanol is very difficult to detect (Kass et al., 2021).

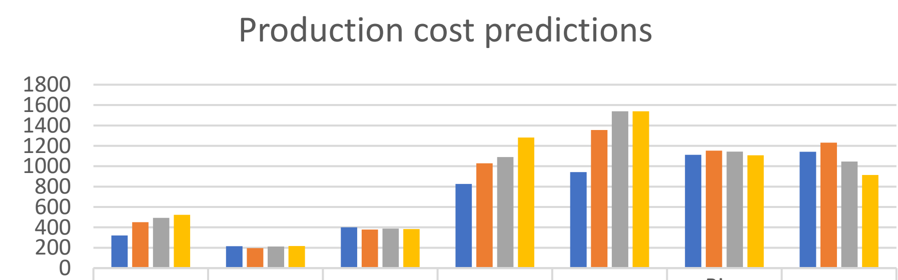
Life cycle performance

Bio-methanol has a significantly lower carbon content in comparison to fossil fuels. This has to do with the low hydrogen to carbon ratio (Deka et al., 2022). The overall tank to wake GHG emissions is 2.5 g CO_2-eq./MJ, which tells that the CO_2 emissions during combustion are not significant (Nelissen et al., 2022). The sustainable feedstocks for bio-methanol are part of a cycle which can capture CO_2 very fast. If the bio-based resource is managed very sustainable the biogenic carbon can be captured from the atmosphere and being recirculated. Like bio-ethanol, bio-methanol has various pathways. First generation pathways are sustainable but still have a significant impact on the environment during the entire supply chain. The total well-to-wake emissions are on average 50 grams of CO_2eq as shown in figure 3. Second-generation bio-methanol fuels are demonstrated to have WTW emissions of 20 grams of CO_2eq.

4.1.2 Economic performance

The shipping industry stakeholders say that cost plays a crucial role in determining viability and competitiveness of alternative biofuels. This is the main reason why this paragraph will discuss the most important economic criteria for alternative biofuels; production costs and fuel prices.

4.1.2.1 Production cost



	MGO	LNG	Methanol	HVO	FAME	Bio-methanol	Bio-LNG
2020	321	215	401	826	942	1112	1141
2030	451	197	378	1029	1356	1152	1231
2040	493	212	388	1090	1539	1143	1046
2050	523	217	383	1282	1539	1107	914

Figure 4 forecast of the cost of alternative maritime fuels (Solakivi et al., 2022)

Figure 4 shows the overall cost including operational cost and investment cost of alternative maritime fuels. This analysis is limited to alternative maritime biofuels, including bio-methanol, bio-LNG and bio-diesel. As a whole, figure 4 shows that the alternative biofuels are more expensive than conventional fuels. In terms of cost, bio-diesels are in comparison to Marine Gas Oil (MGO) and LNG the most competitive. The study of ’t Hart et al. (2023) states that the production cost for bio-ethanol vary considerably based on the feedstocks that are used. When using sugarcane as a feedstock production cost of bio-ethanol is competitive to bio-methanol.

4.1.2.2 Fuel price

Figure 5 indicates a second important indicator for economic performances, fuel prices. In the realm of fuel pricing, bio-diesels like HVO and FAME offer currently the most compelling cost competitiveness compared to conventional fuels. However, based on the forecast of Solakivi et al. (2022) which includes new regulations like EEXI and CII, future fuel price competitiveness will shift. Considering the impacts of new regulations, conventional fuels will stay competitive in the long run. The new regulatory framework will have an impact on relative competitiveness because of efficiency regulations. The biofuels will be competitive till approximately 2040, whereby bio-LNG will be the most competitive. The prices of bio-diesel will increase in the future because of the relatively higher carbon content for the entire supply chain (Solakivi et al., 2022).

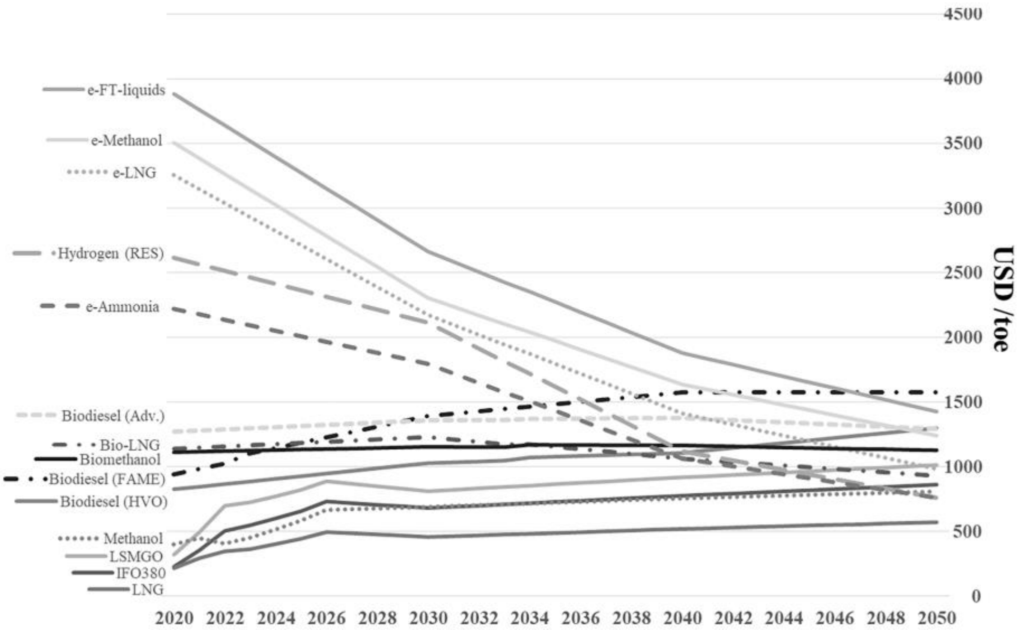


Figure 5 fuel price forecast for maritime fuels (Solakivi et al., 2022)

4.1.3 Overall performance

The well-to-wake emissions, expressed in grams of CO_2eq, vary across different feedstocks. The production pathways for bio-methanol and bio-ethanol demonstrate notably low emissions when utilizing second-generation methods. However, due to inadequate development of these pathways, their economic performance indicator scores suffer. In contrast, bio-LNG and bio-diesel do have favorable scores in terms of environmental indicators. Additionally, the strong economic performance indicators of bio-diesel, makes it a feasible option for the short term. Future mandatory incentives will disadvantage fuels with a high carbon content which makes bio-diesel less attractive. However, in the long run, the economic performance indicators of bio-diesel will decrease significantly which makes them only a feasible option for the next couple of years. On the contrary, the economic performance indicators for bio-LNG will increase over the years which makes it a feasible option for the long run. Similarly, bio-methanol and bio-ethanol have the potential to become compelling options in the future, provided that their production pathways continue to evolve and improve.

4.2 Market evolution of alternative biofuels

To predict the future for alternative biofuels, it is first very important to understand the past. Which patterns did the overall CO_2 emissions show? What are the exact causes of the relative changes in these patterns over the last few years. This section will give a precise analysis of events in the past.

