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# Sustainable shipping: Pathways to Decarbonize the Maritime Industry

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**Abstract**

The maritime industry has a considerable impact on global trade. Statistical data shows that marine transport accounts for around 80% of global commerce volume and more than 70% of total value. Despite playing a major role in international trade, the shipping industry accounts for around 3% of worldwide manmade emissions of greenhouse gases (GHG), which will likely grow in the next decades. Still, cutting emissions is proving challenging due to the industry's significant reliance on fossil fuels, particularly heavy fuel oil (HFO), which produces high levels of CO2 and other pollutants. With mounting pressure to combat climate change, the industry needs to transition toward sustainable practices and start decarbonizing its operations.

Thus, based on research papers, emerging technologies, ambitious projects by stakeholders, case studies and interviews, this thesis seek to identifies possible solutions and opportunities to help accelerate the transition to clean energy. The qualitative research method was used to collect and analyse data. Semi-structured interviews will be arranged where participants are allowed to speak freely, and data will be recorded.

This research project showed that as challenging as it may seem, achieving net-zero GHG by 2050 is possible through a multifaceted approach to decarbonisation. Technologies and measures are being developed and are available that can significantly curb GHG. This project has some recommendations and solutions that can help fast-track a company's transition to green energy by 2050.

Language: English, Key Words: GHG (green house gas emissions), carbon capture technology, carbon intensity index, EU emissions trading system

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# 1 Introduction

Maritime transport is vital for our global economy and about 80% of traded cargo worldwide is transported by ships which continues to rely heavily on fossil fuels. With the current situation, greenhouse gas (GHG) emissions from ships will continue to grow if no action is taken. In 2019, 11.08 billion tonnes of commodities were carried by sea, an 85% increase since 2000, nearly entirely powered by fossil fuels. Heavy fuel oil (HFO), which is effectively refinery waste, accounts for 79% (Balcombe et al, 2019). Thus, based on several normal operations scenarios, maritime CO2 emissions levels in 2050 are expected to grow by 50 to 250% compared to 2012 levels. Given the above statistics, the scope of the decarbonization issue in marine transport is so huge, yet there is presently no legal deadline for the complete decarbonization of the shipping sector. At this rate, if nothing is done, the emission level will double or even triple by 2050 (IMO 2015).

## 1.1 Background

Reducing the carbon footprint in the maritime industry has become a hot topic given that the maritime industry produces about 3% of the global GHG emissions. If nothing is done, this amount might double or even triple by 2050. To the best of our knowledge, there have been several studies on emission reduction, future and available technologies, alternative fuel for the maritime industry. For example, there is a review of the literature on alternative marine fuels, this study focuses only on alternative fuels and no other strategies to curb GHG emissions (Linstad E, Rialland A, 2020). Also, another study focused on examining possible technological and operational measures to reduce carbon emissions in the marine industry. This study aimed to provide a broader array of methods for improving energy efficiency and reducing emissions in the shipping industry (Pariotis et al, 2016).

Research and studies into greener fuel for the maritime industry will only grow given the urgent need to reduce the carbon footprint. As seen above, there are many viable options already which are good since no single fuel source can be the solution (Pariotis et al, 2016).

## 1.2 Research Objectives.

This research work intends to assess the current environmental impact of the maritime industry to identify and evaluate the key technological pathways for decarbonization, the role of international and regional policies and to explore the economic and infrastructure barriers to decarbonization in the maritime industry. The research question adopted for this thesis is “What are some of the most effective pathways and strategies for decarbonizing the maritime sector and how technological innovations and policy frameworks can be leveraged to achieve sustainable shipping?

## 1.3 Scope and limitation

This study is limited only to the maritime industry. Although reducing carbon footprint is a global issue for nations and different business industries, this research is specifically focused on the different technologies, alternative fuels, and policy frameworks that are available for the maritime industry to achieve deep decarbonization by 2050. Also, the findings from this research are not generalizable due to the small size of participants in the interview. This suggests that the findings of this thesis may only provide a limited insight into the broader context.

## 1.4 Task sharing

Our collaboration on the thesis heavily relied on task sharing and teamwork. Our division of roles has been successful because we used our personal strengths to our advantage. My partner explores advanced emission reduction technologies and operational measures while I conduct analyses of related policy frameworks and alternative fuels and energy sources. We both sent out emails to prospective participants for the interviews and conducted interviews separately with different participants at different times and places. Our research benefits from increased efficiency through our strategic division of tasks, which allows us to approach the complexities of our thesis from various perspectives. Through our consistent meetings, we maintain alignment in our work and this results in a stronger and more complete thesis.

# 2 Regulatory Framework and Policy Measures

The maritime industry has become the centre of the debate over environmental sustainability. Shipping, like other sectors of the economy, emits greenhouse gases and must reduce its carbon emissions. Worldwide shipping accounts for almost 3% of global GHG emissions, despite transporting over 80% of global goods by volume. Shipping generates minor amounts of GHG emissions per unit of transport, but without intervention, emissions from this sector are expected to rise from 90% of 2008 levels in 2018 to 90-130 % by 2050 (IMO, 2020). The International Maritime Organization is the primary regulatory body governing the global maritime industry. It is responsible for the safety, security, and environmental performance of the shipping industry. It is very critical in shaping the future of the maritime industry. To better understand why decarbonization is a big topic in the maritime industry, it is necessary to look at the impacts of emissions from ships.

## 2.1 Impacts of the maritime industry on climate change

The operation of marine transportation involves the consumption of fuel, which is burned t o provide propulsion for ships and therefore releases harmful gases such as SO2, NO2, and CO into the environment. The complex interplay between marine operations and their envi ronmental repercussions is a significant and urgent issue that goes beyond the boundaries o f the seas they sail in.

### 2.1.1 Effects On Climate Change

Ships emit carbon dioxide (CO2) from the burning of fossil fuels, which is a significant gre enhouse gas that contributes to global warming and climate change. Shipping accounts for around 3% of worldwide carbon dioxide (CO2) emissions. In addition to carbon dioxide (C O2), the industry also emits other detrimental gases like methane (CH4), nitrous oxide (N2 O), and black carbon. While these gases make up a lesser proportion of overall emissions, t hey enhance the greenhouse effect, resulting in global warming, higher sea levels, severe w eather events, and other consequences associated to climate change (Sinay, 2024).