4.2.1 Carbon dioxide emissions of maritime industry between 2018 and 2021

The study of CE delft (2017), focused on five different vessel types for their analysis. The EMSA\THETIS-MRV dataset uses a much wider scope and included 15 different vessel types. For this analysis, a more narrow scope will be better manageable. Therefore, the categories of EMSA\THETIS-MRV dataset need to be re-categorized:

1. Bulk carrier
2. Container ship
3. Tankers (includes chemical carriers, oil tankers, and refrigerated cargo carriers)
4. Gas carriers (includes LNG carriers)
5. General cargo carriers (includes combination carriers, container/ro-ro cargo ships, other ship types, passenger ships, ro-pax ships, ro-ro ships, and vehicle carriers)

When examing the results from EMSA\THETIS-MRV shown in figure 6 and 7, it becomes evident that the total CO_2 emission for nearly all ship types have decreased. The goal is to reduce 80 percent of CO_2 emissions in 2050 in comparison to 2018. Table 1 shows how much the total emissions per ship type has decreaseds between 2018 and 2021.

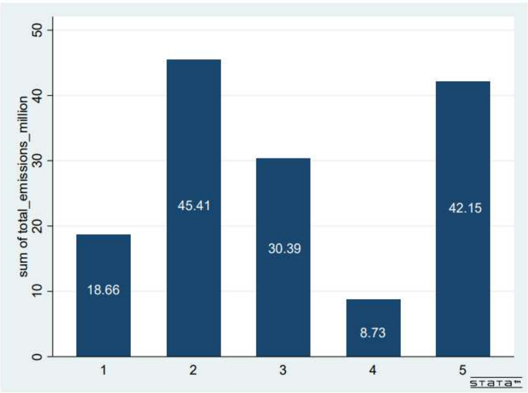


Figure 6 Total CO_2 emissions per ship type in 2018

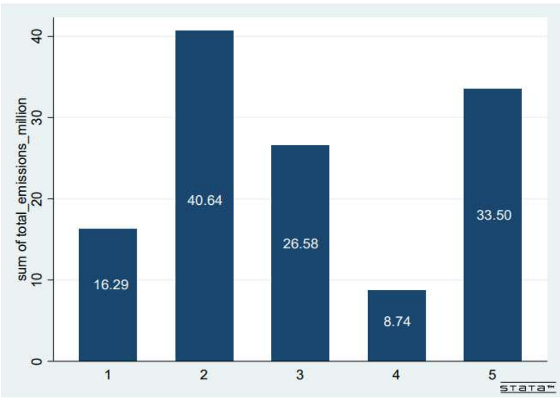


Figure 7 Total CO_2 emissions per ship type in 2021

Table 1 shows how much the total emissions per ship type has decreased between 2018 and 2021. This decline can be attributed to various factors including the possibility of the usage of alternative biofuels. The upcoming sections will explain the reason behinds these declines.

Table 1 delta of Total CO_2 emissions (2018-2021)

Ship type	Δ 2018-2021 Total CO_2 emissions
Bulk Carrier	12.7% decrease
Container ship	10.5% decrease
Tanker	12.5% decrease
Gas Carriers	0.1% increase
General Cargo carriers	20.5% decrease

4.2.2 Switching to Alternative biofuels

One of the possibilities for the carbon dioxide reductions is the usage alternative biofuels. Biofuels, as a whole, generally emit less CO_2 per metric ton fuel consumed, in comparison to conventional fuels. The emissionfactor tells how much CO_2 in milion metric tonnes is emitted per milion metric tonnes fuel consumed. Figure 8 shows that between 2018 and 2021 this emission factor barely changed. The figure tells that vessel companies did not switch to alternative biofuels and continue to use conventional fuels. The decreases pictured in table 1 cannot be deduced from the transition towards alternative biofuels.

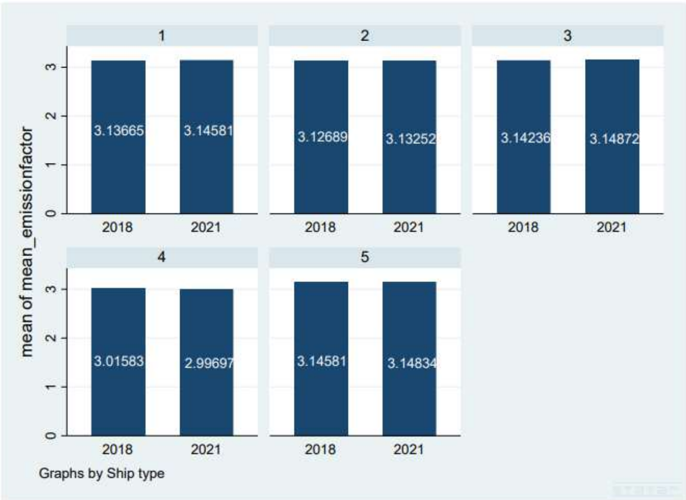


Figure 8 annual average emission factor per ship type per year

4.2.3 Transport work

In 2021, the demand and supply conditions in the container shipping freight market were unusual because of COVID-19. There was an 11 percent increase in global trade volumes after restrictions became less strict. However, the increases in trade volumes do not correspond to the low growth in fleet supply and disruptions in the supply chain. As a consequence, freight rates increased significantly. It means that on average, vessels carry more freight per selected route. The changes in the freight rates do have an impact on the average fuel consumption per transport mode (United Nations, 2022). The dataset of EMSA\THETIS-MRV provides a metric to measure this impact, namely annual average fuel consumption per transport work in mass (g / m tonnes · n miles). The transport work indicator is very crucial and determining. The formula used to calculate the total fuel consumed per transport work is represented in expression 1.

$$\text{Fuel consumption per tranport work} = \text{Total annual fuel consumption} \div \text{Transport work} \quad (1)$$

$$\text{Transport work} = \text{Distance travelled} * \text{Cargo carried}$$

When there is a lower annual average fuel consumption, this implies that less fuel is being consumed to cover a certain distance or carry a certain amount of cargo. As a result, this allows for more distance to be traveled or more cargo to be carried with the same amount of fuel consumption. Figure 9 shows that the annual average fuel consumption per transport work improved in the last couple of years. The average fuel consumption per tranpsort work has decreased across nearly all vessel types. This observation can be strongly linked to the decreases observed in table 1 and the skewed division between supply and demand in 2021.

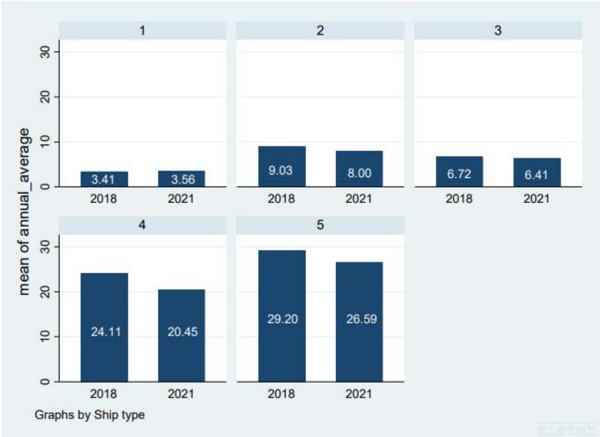


Figure 9 the mean of the average annual fuel consumption per transport work in mass per ship type

On the contrary, due to disruptions across the supply chain an increase in average speed of vessels took place. Vessels sped up in an attempt to prevent liabilities from congestion. However, this growth does not improve the overall efficiency of vessels. The overall decrease of CO_2 demonstrated in table 1 does not come from vessels going more slowely (Miller, 2021).

4.2.4 Time spend at sea

It is remarkable that in 2018, the number of hours at sea per vessel is significantly higher compared to 2021. The main reason for this is due to COVID-19 restriction causing strange patterns in the supply and demand. As vessels had fewer hours of operation, their CO_2 emissions will be less in comparison to 2018. Figure 10 pictures the overall decrease in time spend at sea per vessel type.

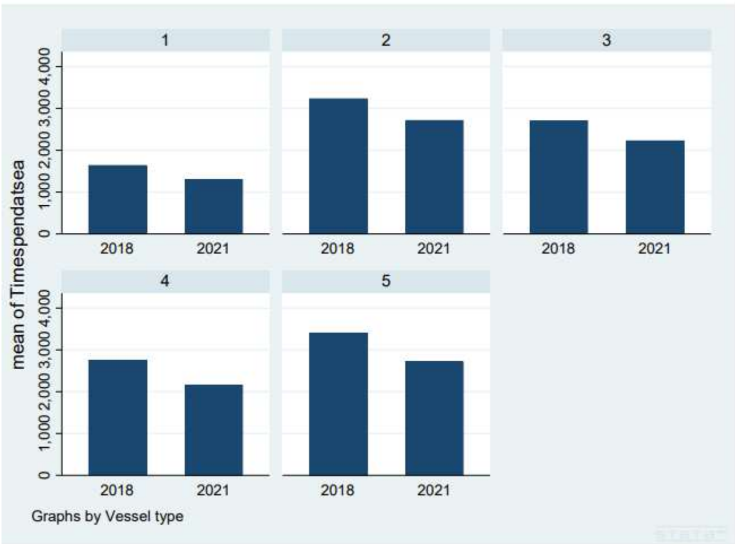


Figure 10 mean of time spend at sea per vessel type per year

4.2.5 Key findings

Table 1 demonstrates that the overall CO_2 emissions between 2018 and 2021 decreased significantly. The objective was to clearly illustrate the main causes of the decline in CO_2 emissions. The primary cause was the decrease in fuel consumption per transport work. The main reason for this decrease was the unusual condition between supply and demand in 2021 due to COVID-19. Because of the recovery of COVID-19 crises demand for trade volumes increased significantly. However, the supply could not meet the levels of demand. This meant that the trade volumes that were typically traded in 2018 could not be achieved due to insufficient vessels and congestion in ports. Because of the unusual conditions during this period, the average fuel consumption per transport mode decreased. This means that more cargo is carried with the same amount of fuel consumed. Additionally, there was a decrease in the average time spent at sea. In 2021, an extended period was marked by substantial COVID-19 restrictions, which significantly reduced maritime traffic. On the contrary, the decrease in table 1 did not come from switching to more efficient fuels, lowering the pace of vessels and vessel retirement. Therefore, the following sections will focus on different scenarios that try to achieve the IRENA goal with the emphasis on improving energy efficiency.

4.3 Demand in the future

The previous chapter gave a clear overview of the events in the past. In order to answer the research objectives and questions, it is necessary to make predictions about possible future events. These events will be predicted via scenario analysis outlined in this chapter.

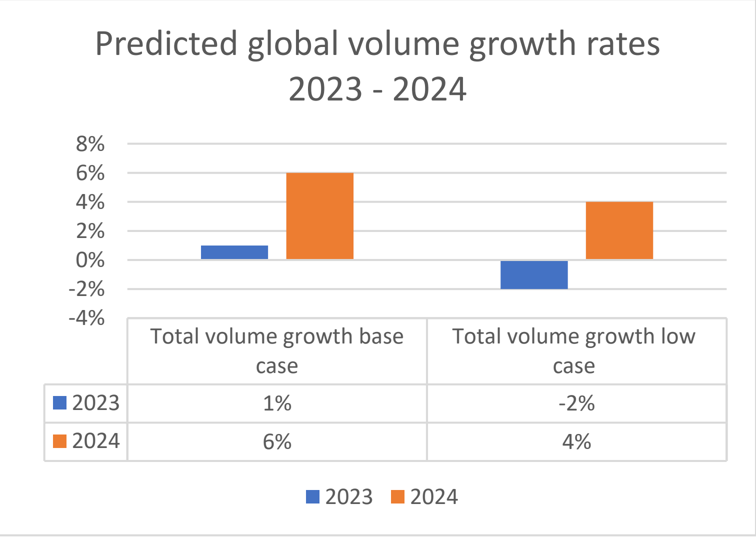
Section 4.2.1 indicated a significant decrease in total CO_2 emissions between 2018 and 2021. However, these results represent a distorted image. Literature suggests that CO_2 emissions have rebounded after the period of COVID-19 (IEA, 2022) (Rasmussen, 2023). Therefore, during this section the EMSA\THETIS-MRV dataset of 2018 is used as a baseline. This dataset is more representative in the context of CO_2 emissions because of pre-COVID levels.

However, the total emissions during the period of 2018 and 2021 shows a skewed perception. These results show that the maritime industry could improve significantly in the context of energy efficiency. Therefore, it is of big importance to focus on this topic to reach certain policy goals in the future.

The objective of IRENA is to achieve a 80 percent reduction of CO_2 emissions by the year 2050 compared to the baseline 2018. Figure 6 illustrates the total amount of CO_2 emissions in million metric tons for 2018, being 145.34. The target set by IRENA is to decrease this value to 29.07 million metric tons of CO_2 by 2050. Via scenarios which will be pictured in the next section, the change in CO_2 in 2024 will be estimated compared to the baseline year. Based on these scenarios, it is possible to estimate the total volume of alternative biofuels required to prevent reaching the tipping point.

4.3.1 Scenarios

Based on the Internationally Monetary Funds (IMF) (Rasmussen, 2023) the world economy could be predicted in a base case and low case scenario. In the base case scenario, the projected global volume growth for 2024 is estimated at 6 percent, while in the low case scenario, it amounts to 4 percent. According to the IMF, the projected global volume growth for the year 2023 is 1 percent in the base case scenario, and it is expected to be minus 2 percent in the low case scenario. These growth rates are represented in figure 11.



	Total volume growth base case	Total volume growth low case
2023	1%	-2%
2024	6%	4%

Figure 11 total volume growth rates in 2024 (Rasmussen, 2023)

According to the data presented in figure 12 from Statista (2022), the total volume growth between 2019 and 2022 indicates a 10.3% increase. Based on this trend, the projected total growth rates for the base case scenario in comparison to 2018 are estimated to be 11.3% and 17.3% for the years 2023 and 2024, respectively. Compared to the base case scenario, the projected total growth rates for the low case scenario, are expected to be 8.3% and 12.3% for 2023 and 2024, respectively.