### 2.1.2 Effect on the atmosphere (Air Pollution)

Shipping operations produce emissions that contribute to air pollution in coastal regions and port towns. These emissions may also be carried inland by prevailing winds, affecting human health. Particulate matter (PM), sulfur oxides (SOx), and nitrogen oxides (NOx) have the potential to cause acid rain and worsen respiratory ailments and other disorders. Nitric oxide (NOx) chemically combines with ammonia to produce nitric acid vapors and particles that have the ability to rapidly enter lung tissue, resulting in its damage and, in severe instances, leading to premature death (Sinay, 2024).

### 2.1.3 Effect on the Ocean

The carbon dioxide (CO2) released by the maritime industry and its other operations related to the marine industry is not just absorbed by the atmosphere, but also by the bodies of water. This process leads to ocean acidification, which may have detrimental consequences on marine ecosystems, worsening problems associated with water pollution. Organisms that depend on structures made of calcium carbonate, such as coral and shellfish, are particularly susceptible to harm. The consequences have a far-reaching influence on marine animals and fish, affecting the variety of species and disturbing the fragile balance of aquatic ecosystems. More generally, there exists a possible danger to the stability of food availability (Sinay, 2024).

Given the effect of maritime emissions on our planet, and to achieve decarbonization and prevent disastrous levels of global warming, the International Maritime Organization (IMO) is playing a crucial role in implementing and adopting regulatory obligations for the decarbonization effort.

## 2.2 International Maritime Organization (IMO) Regulation

Since the 1960s, the International Maritime Organization (IMO) has worked to mitigate the negative impact of shipping on the environment. The MARPOL convention, established in 1973, serves as the foundation for environmental protection in the sector (IMO, 2001). However, IMO regulatory obligations are of utmost importance in the endeavour to reduce carbon emissions and enhance energy efficiency within the shipping industry. Since 2011, after the implementation of several short-term measures, the International Maritime Organization is presently devoting its efforts to comprehensive impact assessments on states and medium and long-term measures. IMO convened the 80th session of the Marine

Environment Protection Committee (MEPC 80) in July 2023, wherein it adopted a Revised Strategy featuring increased levels of ambition (IMO, 2023a, Annex 15).

### 2.2.1 The International Convention for the Prevention of Pollution from Ships (MARPOL)

Within MARPOL Annex VI, the level of Sulphur of any fuel used aboard could not exceed 4.5%, while in the Baltic Sea area, this restriction was reduced to 1.5%. Higher levels of sulphur were permitted provided an authorized exhaust cleansing system was utilized. The waste products from these systems were not permitted to be released into enclosed ports or comparable areas of waterways except they could be certified as safe. The supplier was additionally mandated to document the Sulphur level of the fuel (IMO, 2001).

### 2.2.2 Energy Efficiency Design Index (EEDI)

The Energy Efficiency Design Index (EEDI) was included into MARPOL in 2001 [1]. The EEDI is a tool that ship owners and operators may use to assess the possible effect of management changes on new ships. It allows them to make better-informed decisions by providing a means to evaluate different possibilities. Therefore, the Energy Efficiency Design Index (EEDI) decreases carbon dioxide (CO2) emissions via enhancements in technological efficiency. The EEDI, is the first worldwide guideline that establishes requirements for CO2 emissions [18]. According to the International Council of Clean Transportation (ICCT), it is projected that not all ships worldwide will meet the requirements of the EEDI rules by the years 2040-2050 (J Dong et al, 2022).

### 2.2.3 Energy Efficiency Operational Index (EEOI)

The IMO wants the Energy Efficiency Operational Indicator (EEOI) to be used to measure how efficient ships already are. Anyone can use it, but it's not required. The EEOI is the amount of CO2 released per unit of work done on transportation (a "capacity mile"). The index looks at how much fuel was used and how much CO2 was released. It does this by counting all the fuel used at sea and in port during the time, by both main and auxiliary engines, as well as boilers and incinerators (George M, & Elias A Y, 2021).

### 2.2.4 Ship Energy Efficiency Management Plan (SEEMP)

Applicable to both new and existing ships, the Ship Energy economy Management Plan (SEEMP) is a management strategy that increases energy efficiency via operational enhancements. Existing ships must have SEEMP. Among the enhancements provided by SEEMP include greater frequency of hull or propeller cleaning, improved vessel speed, and even alternative route options (including avoiding bad weather) to reach a destination. It should be highlighted that SEEMP is particular to a ship because it considers elements such as cargo, routes, dry docking schedule, and more general corporate or fleet-level tactics (UNCTAD, 2023).

### 2.2.5 Carbon Intensity Index (CII)

Ships with a gross tonnage (GT) above 5000 are obliged to report their yearly operating carbon intensity indicator (CII) as per the proposed regulations. The CII calculates the yearly reduction factor required to guarantee ongoing improvement of the ship's operating carbon intensity within a designated rating level, which ranges from A to E. Unlike the EEXI, the CII is a practical and immediate measure. The performance of the CII will be documented in the ship's SEEMP (UNCTAD, 2023).

### 2.2.6 Market-Based Measures (MBM)

Given the expected growth of the shipping sector, relying solely upon operational and technological measures would not be sufficient to decrease GHG emissions. Therefore, implementing market-based measures (MBM) as part of a comprehensive plan will be necessary to achieve the IMO objectives. Stakeholder conflicts have caused delays in discussions, like programs aimed at reducing CO2 emissions. The talks for the Market-Based Measures (MBM) started at the 56th session of the Marine Environment Protection Committee (MEPC) in 2006 but encountered a halt during the 65th session of the MEPC in 2013. The objective of implementing measures based on economic considerations and/or taxes in the maritime sector is to reduce fuel consumption by promoting investments in ships that are fuel-efficient, advanced technology, and energy-efficient operations. Also, compensates for the increasing emissions from the shipping sector in other sectors (George M, & Elia AY, 2021).

## 2.3 European Union (EU) Regulation

Shipping contributes to approximately 25% of all transport-related CO2 emissions in the European Union. To reduce greenhouse gas emissions, the European Union has advocated for the most proactive legislation and policies. The "Fit for 55" initiative, which the European Union (EU) intends to implement, encompasses a range of regulatory policies.

These include the Fuel EU Maritime Initiative, the Energy Taxation Directive, and the Renewable Energy Directive.

### 2.3.1 EU Emission Trading System (EU ETS)

Since its establishment in 2005, the EU ETS has functioned as the dominant carbon market globally. The EU Green Agreement pledged to incorporate shipping into the EU ETS by 2020. This was reaffirmed in July 2021 by the EU's "fit for 55" program (European Commission, 2021). The proposed EU emissions trading plan stipulates that vessels exceeding 5000 gross tons and exclusively operating within the EU shall be responsible for paying for all carbon dioxide emissions. However, vessels entering and exiting the EU shall be obligated to pay for 50% of their carbon dioxide emissions, irrespective of the portion of the voyage occurring within or outside the EU (Shi, 2016; Christodoulou et al., 2021).

The European Parliament ratified its version of the legislation on June 22, 2022. The assembly substantially revised the Commission's proposition in the text. The most significant is shipping, which proposes modifying the number of voyages between EU and non-EU ports. This substantially broadened the EU ETS's influence beyond the borders of Europe. Its objective is to reduce greenhouse gas emissions further, but the increase in compliance costs will undoubtedly have a negative financial impact on the transport industry. Moreover, the European Parliament's version eliminates the phased implementation period and applies the ETS to all emissions beginning in 2024, at a rate of 100 percent.

The positions on the ETS proposal have been made by both the European Parliament and the Council. However, there remain certain matters that require agreement between the two institutions and the Commission prior to the proposal being enacted into law during the subsequent legislative procedure (European commission, 2021).

### 2.3.2 Fuel EU Maritime Initiative

To encourage vessels docking at European ports to implement renewable marine fuel and zero-emission technology, the Fuel EU Maritime Program will establish a maximum emission content limit for the fuel used by vessels. The European Union intends to enforce increasingly stringent regulations on the greenhouse gas intensity of marine fuels beginning in 2025. Additionally, the EU has established distinct objectives for the reduction of greenhouse gas emissions: 2% by 2025, 6% by 2030, 13% by 2035, 26% by 2040, 59% by 2045, and 75% by 2050 (Cullinane and Yang, 2022).

The Fuel EU Maritime Initiative is anticipated to have a significant influence on the advancement of zero-emission technologies and sustainable marine fuels. This includes the development of electronic liquids, decarbonized gases (including biological LNG and electronic gases), liquid biofuels, hydrocarbons, and fuels derived from hydrocarbon (European Commission, 2021).

### 2.3.3 Energy Taxation Directive

The EU plans to gradually eliminate the fossil fuel tax exemption policy in the shipping sector and reintroduce taxes on fossil fuels used in transport. Additionally, a minimum tax rate will be established. According to the preceding stipulations of the Directive, marine fuels are free from taxation inside the European Union. Starting in January 2023, a tax will be imposed on all maritime fuels that are sold and consumed inside the European Union (European Commission, 2021). Consequently, marine fuels that have significant pollution will be subject to the highest taxation. As an example, when conventional fossil fuels are used as energy sources, they will be subjected to a higher taxation rate, namely 10.75 euro per gigajoule (GJ). When using advanced sustainable biomass fuels and non-biomass renewable fuels such as green hydrogen, they may be subject to the lowest tax rate of 0.15 euro/GJ (Duscha and del Rio, 2017; Voulis et al., 2019).

### 2.3.4 Renewable Energy Directive

The Renewable Energy Directive has established a more ambitious objective of achieving 40% renewable energy by the year 2030. Specifically, a reduction of 13% in greenhouse gas (GHG) emissions is necessary in the transport sector. The implementation of these new objectives will enhance the need for green hydrogen in the transportation industry (Kohl et al., 2021). The plan further seeks to advance the use of renewable fuels to achieve the highest possible reduction in greenhouse gas (GHG) emissions. It establishes a goal of reducing carbon emission intensity in the transportation sector, which includes international aviation and marine fuels, by 13%. The desired threshold for advanced biofuels in the transportation sector has been increased to 2.2% of energy consumption. Additionally, a goal of 2.6% has been established for hydrogen and hydrogen-based synthetic fuels in this industry. The Directive just establishes objectives, whereas more precise and closely correlated measures such as the EU ETS, Fuel EU Maritime Initiative, and Energy Taxation Directive are designed to assist in their attainment (European Commission, 2021).

## 2.4 National and Regional Measures and Efforts

### 2.4.1 Norwegian Government

The Norwegian government, a prominent figure in the worldwide effort to make shipping more environmentally friendly, has set a target of reducing carbon emissions from domestic shipping and fishing vessels by 50% by 2030. They are committed to furthering the sustainable growth of the shipping industry by implementing laws, strategic planning, providing financial assistance, and employing other methods. Norway has developed a comprehensive and enduring strategy to provide subsidies and tax incentives for the acquisition of eco-friendly vessels. In 2019, Norway's national budget established a dedicated fund to facilitate the implementation of low-emission and zero-emission initiatives for high-speed passenger ships. This money was used as a subsidy by local governments to acquire environmentally friendly high-speed ships. By July 2020, the Norwegian government mandated that all ships navigating the Norwegian Fjord region, a designated world heritage site, must achieve complete emission reduction by 2026. This initiative establishes the Norwegian fjord area as the world's first zero emissions zone for ships. The GreenVoyage-2050 project was initiated in November 2020 by the International Maritime Organization (IMO) in collaboration with the Norwegian government. As part of this initiative, the Norwegian government contributed an extra $4.3 million to the IMO. The project's objective is to facilitate the decarbonization of the shipping sector in alignment with the International Maritime Organization's first plan for decreasing greenhouse gas emissions from shipping (J.Dong et al, 2022).

### 2.4.2 UKs Government

The latest emission reduction target disclosed by the UK government in its sixth carbon budget on April 20, 2021, is a 78% reduction in carbon dioxide emissions relative to 1990 levels by 2035. The United Kingdom implemented a national carbon budget that incorporated international shipping and aviation for the first time ever. Furthermore, the UK Shipping Office for Reducing Emissions will receive 206 million pounds from the UK Ministry of Transport in support of government research initiatives. The purpose is to support innovative businesses and provide funding for British firms to conduct research and development on maritime emission reduction technologies (J.Dong et al, 2022).