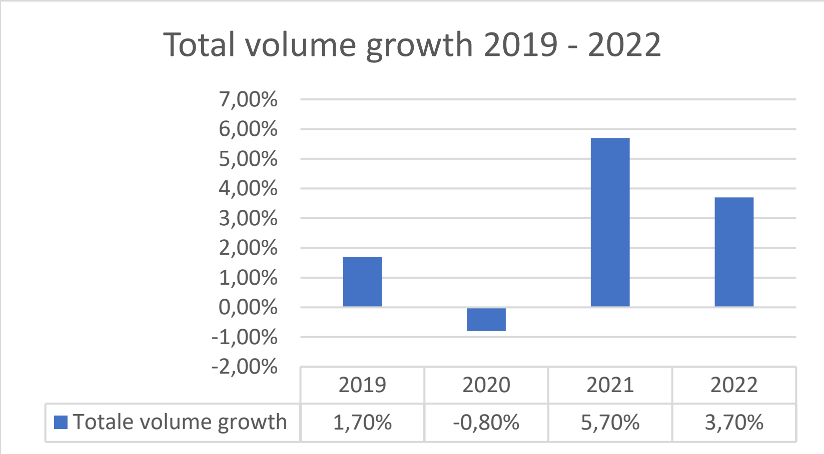


Figure 12 Total global volume growth 2019 - 2022 (Statista, 2022)

Crude oil prices, which are for the maritime industry very important, serve as the second indicator for the scenarios. Again, a base case and a low case are described for crude oil prices. The OPEC members have a big influence on the crude oil prices. It is expected that the members will cut their production in 2024 which will increase crude oil prices.

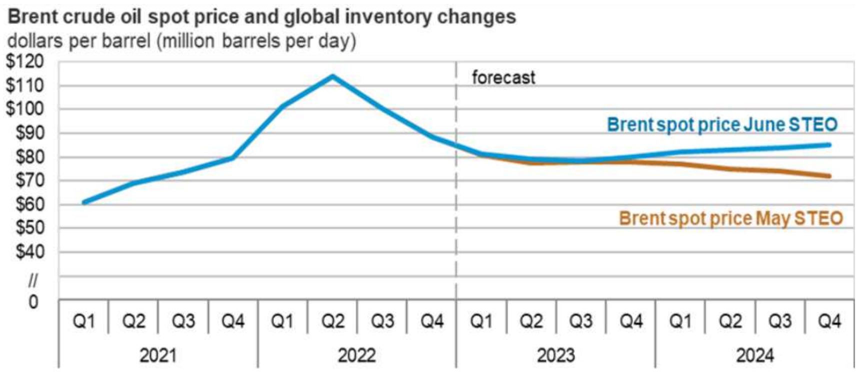


Figure 13 Prediction of crude oil prices (U.S. department of energy, 2023)

Based on the latest predictions in June 2023, crude oil prices equal 79 dollars per barrel, and are expected to increase to 84 dollars per barrel in 2024. However, these predictions could be wrong and OPEC members may decide not to cut production. If this scenario will become reality, prices may experience a decline to 75 dollars per barrel in 2024 as shown in figure 13.

Figure 12 illustrates the relative change in volume growth rates compared to the baseline of 2018. If the projected values depicted in figure 11 will be incorporated, the relative estimated global trade volumes of 2024 shown in table 2 may become possible. According to the study of Trading Economics (2023), the crude oil price in dollars per barrel was 71.34 in the year 2018, serving as the baseline year. Figure 13 presents the projected values for crude oil prices in 2024. Using this data, the relative change can be calculated pictured in table 2.

Table 2 possible scenarios to predict future demand, left side crude oil prices % | right side global trade volumes %

Scenarios in 2024; percentage change compared to 2018	***Global volume +***	***Global volume -***
	*Crude oil prices % |**Global volume %***	*Crude oil prices % | **Global volume %***
Crude oil prices +	30.6% - ***17.3%***	30.6% - ***12.3%***
Crude oil prices -	12% - ***17.3%***	12% - ***12.3%***

4.3.2 The correlation between alternative biofuel and crude oil prices

Crude oil prices do have a big impact on biofuel demand. The correlation between crude oil and biofuel prices depends on the economic conditions. The higher the magnitude, the stronger the correlation, which means prices of crude oil and bio-diesel move more simultaneously. According to figure 14, the correlation magnitude was higher compared to other years during the economic crises in 2012. However, at the end of the sample the magnitude flattens out which suggests that high crude oil prices do barely influence bio-diesel prices. Figure 13 indicates that during the base case scenario prices of crude oil increase. Assuming that the correlation magnitude stays the same, as illustrated in figure 14, it tells that biofuels become relatively cheaper in comparison to conventional fuels. Prices of crude oil and biofuel do not move simultaneously, an increase in crude oil prices makes the price for biofuel more attractive which can increase demand. However, as figure 4 shows the production cost of biofuels are significantly higher than conventional fuels. Despite the relative decrease in biofuel prices, they still remain higher than conventional fuels. The transition to biofuels will be done out of social responsibility, attractive long-term investments or regulatory requirements.

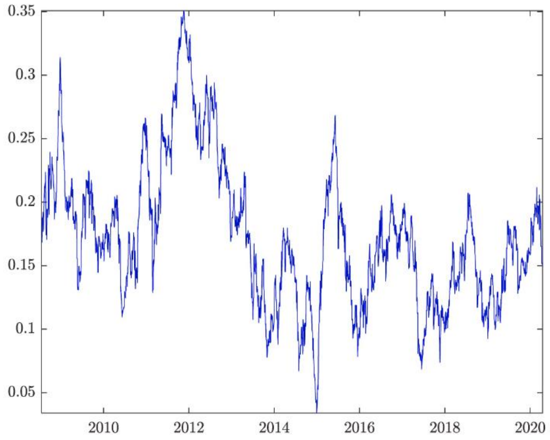


Figure 14 correlation magnitude between crude oil and bio-diesel (Yahya et al., 2022)

4.3.3 Prediction of the overall CO_2 emissions in 2024

The goal of IRENA is to reduce the total maritime CO_2 emissions up to 80 percent in 2050. To accomplish this, it is necessary to enhance the presence of alternative biofuels. Estimating the required amount of alternative biofuels to meet the IRENA goal, makes it necessary to predict the overall CO_2 emissions in the future.

4.3.3.1 Linear regression analysis

We know the total maritime CO_2 emissions in 2018 as calculated in section 4.2.1. In order to predict the maritime CO_2 emissions, understanding the relation between global trade volumes, crude oil prices and CO_2 emissions is crucial. Via de formula pictured in expression 2 the correlation between the variables can be calculated.

$$\ln(Y_1) = \beta_0 + \ln(\beta_1 X_1) + \ln(\beta_2 X_2) + \varepsilon \ (2)$$

$$Y_1 = Global\ internatinal\ shipping\ CO_2\ emissions$$

$$\beta_0 = Intercept$$

$$X_1 = Global\ \ trade\ volume$$

$$X_2 \ = Crude\ oil\ price$$

$$\varepsilon = error\ term$$

The relationship between the variables will be calculated via a linear regression analysis in STATA. The outcome of this analysis is shown in table 3. To understand the process of the regression analysis, information about indicators is crucial. The unit of observation is a crucial measure; variable Y_1[2] is measured in million metric tons, variable X_1[3] is measured in billion US dollars and variable X_2[4] is measured in US dollars per barrel. As depicted in table 3, the analysis used 32 observations for the linear regression. The observations are expressed in years, covering the period from 1990 to 2021. To summarize these indicators, several statistics are crucial. The mean and standard deviation will be discussed during this section. The mean of carbon dioxide emissions in the marine industry between 1990 and 2021 is 556.67 million metric tons. The standard deviation allows to understand the spread of variability. Therefore, a standard deviation of 108.75 million metric tons indicates that there is a notable amount of variability, the diversity is significant.. The mean of world trade volumes during the mentioned period equals 11262.78 billion US dollars. A standard deviation of 6055.03 billion US dollars suggests that a significant amount of diversity in the variable being measured. The average crude oil price between 1990 and 2021 equals 49.63 US dollar per barrel. However, the variation for the dataset of this indicator is again significant, the standard deviation is equal to 31.59 US dollar per barrel. Overall, the data points for this dataset are widely dispersed.

Table 3 linear regression analysis (data source: (WTO, 2022) (Aizarani, 2023) (Statista, 2023))

Ln (Co2 emissions marine industry)	Coef.	St.Err.	t-value	p-value	[95% Conf	Interval]	Sig
Ln (World trade volumes)	.371	.028	13.30	0	.314	.428	***
Ln (Crude oil prices)	-.048	.025	-1.88	.07	-.1	.004	*
Constant	3.079	.175	17.59	0	2.721	3.437	***

Mean dependent var	6.302	SD dependent var	0.205
R-squared	0.963	Number of obs	32
F-test	381.900	Prob > F	0.000
Akaike crit. (AIC)	-111.630	Bayesian crit. (BIC)	-107.232

****** p<.01, ** p<.05, * p<.1*

[2] https://www.statista.com/statistics/1291468/international-shipping-emissions-worldwide/

[3] https://www.wto.org/english/res_e/statis_e/trade_evolution_e/evolution_trade_wto_e.htm

[4] https://www.statista.com/statistics/262858/change-in-opec-crude-oil-prices-since-1960/

An additional important measure during a linear regression is significance. The coefficient World trade volumes has a p-value less than 0.01, indicating that the coefficient is statistically significant at 1 percent level. The probability that there is a relationship between the variables is very high in this analysis. On the other hand, the coefficient Crude oil prices is not statistically significant. The p-value equals 0.07 which means that the coefficient is significant at the 10 percent level. This level of significance does not indicate a strong relation. The main reason for this low significance is the small number of observations in the dataset.

4.3.3.2 World trade value

Table 3 presents the results of the linear regression analysis. According to the results, the correlation between maritime CO_2 emissions and world trade volumes is positive, with a coefficient of 0.371. This coefficient indicates that a 1 percent increase in world trade value results in a 0.371 percent increase in total CO_2 emissions. Initially, this looks quite straightforward. An increase in the overall world trade volumes has a significant impact on the maritime industry. The demand for containers and shipping will increase which eventually will lead to an increase in the total CO_2 emissions within this industry.

4.3.3.3 Crude oil price

Table 3 pictures that the correlation between maritime CO_2 emissions and crude oil price is negative, with a coefficient of -0.048. The coefficient explains that a 1 percent increase in crude oil price results in a decrease of 0.048 percent in total CO_2 emissions. If crude oil prices increase, conventional maritime fuel costs also increase. In response, vessel owners switch to different types of fuels which are in general more sustainable resulting in lower carbon dioxide emissions. Figure 14 suggests that the biofuel prices show little response to changes in crude oil prices. If crude oil prices increase, the selling price of biofuels barely change which makes this fuel more attractive. However, figure 4 shows that the production cost and therefore the selling price of biofuels in comparison to conventional fuels are significantly higher. This will imply that, the transition to biofuels is not very common for many vessel owners. This explains that the coefficient in table 3 is still very low. However, when the selling price of biofuels becomes more competitive, this coefficient will increase.

4.3.4 Scenario elaboration

The regression analysis pictured in table 3 has calculated the correlation coefficient between total CO_2 emissions in the maritime industry as dependent variable and world trade volumes and crude oil prices as independent variables. By knowing the coefficients, an analysis of the scenarios can be proceeded, presented in table 4.

Table 4 relative change in CO_2 emissions per scenario in 2024

Change in total CO_2 emissions in 2024; cumulative percentage change compared to 2018 – million metric tons in 2024	***Global volume +***	***Global volume -***
Crude oil prices +	4,95%	3,09%
Crude oil prices -	5,84%	3,99%

Table 2 shows the projected relative changes in global world trade and crude oil prices in 2024. By multiplying these relative changes with the coefficients depicted in table 3, the results in table 4 are obtained.

According figure 6 is the total CO_2 emissions in 2018 equal to 145.34 million metric tonnes. However, this number does not take into account retrofitting or retirement of vessels stimulated by EEXI and CII. Chapter 3 shows that 19 percent, including the most inefficient vessels of the overall fleet, will improve their energy efficiency with 0.65 percent. The total CO_2 emissions in 2024 will be 145.16 million metric tons, including retrofitting or vessel retirement. Table 5 shows the projected carbon dioxide emissions in 2024 per scenario including energy efficiency improvements and the estimated relative changes shown in table 4.

Table 5 projected CO_2 emissions in 2024 per scenario in million metric tonnes

Projected CO_2 emissions in 2024 per scenario in million metric tonnes	***Global volume +***	***Global volume -***
Crude oil prices +	152.35	149.65
Crude oil prices -	153.64	150.95

In order to achieve the climate goals, the required volume of biofuel in liters, outlined in the appendix, is calculated using an emission factor (Lijst emissiefactoren | CO2 emissiefactoren, 2023). This measurement is expressed in kg CO_2 / L biofuel. Figure 15 illustrates the amount of carbon dioxide reduction necessary to prevent the tipping point. By dividing this value by the emission factor, the total volume of biofuel required is calculated as shown in the appendix.

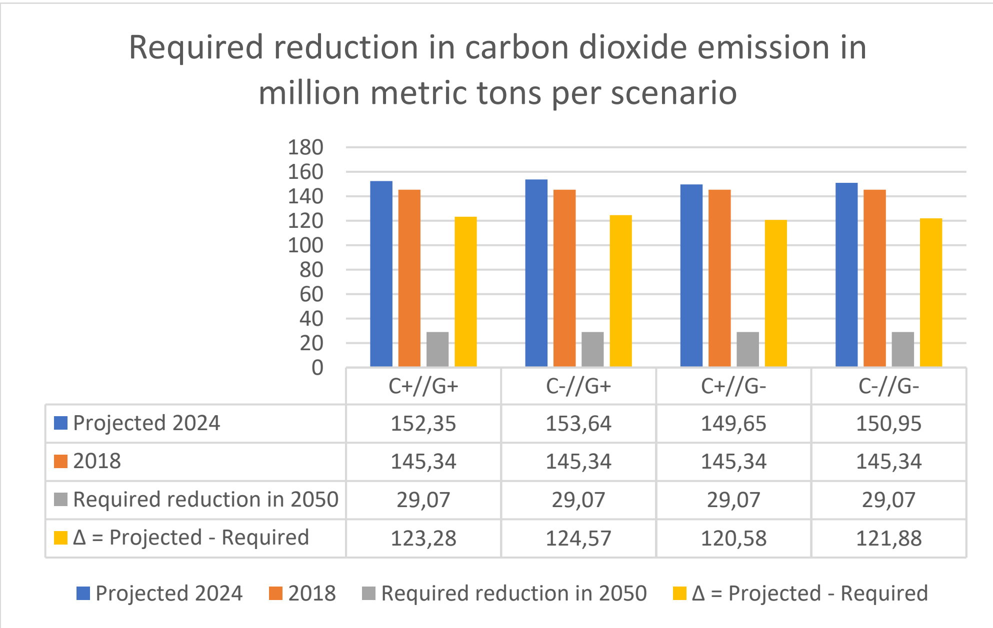


Figure 15 required reduction in carbon dioxide emissions

The subsequent section will delve into each scenario. These scenarios will provide an analysis of their likelihood to occur and their underlying reason why