### 2.4.3 Singapore government

The Singapore Maritime and Port Authority (MPA) is the primary organization advocating for the maritime industry's decarbonization reform in Singapore. The Singapore Maritime Green Initiative (MSGI), which MPA established in 2011, was designed to lessen the environmental impact of shipping and related activities. Within five years, MPA pledged to invest a maximum of one hundred million Singapore dollars in MSGI. The MSGI underwent an update in 2016, and in 2019, the duration of the initiative was extended to December 31, 2024. To establish a sustainable development strategy for the marine sector over an extended period, MPA unveiled the Singapore Maritime Decarbonization Blueprint 2050 in March 2022. The blueprint will prioritize the assistance of seven critical domains on the decarbonization of the maritime industry. To ensure its execution, MPA will contribute over $300 million (J.Dong et al, 2022)

### 2.4.4 Chinese Government

China actively adopts international shipping emission reduction regulations to promote the environmentally friendly growth of its shipping industry. China published in 2012 the Limits and Verification Methods for CO2 Emission of Operating Ships and the Limits and Verification Methods for Fuel Consumption of Operating Ships, both of which were based on the International Maritime Organization's practice of enhancing the design level of ship energy conservation and emission reduction via EEDI. Based on the "Ship Emission Control Area" (ECA) policy outlined in the MARPOL Convention, China initiated the implementation of ECA in coastal waters in 2015, in compliance with the Air Pollution Prevention Law. The Limits and Measurement Methods for Exhaust Pollutants from Ship Engines (China's first and second stages) were published by China in 2016 to impose stricter regulations on the emission of atmospheric pollutants from ships. The extent of water areas that can be utilized to regulate the sulphur content of fuel oil utilized by ships has been steadily expanded since 2017. The Measures for the Collection and Management of Energy Consumption Data of Ships were issued by the Maritime Safety Administration of the People's Republic of China in 2018. These regulations mandate that vessels with a main propulsion power unit of 750 kilowatts or more or a gross tonnage of 400 tons or more must collect data on fuel consumption, sailing time, mileage, cargo turnover, and other relevant factors in accordance with the prescribed methods and procedures. This establishes a groundwork for the development of a monitoring system for such data (J.Dong et al, 2022)

### 2.4.5 The US government

The state of California in the United States mandates the usage of shore power by law. In 2010, California enacted legislation known as the "Control of Toxic Air Pollutants Emission from Auxiliary Diesel Engines of Ocean-going Ships at Ports." This law requires container ships, mail ships, and refrigerated cargo carriers that travel to California ports to enhance their use of shore power while docked. As per the legislation, the shipping company's use of shore power while at a California port constitutes 50% of its total port affiliations from 2014 to 2016, 70% from 2017 to 2019, and will increase to 80% after 2020. If it does not satisfy the specified criteria, it will incur a penalty. As a result of implementing this legislation, the adoption of shore power at California ports has seen a substantial rise, surpassing 80% in 2020 (J.Dong et al, 2022)

# 3 Alternative Fuels and Energy Sources in shipping

The phrase "Alternative fuels" in relation to the shipping sector encompasses any fuels or energy sources that are not considered traditional for propelling ships. To be considered as next-generation fuels for industry, alternative fuels must meet certain criteria. These fuels should not include Sulphur and should have lower carbon, biogenic carbon, or zero-carbon levels compared to traditional marine fuels (Dr. Prapisala, 2020).

In contrast to the aviation and road transportation industries, the maritime industry consumes a relatively smaller quantity of refined and processed fuels. Heavy fuel oil (HFO) is the predominant fuel utilized to operate marine engines. HFO is extremely viscous and has substantial quantities of Sulphur, which emits hazardous SOx when combusted. Alternative fuels with reduced Sulphur content and viscosity, such as marine gas oil (MGO) and marine diesel oil (MDO), are employed in the maritime industry and still produces substantial amount of GHG. Marine gas oil is specifically designed for smaller vessels (Hsieh & Felby, 2015). Given all this, there is a need for alternative fuels to reduce GHG emissions drastically. At the United Nations Climate Change Conference (COP21) in 2015, several nations agreed to maintain the rise of global temperature to below 2 degrees Celsius (UNFCCC, 2016). Thus to meet greenhouse gas (GHG) emission reduction goals, the shipping sector must contemplate the use of alternative fuels.

According to Issa et al, the below table illustrates the contribution of alternative fuel and energy sources to curb GHG emissions ( Issa et al, 2019)

| Types of Alternative fuels | CO2 Emissions reduction |
|---|---|
| 1. LNG | 0 – 20% |
| 2. Ammonia | 0 – 100% |
| 3. Biofuels | 25 – 100% |
| 4. Hydrogen | 0 – 100% |
| 5. Fuel cells | 2 – 20 % |
| 6. Wind | 1 – 20% |
| 7. Solar | 0 – 12% |
| 8. Nuclear | 0 – 100% |
| 9. Electricity | 0 – 100% |

Figure 1. CO2 Emission reduction by using alternative fuel and energy sources (Issa et al, 2015)

## 3.1 Hydrogen ($H_2$)

Hydrogen is the most basic and least dense element and is very prevalent in nature. Hydrogen is often found in compound (bound to other elements) forms, such as water ($H_2O$) or methane ($CH_4$) , rather than in its pure form of $H_2$. To get pure hydrogen, these molecules need to be divided using energy. (Biert, et al., 2016). Hydrogen has been promoted as an optimal energy transporter for the future due to three significant and distinct benefits. Firstly, it may be generated from a diverse range of basic energy sources, such as fossil fuels, biomass, and non-biorenewable energy. it has the most substantial energy density when considering its weight. Consequently, it can deliver greater energy density per unit weight in comparison to conventional fossil fuels. Additionally, the primary by-products produced from the combustion of this substance are mostly water, with a little quantity of $NO_x$. By substituting the internal combustion engine (ICE) with a fuel cell, the only resulting waste will be water. Three distinct categories of hydrogen exist: (1) Grey hydrogen, which is derived from a fuel containing hydrocarbons and consequently produces $CO_2$ emissions; (2) Blue hydrogen, which is produced in conjunction with carbon capture technology; and (3) Green hydrogen, which is generated entirely from renewable energy sources and produces no emissions. Also, it is important to note that hydrogen can only be considered as a clean fuel if the technologies utilized in its generation and consumption are also clean (United Nations Environment Program (UNEP, 2006).

### 3.1.1 Hydrogen Availability and Production

As earlier mentioned, Hydrogen is the most abundant element on earth and is mostly found bonded to other elements. Thus to get pure hydrogen, it must be separated through certain processes. Hydrogen is often generated from various primary energy sources, such as fossil fuels (coal, oil, and natural gas) with or without carbon capture technology to minimize emissions. It can also be generated from biomass and non-bio renewable electricity (such as solar and wind power). Hydrogen can be produced in three of the following ways:

water electrolysis, which involves water being electrolyzed at low temperatures by alkaline or PEM electrolyzers or steam at high temperatures by solid oxide electrolyzers (John, 2022).

Steam methane reformation, which involves methane and steam undergoing elevated pressure and temperature to produce syngas (CO2 + 3H2), which is further filtered using a water gas shift process to produce hydrogen (John, 2022).

Partial Oxidation and Autothermal Reforming involve using enough oxygen or air combined with methane to generate syngas. This syngas is further processed using the water-gas shift reaction to generate more hydrogen (John,2022).