4.3.4.1 Crude oil prices + // Global volume +

This scenario is likely to happen when the global economy grows. Growth in the global economy results in larger world trade volumes due to higher consumer demand. As a result of higher trade volumes, there is a greater need to transport goods. An essential element for the transportation of goods is crude oil. The demand for crude oil, depending on the OPEC-countries, is highly likely to increase. For this scenario, both global trade volumes and crude oil prices follow the base case scenario. This results in a total projected CO_2 emissions in 2024 of 152.35 million metric tonnes.

This scenario project a significant increase in CO_2 emissions in 2024. Despite the high carbon dioxide numbers, the potential demand for biofuels for this scenario is favorable. High crude oil prices can lead to a transition to biofuels. The alternative fuels become more competitive in the fuel market due to higher crude oil prices. On top of that, more resources are available for the implementation of sustainable measures due to the fact the economy is growing. This environment is favorable for biofuel demand in the long run.

4.3.4.2 Crude oil prices + // Global volume –

Global trade volumes can lag behind due to disruptions in the global economy like the outbreak of the war between Russia and Ukraine (Unctad, 2022). During this war it can be hard for the world economy to recover. This has a major impact on the global trade volumes. An accompanied problem is the high inflation rates caused by these disruptions. For this scenario, global trade volumes follow a low case scenario. Despite the decreasing trade volumes, the prices in crude oil can still increase following a base case scenario. The cause of this can supply disruptions in oil caused by OPEC decisions. A second reason can be a low value of the U.S. dollar currency. This configuration results in a total projected CO_2 emissions in 2024 of 149.65 million metric tonnes, the lowest compared to other scenarios.

This scenario projects the lowest amount of carbon dioxide in 2024 compared to other scenarios. As a result of this relatively low projection, the urgency for a transition to alternative biofuels is lower compared to the other scenarios. On top of that, the conditions for this scenario are not optimal. The global economy shrinks, resulting into a decrease of resources available for a green transition.

4.3.4.3 Crude oil prices - // Global volume +

The global trade volumes are likely to increase when the world economy recovers well from the COVID-19 crises and the war in Ukraine as discussed in section 4.3.4.1, In that case, the global trade volume follows a base case scenario (Unctad, 2022). The increased global trade volumes go together with an increase in crude oil prices. However, the cumulative change in crude oil prices is smaller in comparison to section 4.3.4.1 according to table 2. For this scenario, the selected case for crude oil prices assumes the low change in prices. Periods of geopolitical stability and reduced tension can contribute to downward trends in crude oil price. On top of that, an increased transition to alternative biofuels and advancements in energy efficiency can result in a downward shift to demand for crude oil. This downward shift may lead to lower crude oil prices, which makes conventional fuels more attractive in the short run. This relatively smaller change in crude oil prices and corresponding changes in global trade volumes resulting in 153.64 million metric tonnes CO_2 projected in 2024.

This scenario projects the highest amount of CO_2 emissions compared to other scenarios. Despite the highest projections in carbon dioxide emissions and lower crude oil prices, this scenario will pay off in the long run. By the implementation of mandatory incentives discussed in the literature review the demand for conventional fuels will not increase despite the low crude oil prices. This, in combination with a growing economy, resulting in more available resource to provide sustainable measures, creates an environment which is favorable for biofuel demand in the long run.

4.3.4.4 Crude oil prices - // Global volume -

As discussed in section 4.3.4.2, global trade volumes can lag behind due to a difficult recovery of the global economy due to the COVID-19 crises and the Ukraine war in combination with high inflation rates. Decreased global trade volumes can impact economic conditions worldwide, resulting in reduced oil consumption. These interconnected markets influence each other. Lower oil consumptions causes a reduction in demand for crude oil resulting into lower crude oil prices. For this scenario, both variables follow a low case scenario, resulting in 150.95 million metric tonnes CO_2 projected in 2024.

This scenario projects a relatively low amount of carbon dioxide in 2024. Like discussed in section 4.3.4.2, the low projection does not benefit demand for alternative biofuels. Furthermore, the environment for biofuels is even worse than section 4.3.4.2. This scenario depicts an environment which is less favorable for demand of biofuels in comparison to other scenarios.

4.3.5 Key findings

The projected carbon dioxide emissions in 2024 and conditions for projections of the global economy, make clear how demand will evolve in the next few years. The results of the scenarios show that there are two favorable and two less favorable scenarios, considering future demand for alternative biofuels. Section 4.3.4.1 and 4.3.4.3 demonstrate the most favorable scenarios. Remarkably, in both scenarios, global trade volumes increase, which is an important indicator for a growing global economy. This growing economy results in greater availability of resources for a green transition in the fuel market. Furthermore, the implementation of mandatory incentives will have a major impact on demand for conventional fuels. When incentives suppress conventional fuels, fluctuations in crude oil prices, like in the scenarios, become less important. However, an increase in crude oil prices stimulates the usage of alternative biofuels. The scenarios which are not very promising are discussed in section 4.3.4.2 and 4.3.4.4, both scenarios show a decline in the global economy growth rates assuming a diminishing probability of a green transition.

Despite the comprehensive analysis conducted through scenarios, the outcomes do not differ significantly. Governments, especially in Europe, increasingly stimulate the transition to green fuels through MBMs. Vessel owners that do not participate in this transition will face negative financial consequences. As a result of these incentives, the demand for alternative biofuels will increase regardless of economic conditions. However, certain conditions like mentioned in the scenarios will stimulate the transition to biofuels and increase demand. Nonetheless, the share will not be significant.

Figure 16, 17, 18 and 19 in the appendix show how many liters of biofuel are necessary to avoid the tipping point of 1.5 °C. This shock in demand, to prevent reaching the tipping point is significant. In comparison to the projected total number of liters of alternative biofuel consumed in 2024 shown in figure 1, there is work to be done. An increase of more than 250 percent in biofuel consumption is necessary to reach to IRENA goals in 2050 for the most favorable scenario. This gives answer to the question how projected demand for alternative biofuels in the future will be affected by certain indicators. These estimations are based on a 100 percent blend rate of biofuels during combustion. However, in the current biofuel market, this is rarely implemented. Blend rates of 20 to 50 percent are more common. As a result, the required biofuel consumption to prevent reaching the tipping point will double or quintuple with lower blend rates. Since a 100 percent blend rate already requires a huge shock in consumption patterns for biofuels, achieving the required quantities to prevent the tipping point with 20 and 50 percent blend rates will be very challenging.

In the short term, it is very likely that bio-LNG and bio-diesel will be mostly consumed, mainly with blend rates between 20 and 50 percent. The main reason for the high shares of these biofuels is competitive to conventional fuels. As depicted in figure 5, the production costs of biofuels are relatively competitive. The opposite applies for bio-methanol and bio-ethanol. However, the expectation are that those biofuels will continue to develop in the future, resulting in increasing market shares. As a result, not only one biofuel will dominate the market. The mentioned biofuels in this study will each have their own share on the market. Therefore, the required carbon dioxide reduction will be achieved more easily. The potential of biofuels is tremendous in light of the Paris Agreement goals, prevent reaching the tipping point of 1.5 °C. The fuels become even more attractive when they continue to evolve and become more competitive which can be stimulated with the discussed incentives. Resulting in a significant increase in demand for biofuels in the future.

5.Discussion

This chapter will discuss the findings of this study. By restating the research objectives and questions, the purpose of the research will be highlighted. Following that, key findings will be discussed and interpreted, how relevant and significant are the results in order to answer the research objectives. Given the fact that every set of results show imperfections, it is crucial to address the limitations of the results in this chapter. After discussing the limitations it becomes clear what can be further explored to strengthen the research, which will also be discussed during this chapter. In conclusion, this chapter provides a comprehensive analysis of the findings to summarize the research.

5.1 Key findings

Finally, the analysis of market potentials for alternative biofuels based on the criteria; feasibility, market evolutions and future projections reveals key findings. In the last couple of years, fluctuations in demand and limited competitiveness caused limited growth rates in alternative biofuel usage in the maritime market. However, there is room for improvement and turn the tie to an upward trend with the right conditions.

Environmental and economic indicators show the strengths and weakness of four different biofuels. Bio-diesel and bio-LNG show great potential in the short run. On the other hand, the long run potential is limited due to decreasing economic performances. Bio-methanol and bio-ethanol are very promising for the future. However, it really depends on their developments in production pathways. The market evolutions of the maritime industry in the past show a decrease in CO_2 emissions, although this decline is not attributed to a green transition to alternative biofuels. The average fuel consumption per transport work has decreased during the period of 2018 and 2021. The scenarios which have analyzed the potential future projections of alternative biofuels show both favorable and less favorable conditions for demand shocks for alternative biofuels. Global trade volumes and mandatory incentives play a significant role for future projections. Achieving the necessary volumes to prevent the tipping point of 1.5 °C is a very challenging task. The task will become very challenging with very low alternative biofuel blend rates during combustion. The implementation of other energy efficiency measures is crucial to prevent reaching the tipping point.

Nevertheless, the potential of alternative biofuels based on specific criteria remain very high, particularly with mandatory incentives, a growing economy and ongoing development.

5.2 Limitations

A limitation of this analysis is that synthetic alternative maritime fuels, also known as e-fuels, are ignored. A great example of an e-fuel is hydrogen, this maritime fuel will be obtained from sustainable sources like wind, solar and nuclear power. The main reason for not including the e-fuels in the analysis is that the production pathways are not mature. This results in extreme high production and fuel cost which makes them anything but competitive. However, the development of these e-fuels is highly uncertain, making it very difficult to predict their feasibility indicators. Therefore, there are arguments in favor and against including those e-fuels in this analysis. In this analysis it will be assumed that only biofuels will be used in the short run. However, the synthetic fuels have a high potential to significantly reduce CO_2 emissions. This could greatly impact the future outcome in terms of required amount of biofuels necessary to achieve climate goals. Furthermore, environmental performance indicators are based on existing literature studies. Through Research and Development, performance indicators can improve over the years which can alter the outcome of the analysis. The same applies for the economic performance indicators, those rely on projections which are influenced by changes in economic stability resulting from geopolitical situations.

The limitation regarding the second criteria is that the EMSA\THETIS-MRV dataset only focuses on the EU. Although the market incentives to stimulate biofuels also work on a EU scale, a problem arises. The objective of IRENA is to reduce the global CO_2 emissions with 80 percent in 2050. Due to market incentives in Europe, vessel companies may decide to operate outside of Europe as production cost will increase. Outside of Europe, vessel companies can operate under cost minimization, associated with very polluting fuels. This phenomenon is known as carbon leakage. Within this analysis results do not take into consideration this phenomenon. A good example of carbon leakage can be explained through vessel retirement. Due to the implementation of mandatory incentives in Europe, certain ships are required to undergo energy efficiency measures to meet policy objectives. For older ships, the cost associated with retrofitting can be significant, whereby ship owners decide to sell their vessel. Subsequently, those vessels will be purchased by ship owners in developing countries where climate policies are less strict. As a result, the emissions reduced in Europe will be overshadowed by developing countries which continue to operate with unsustainable vessels. If carbon leakage were taken into account during this analysis, the findings of this study could be different. An additional second limitation for this criteria is the incompleteness of certain indicators in the EMSA\THETIS-MRV dataset. For more than half of the datapoints, the annual fuel consumption per transport work was unavailable in the dataset. As a result, the calculations pictured in figure 10 may be skewed and incorrect. An additional limitation is that the analysis only focuses on CO_2 emissions, whereas, during the combustion of biofuels many other harmful substances are emitted. During the combustion of bio-LNG a significant amount of methane is emitted which is more harmful to the environment than CO_2 in the context of GWP. If during this analysis, other emissions were taken into account, the environmental performance indicators could potentially look different resulting into different market potentials.

The third criteria pertains to limitations associated with the figures demonstrated in the appendix, concerning the quantity required to prevent achieving the tipping point. This analysis assumes that the entire shipping industry uses only one alternative biofuel. However, it is much more likely that the discussed alternative biofuel in this research will be combined among different vessel companies. Resulting into less required liters biofuel, the quantities will be distributed based on feasibility criteria to ensure a balanced distribution. However, this does not impact the overall demand for biofuels. The last limitation for this analysis is related to operational energy efficiency measures. This analysis takes into account energy efficiency improvements due to the implementation of EEXI. This reduction is based on existing literature numbers. Besides the implementation of alternative biofuels vessel owners can retrofit their vessels in various ways. During this analysis, not enough consideration is given to this aspect. The required volume of biofuel necessary can significantly reduce when vessels find different ways to improve their overall energy efficiency.

5.3 Recommendations for further research

For further research, it is important to take e-fuels into account. Those fuels will have such a big impact on the overall shipping market that researching this topic is highly relevant. On top of that, the impact of EEXI should be investigated, to understand the overall effects on the energy efficiency of vessels resulting in a decrease of CO_2 emissions. Lastly, it is very relevant to examine the global potential of biofuels. The potential at a global level can differ significantly from the EU-level. This difference can be attributed to the absence of global incentives and carbon leakage.