### 3.1.2 Using Hydrogen Onboard Ships

There are two primary energy conversion methods for using hydrogen as the principal fuel aboard ships: hydrogen-fueled internal combustion engines and fuel cells. The hydrogen-fuel cell alternative is more popular owing to its energy efficiency and its clean by-product (H2O). The low-temperature proton exchange membrane fuel cell (LTPEM FC) has advanced rapidly in recent years and is currently an established technology with an efficiency of over 60%. This technique has been tried on both naval and passenger vessels. Due to its low working temperature (65°C-80°C), LTPEM FC needs a platinum catalyst for electrochemical processes. A complicated water-management system is needed to maintain a moist membrane while keeping gas-diffusion holes dry. LTPEM FC has low tolerance for fuel contaminants, especially CO2. Low temperature causes CO2 to significantly adsorb on the catalyst surface, causing deactivation. To produce electricity using fuel cell stacks, auxiliary components are necessary in addition to fuel cells. Examples include pumps, blower compressors, heat exchangers, and system controllers (Biert, et al., 2016).

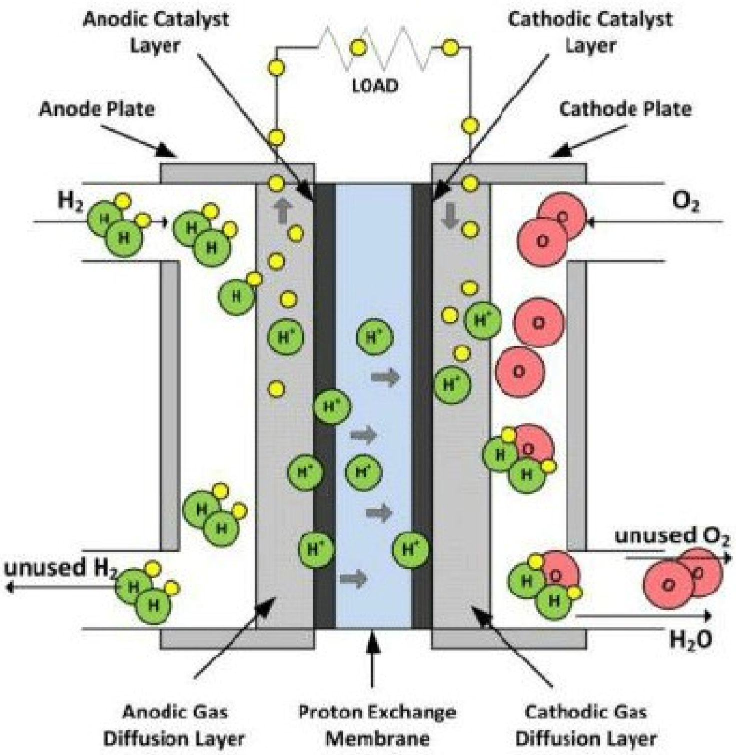

Fig 2. LTPEM FC representation (Alireza et al, 2014)

On the other hand, hydrogen has traditionally been used as a mixed fuel blend in conventional gas and dual-fuel engines. Hydrogen possesses numerous properties that make it an ideal choice as a combustible fuel. The minimal ignition energy plays a crucial role in combustion, as the energy required to ignite hydrogen is significantly lower compared to MGO. The autoignition temperature of hydrogen is crucial in determining the compression ratio of the engine and has a significant impact on the maximum power output, also known as mean effective pressure. Wartsila and MAN engines have confirmed the feasibility of hydrogen combustion in certain engine types, such as dual-fuel engines that can run on natural gas or other gas fuels. Multiple studies have demonstrated that the inclusion of hydrogen in blended gas fuel can enhance engine efficiency and reduce carbon emissions, even at low percentages. When utilized as a mono-fuel, hydrogen engines necessitate adjustments to enhance combustion timing and minimize engine knock. Usually, mono-fuel hydrogen engines necessitate a larger cylinder and engine size. Depending on the air-fuel ratio and engine emissions performance, it may not be necessary to have enormous aftertreatment systems to control NOx and particulate matter (PM) (ABS, 2021).

Furthermore, hydrogen can be combusted with gas or other conventional fuels like diesel, in addition to mono-fuel hydrogen combustion. In Dual Fuel applications, hydrogen is introduced into the cylinders, compressed, and a small amount of pilot diesel fuel is injected to start the combustion process. This particular combustion system is utilized in Behydro© H2/diesel DF engines, which can accommodate hydrogen fuel content of up to 85 percent. The percentage of hydrogen in the blend is closely tied to the load profile and size of the engine. In situations where higher loads are required, higher percentages of hydrogen can be used as fuel. Combining H2 and diesel co-combustion allows for the perfect balance of fuel flexibility, efficiency, and environmental performance. There are multiple ways to achieve hydrogen combustion in internal combustion engines, each with its own set of advantages and difficulties (ABS, 2021)

Hydrogen engines have a broad flammability range, allowing them to operate on various air-to-fuel ratios, from 34:1 to 180:1. Both mono-fuel and dual-fuel hydrogen engines have the capability to operate on a lean-burn combustion cycle, resulting in reduced NOx emissions. Depending on the air/fuel ratios achieved, there may be a need for NOx reduction technologies like selective catalytic reduction (SCR) or exhaust gas recirculation (EGR) technologies (ABS, 2021).

### 3.1.3 Handling of Hydrogen onboard ships

Hydrogen storage is a major barrier to using hydrogen as a fuel on ships owing to its poor energy density and safety concerns. Hydrogen storage options include compressed, liquefied, metal hydride, high-surface-area adsorbents, and chemical H2 storage materials like methanol and ammonia. Storage in solid medium is both safer and more effective than compression and liquefaction because of its leak-proof status, greater charging efficiency, and less self-discharge (Conte, et al., 2001). Also, storing hydrogen in its liquid form offers the highest storage capacity in a small space. However, to preserve hydrogen in its liquid form, it must be stored below -253 C which will be challenging in terms of insulation techniques. The energy density of compressed and liquefied hydrogen is much lower than traditional maritime fuels for the same tank capacity. Thus to store hydrogen of equivalent energy content as MGO, it will require a space of 8 times the capacity. Hydrogen may be stored in chemical H2 storage materials like methanol, ammonia, or natural gas, however, onboard conversion systems are needed for reforming, CO removal, and desulphurization. These have a substantial influence on system performance, including efficiency, size, weight, and cost. (Biert, et al., 2016).