6.Appendix

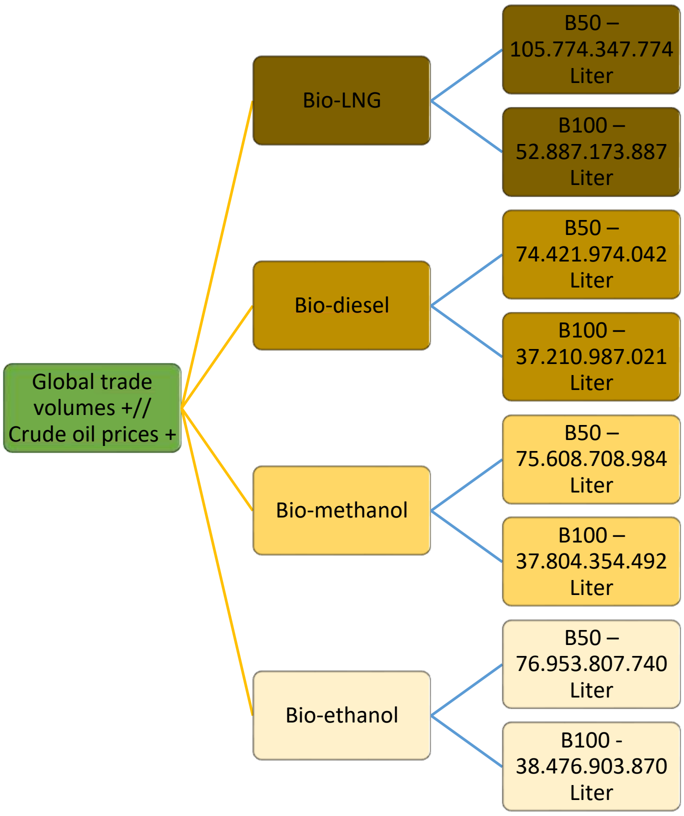


Figure 16 the most promising scenario for biofuel demand

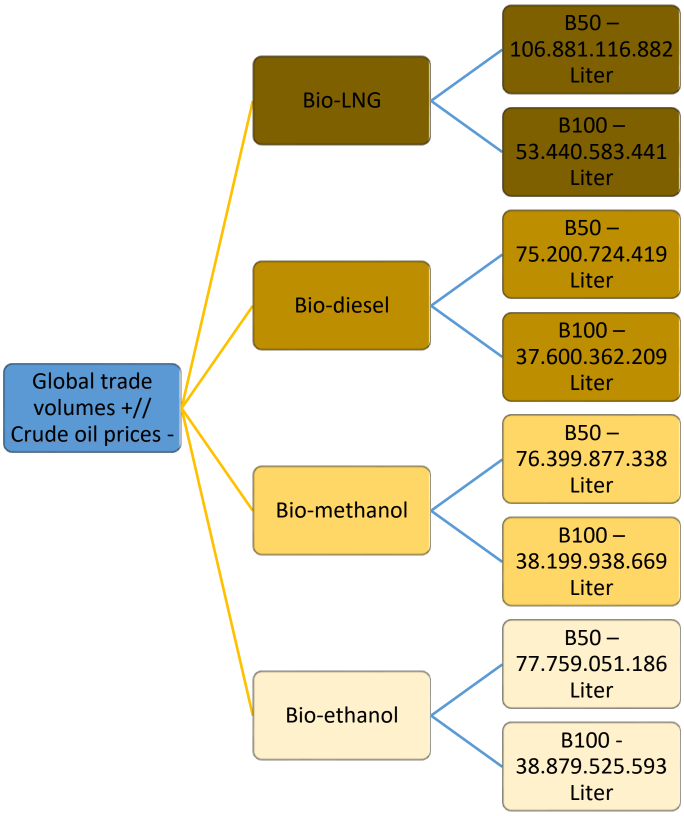


Figure 17 a scenario which is likely for biofuel demand

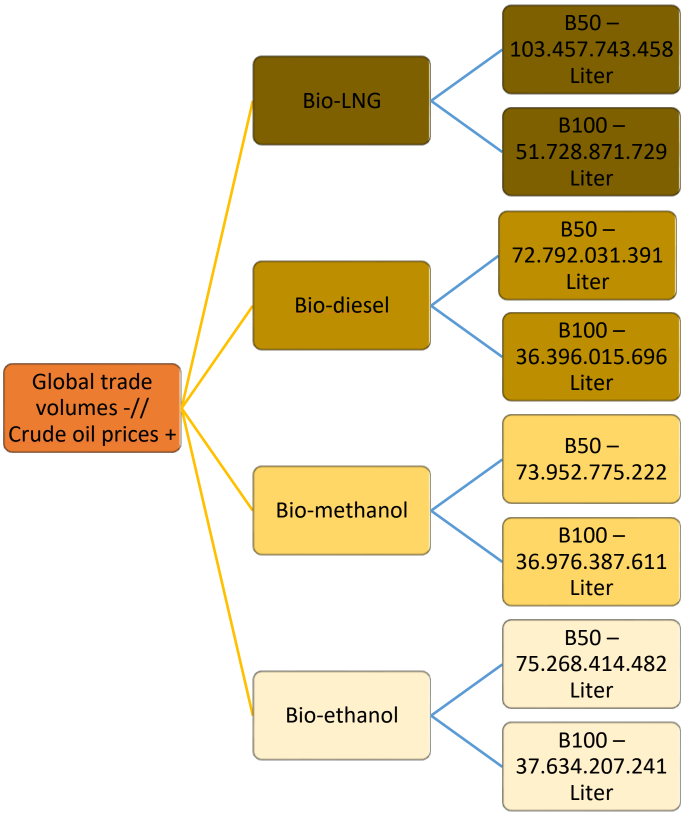


Figure 18 a scenario which is not promising for biofuel demand

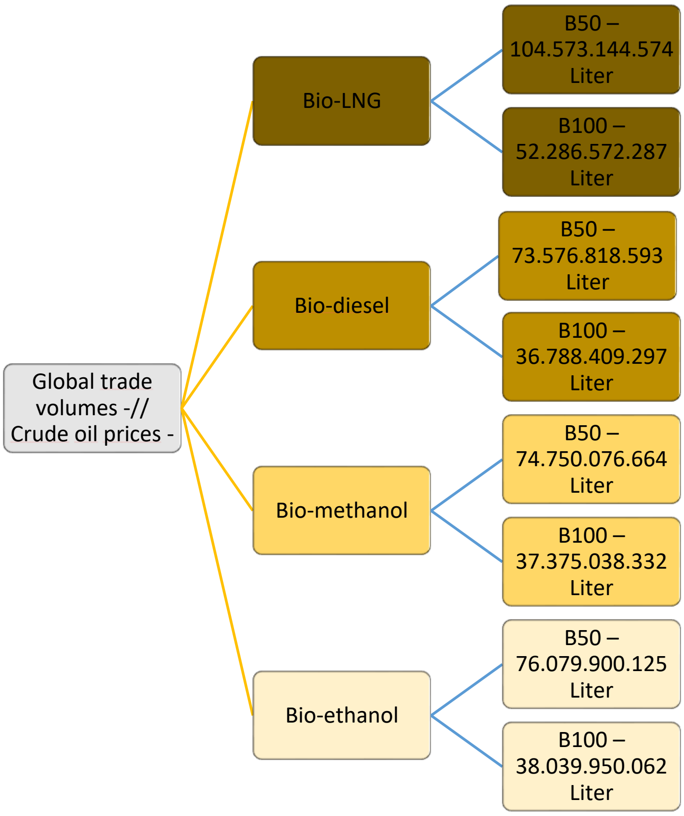


Figure 19 the least promising scenario for biofuel demand

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