Hydrogen has a large combustibility range, ranging from 4%-75% by volume in air, compared to other fuels. Hydrogen has no colour or smell, and it is also the simplest and lightest element in nature. it glows pale blue but is undetectable in daylight and it is extremely difficult to see it with the bare eye. Thus, handling hydrogen onboard must be safe. The Bureau Veritas (BV) Classification Society is developing standards for using hydrogen as a fuel on commercial ships. The rules combine gas-fuelled ship restrictions with terrestrial fuel cell power system requirements for ship use. The criteria have been tested in experimental projects, such as a hydrogen-powered hybrid electric harbour tug (Seddiek, et al., 2015).

When it comes to alternative fuels, one approach stands out as the only way to achieve zero-emission onboard ships: green hydrogen in fuel cells. The waste product generated from this fuel is pure water, with no emissions of pollutants into the atmosphere or greenhouse gases. When alternative fuels are used in fuel cells, it is important to consider the potential for greenhouse gas emissions and other atmospheric pollutants. This is because these fuels may contain carbon and other impurities that can contribute to environmental harm. Some of the fuels mentioned are diesel, LNG, and methanol. Regarding H2-ICE, the combustion of hydrogen in the presence of excessive oxygen produces water (H2O) and nitrogen oxides (NOx). Furthermore, a small quantity of carbon dioxide and carbon monoxide may be found in the exhaust gas because of using lubrication oil in the internal combustion engine system (Dr Prapisala, 2020).

### 3.1.4 Pilot project for Hydrogen (Ulstein X190 offshore support vessel)

The ULSTEIN SX190 Zero Emission DP2 construction support vessel is Ulstein's inaugural offshore vessel powered by hydrogen, utilizing a cutting-edge Nedstack fuel cell power system. The design utilizes established and accessible technology, allowing for eco-friendly shipping operations that minimize the environmental impact of offshore projects (Ulstein,2019).

Fig 3. Ulstein’s SX190 Zero Emission Offshore Service Vessel (Ulstein, 2019)

When hydrogen fuel cells are used for onboard power generation, CO2, NOX, and particulate matter are completely eliminated. Nevertheless, current technology and hydrogen infrastructure have limitations that restrict operations to approximately 5 days in zero-emission mode. However, achieving a hydrogen marine economy requires more than just this initial step. It is essential to ensure that hydrogen can sustain zero-emission marine operations for extended periods, lasting multiple weeks (Ulstein, 2019).

At present, there are no hydrogen bunker facilities in place. Therefore, the designers of the ULSTEIN SX190 design opted for a versatile containerized gas storage system on the aft deck. The existing storage system has a capacity that restricts the range to 4-5 days while operating in zero-emission DP mode. However, it enables the vessel to operate without relying on H2 bunkering infrastructure. Hydrogen gas can be replenished by trucks at the quayside, or the storage containers can be taken off the vessel and transported to a hydrogen plant if refilling at the port is prohibited by port officials. This easily accessible technology helps to connect the divide between future hydrogen laws and infrastructure (Ulstein, 2019).

Meanwhile, to increase the vessel's range to a practical distance, Ulstein implemented a dual-fuel solution. The 2 MW electric power generated by fuel cells is complemented by 5.5 MW of a conventional diesel-electric system. This allows the vessel to rely on its diesel-electric system, utilizing low sulphur marine diesel oil for longer missions and enhanced capabilities. Naturally, hydrogen can also be utilized exclusively while entering or being in port, thereby decreasing local emissions in crowded regions (Ulstein, 2019).

Because of the success of Ulstein X190, several ports have expressed their plans to invest in the hydrogen economy, such as Zeebrugge and the Port of Rotterdam. In 2025, the latter revealed plans to create a hydrogen center that will link green hydrogen production with consumers (IRO, 2020). Once liquid hydrogen bunker facilities are widely accessible globally, it becomes possible to create a ship that runs entirely on hydrogen power. In the years to come of transition towards a hydrogen economy, the operational flexibility of the hydrogen storage and dual fuel solutions in the ULSTEIN SX190 will be crucial (Ulstein, 2019).

Although hydrogen fuel has several benefits, there are also certain obstacles that must be o vercome in order to use it on ships. A primary obstacle is the exorbitant expense associated with the generation and storage of hydrogen.  Despite the cost reductions brought about by technological advancements, using hydrogen energy sources remains more costly than con ventional fossil fuels. Furthermore, hydrogen has high flammability and requires certain pr ecautions and safety protocols, presenting a possible safety risk when used aboard ships. H ydrogen diesel engines can be created by either building them from standard medium-spee d marine diesel engines or by retrofitting existing engines to run on hydrogen. This suggest s that using hydrogen as a fuel on ships is not just a distant possibility, but a fully achievabl e possibility from a technical standpoint.

## 3.2 Liquified Natural Gas (LNG)

An alternative for ship owners to adhere to the IMO 2020 sulfur regulations is to transition to engines that utilize liquefied natural gas (LNG) as a fuel source for their vessels. LNG is methane ($CH_4$) transformed to liquid and stored at -160°C. LNG has a relative density of 0.72-0.81 at 15°C and is colourless and lighter than air (Mokhata and Poe, 2012). LNG-powered ships release minimal quantities of sulfur oxides in their exhaust emissions, which are well below the 0.1% fuel-equivalent limit set in certain ECA zones. As a result, such vessels fully adhere to the criteria established by the International Maritime Organization (IMO). Additionally, utilizing LNG as a fuel for engines would result in a decrease in particulate matter (PM) and $CO_2$ emissions compared to both high- and low-sulfur marine fuel oils (Heather et al, 2015).

Fossil-based LNG is acquired through the extraction of natural gas from reservoirs beneath the earth, followed by the processing of the extracted natural gas to eliminate non-methane hydrocarbons and impurities. The treated natural gas is then liquefied to transform it from a gaseous state to a liquid state.

Biomethane is generated by the process of anaerobic digestion and the decomposition of biomass in landfills. This biomass might include agricultural waste, organic waste, manure, and sewage sludge. The gas obtained from this process commonly referred to as biogas, mostly comprises of $CH_4$ and $CO_2$. Biogas can be enhanced further through the utilization of separation technologies in order to attain a final product that matches the quality of natural gas derived from fossil fuels. These methods encompass membrane separation, chemical washing, and pressure swing adsorption. The biomethane produced can be delivered in either gaseous or liquefied forms using the existing natural gas infrastructure (Florentinus, et al., 2012; UNIDO and Fachverband Biogas, 2017).

### 3.2.1 Using LNG onboard ships

The utilization of LNG aboard ships necessitates two key components: the LNG fuel propulsion system and the LNG fuel tank with supporting systems.

Medium-speed dual-fuel diesel engine is widely preferred for onboard ship applications. It has a proven track record of reliable performance, making it a popular choice among available LNG fuel propulsion options. Additionally, it offers a safer alternative to the high pressure required by low-speed diesel engines and provides a wide range of power sizes to suit different needs.

The IMO tank types available are Type A and B, which are structural tanks built into the vessel's hull with the requirement of low pressure and constant consumption of boil-off gas (BOG). Another option is Type C, which is the most widely used due to its allowance of BOG retention, resulting in less wasted fuel. Fuel tanks can be quite costly due to the need for specialized materials to withstand extreme temperatures, as well as the requirement for pressurized vessels and gas control equipment. Large fuel tanks can sometimes reduce the amount of cargo a vessel can carry, as they take up a significant amount of space needed to store the desired amount of fuel.

Furthermore, a particular safety system is required in addition to the mentioned components. These features include the use of double wall piping, where the space between the inner and outer pipes is vented to the atmosphere. This allows natural gas pipes to be safely routed through machinery spaces without creating hazardous areas. Another safety measure is the vent rise mast, which extends to a height of one-third of the beam above the weather deck. This mast provides a hazardous outlet for any potential hazards (CCD TT and Herbert Engineering Corp, 2013).

Because of the intricate fuel and machinery systems and the requirement for additional safety features, LNG-fueled ships can be up to 30% more expensive than traditional ships. When it comes to managing the operation of LNG-fueled ships, unique crew training is necessary for onboard service and the bunkering process. The intricate nature of the system could potentially result in higher maintenance expenses. Additionally, there are also a few operational concerns that arise when utilizing a medium-speed diesel engine. These include a 10% increase in fuel consumption when running on diesel oil, the potential for methane slip, and maneuvering difficulties when operating on gas at low power levels (<15% of maximum continuous rating) (DR.Papisala, 2020)

### 3.2.2 Exhaust Emissions of LNG Onboard

Both fossil-based LNG and bio-LNG are considered cleaner fuels, emitting lower levels of pollutants such as SOx, NOx, and PM compared to conventional fuels. Usually, LNG has v ery low levels of SOx and PM emissions, and it can reduce NOx emissions by over 80%. N evertheless, the utilization of fossil-based LNG may not effectively decrease greenhouse ga s emissions due to methane slip during its operation. The efficiency of GHG emissions fro m LNG can be reduced by approximately 8% to 20%. However, it's important to note that even a small leakage of CH4 can offset the positive impact of this reduction. Multiple lifec ycle studies have been conducted to analyze the greenhouse gas emissions per kilowatt-hou r for liquefied natural gas (LNG) as a shipping fuel. In their analysis, Balcombe et al. exam ined multiple lifecycle studies and determined that the average total greenhouse gas emissi ons, encompassing both combustion and upstream processes, amount to 650g CO2 emissio ns /kWh (Balcombe et al., 2019)

Engine manufacturers have been making ongoing research and development efforts to redu ce methane slip. It is worth mentioning that addressing methane slip can be achieved throu gh enhancing the combustion process and implementing catalytic. As per MAN Diesel & T urbo, it has been observed that low-speed diesel engines with high-pressure injection exhib it minimal methane slip, accounting for only 0.1% of SFOC. Nevertheless, there are certain trade-offs to consider, such as the expenses associated with the intricate fuel gas supply sys tem and the release of NOx emissions (Sharafian, et al., 2019).

The LNG supply system comprises a vacuum-insulated storage tank, together with other eq uipment such as an LNG vaporizer, a pressure build-up unit, and a bunker station. The syst em's objective is to facilitate the process of filling, storing, and vaporizing LNG, as well as supplying natural gas to ship engines. The system is designed to minimize heat leaking, ens uring the highest possible holding duration. The gas is supplied to the engines by the use of tank pressure. Therefore, the absence of pumps eliminates the need for them and results in reduced maintenance expenses (MAN, 2016).

### 3.2.3 LNG Pilot Project (AIDANOVA cruise ship)

The AIDAnova stands as a remarkable achievement in German shipbuilding, boasting impr essive size and an unparalleled commitment to environmental sustainability. This ocean lin er is the pioneer in using an LNG propulsion system, which guarantees a remarkable decre ase of 95 to 100% in sulfur oxides (SOx), an 85% decrease in particulate matter, and a 22

% reduction in greenhouse gas emissions (GHG) compared to marine gas oil. (Shell, 2022). Thanks to this technology, AIDAnova has become the proud recipient of the German gove rnment's prestigious "Blauer Engel" environmental seal, making it the first cruise ship to ac hieve this recognition. The impressive vessel was developed over a span of ten years by M EYER WERFT MW (Meryer werft, 2018).

AIDAnova has a length of 337m, a width of 42m, a maximum draught of 8.8m, and a gross tonnage of 183900t. The ship's three tanks have a capacity of around 3,500 cubic meters of liquefied natural gas, sufficient to power a two-week journey. The gas is subjected to a coo ling process, reducing its temperature to -162°C, causing it to undergo a phase change and transform into a liquid state. The vessel's electrical power source for the hotel consumers a nd the cruise ship's powerful propulsion system are provided by four Caterpillar MaK 16 V M 46 DF dual-fuel engines, each with a power capacity of 62 MW (Meryer werft, 2018).

## 3.3 Biodiesel Fuel

Biodiesel is a domestically produced renewable fuel that can be manufactured from vegeta ble oils, animal fats, or recycled restaurant greases. Biodiesel exists in a liquid state at nor mal room temperature. it is a non-flammable liquid with a rather high flash point, which fal ls within the range of 150°C to 160°C. The color of biodiesel may range from transparent t o very dark brown, depending on the feedstock utilized. However, it is important to note th at the color of biodiesel does not indicate its quality (Bello, 2016). Biodiesel, which includ es carbon derived from living organisms, releases naturally occurring CO2 when burned on ships. This emission has not been proven to contribute to global warming. Given its compa tibility with diesel oil, this fuel may be directly utilized as a substitute for marine distillate fuel. It can also be used in current marine engines, perhaps requiring only minimal adjustm ents.

### 3.3.1 Using Biodiesel onboard ship

Biodiesel is suitable for use in internal combustion engines and their corresponding fuel sy stems. It may be used as a substitute marine fuel in any proportion without necessitating si gnificant alterations to internal combustion engines and its accompanying systems. While n umerous marine engine manufacturers have obtained certification for using biodiesel or a b iodiesel-fossil diesel blend, it is crucial to consult the engine manufacturer to determine the appropriate blending ratio for their engines.

Also, because of its compatibility with fossil-based diesel, biodiesel can be used with curre nt bunkering infrastructure. The manufacture of biodiesel-blended marine distillate such as B2, B10, and B20 may be carried out in refineries before distributing it for bunkering at po rts. Nevertheless, biodiesel is biodegradable. Thus, prior to prolonged storage, it is importa nt to address the quality of biodiesel, particularly its oxidative stability (DR.Papisala, 202 0).

Furthermore, biodiesel is free from sulphur, thus when it is burned, it does not release sulp hur oxides (SOx). According to the National Renewable Energy Lab, biodiesel decreases t he release of exhaust particulate matter (PM), hydrocarbon (HC), and carbon monoxide (C O) emissions in the majority of current four-stroke or diesel engines. The advantages arise from the fact that biodiesel has a weight percentage of 11% oxygen. The presence of oxyge n in the fuel enables a more thorough combustion process, hence reducing the amount of u nburned fuel pollutants (Mr Pradeep, 2010).

In addition, the emissions of particulate matters (PM), hydrocarbon (HC), and carbon mon oxide (CO) decrease as the proportion of biodiesel in the blended gasoline rises. On the oth er hand, the use of biodiesel in boilers often results in a reduction in NOx emissions due to the distinct combustion processes involved. This is because boilers employ an open flame, while engines utilize an enclosed cylinder with high-pressure spray combustion (Mr Pradee p, 2010).

### 3.3.2 Biodiesel Pilot Project (CSL Case Study)

CSL is a multinational company based in Montreal and has activities in several regions wo rldwide, including the Americas, Australia, Europe, and Asia. The company transports mill ions of tons of cargo annually for clients in construction, steel, energy, and agriculture. In 2 019, The CSL Group ("CSL") initiated its biodiesel demonstration program to accelerate th e process of reducing carbon emissions from its ships. The initiative included conducting te sts on the auxiliary engine of one vessel in its Great Lakes fleet. In 2020, the program adva nced to conducting tests on the primary and secondary engines of two vessels. In 2021, tria ls were carried out on eight CSL Lakers (CSL, 2021).

During CSL's testing, several grades of biofuels were tried on bulk carriers and self-unload ing bulkers under varied engine loads and configurations. The NOx emissions of the fuel w ere assessed using the EPA 7E standard, while the sulphur content was measured following the ISO 8754 standard. Environmental compliance was assessed by conducting emissions t esting and fuel analysis at various amounts of bio-content. In 2019, the first testing of B50 fuel, which is a combination of 50% biodiesel and 50% marine diesel oil (MDO), was carri ed out. Subsequently, the blend was further raised to B80 fuel, consisting of 80% biodiesel and 20% MDO (CSL, 2021).

In 2020, the ship's trials began using B50 fuel, then advanced to B80, and ultimately used B100, a kind of biodiesel that consists entirely of second-generation biofuel with 100% bi o-content. During the year 2021, a total of eight CSL boats used B100 fuel consistently for a period ranging from five to eight months. Engine emissions were tested at various load le vels, including 25%, 50%, 75%, and 100% as specified in the technical file. Additionally, e missions were recorded at regular operating loads to represent typical operation (CSL, 202 1).

The biodiesel utilized during CSL's experiments was obtained from North America and pro vided by Canada Clean Fuels. It was manufactured exclusively from waste plant material, primarily turn down soybean oil. This Biodiesel is of the FAME type, which stands for fatt y acid methyl esters. It is created by the process of transesterification, which involves conv erting soybean oil into biodiesel. The generation of biofuel had little impact on food produ ction or supply systems.

The chosen biofuel had a carbon intensity of 1.8 gCO2eq/MJ, as determined using the Can adian GHG life-cycle emission inventory program. CSL's testing have shown that biodiesel is a technically feasible and practicable fuel choice for current ships to decrease well-to-wa ke GHG emissions and lower SOx and NOx emissions below regulatory thresholds. Some of the observations include:

- The total amount of nitrogen oxide (NOx) emissions did not exceed the maximum a llowed levels (Tier II limits) for all types of biofuels that were tested.
- The NOx emissions during the B50 and B80 trials were lower than what was stated in the technical documentation. This indicates that biofuels have the potential to eff ectively reduce NOx emissions.
- The levels of sulphur found in all tested biofuels were below the limits set by the N orth America Emissions Control Area. • The emissions of sulphur oxides (SOx) we re so low that the equipment aboard the vessel could not accurately quantify them.

- The carbon factor evaluation revealed that biofuels may provide an immediate decr ease of 11.7% in $CO_2$ emissions, even without doing a life cycle study (CSL, 2021).

Thus, biofuels provide a practical solution for reducing airborne emissions from shipping, r equiring little financial input from shipowners. The absence of technical complications link ed to their use aboard ships also makes them a low-risk alternative for shipowners and the maritime sector as a whole.

# 4 Technological innovation and operational measures

Technological innovations are at the forefront of efforts to decarbonize the maritime industry. These advancement aims to reduce greenhouse gas emissions, improve energy efficiency and transition to sustainable and renewable fuels. Below are key technological innovations driving decarbonization effort in the maritime industry.

## 4.1 Wind power

Wind-assisted ship propulsion (WASP) technologies provide substantial cost reductions an d reduced GHG emissions for existing ships, enabling ship owners to maintain competitive operations and meet regulatory standards compared to new ships. WASP may be used for s hip propulsion using three distinct technologies: Flettner rotors, kites, and sails. The potent ial fuel savings resulting from these wind-assistance systems are conditional upon the shi p's design, namely the rig and hull, as well as the operating speed, and the wind speeds and directions encountered. Experts assert that when wind power is harnessed well, fuel saving s of up to 50% may be achieved, particularly on routes with high wind conditions (Nishatabbas et al. 2017).

The velocity of wind fluctuates based on the specific route and time of year. Increased win d speeds enable a ship to use a greater amount of wind energy for propulsion resulting in m inimal GHG emission. The operating profile and routes of many ships are subject to variab ility and might range from one trip charter to another, resulting in varying fuel savings for various kinds of ships. This introduces some uncertainty when attempting to anticipate fuel savings.

### 4.1.1 Application of Wind Power on ships

Several global initiatives are now being developed to ascertain the advantages of wind pow er in the maritime sector. Outlined below are some of the prominent environmentally-frien dly ship designs and technologies that are anticipated to provide positive outcomes for the shipping sector.

- **Rotor Sails:** These rotors use the Magnus effect. When the rotor is in motion, it cre ates a thin layer of air surrounding it called a boundary layer. This boundary layer causes a difference in pressure between the two sides of the rotor when it is exposed to an airflow, s uch as wind. The optimum exploitation of the wind occurs in beam-reaching directions to t he ship, as a resultant perpendicular to the wind flow force is generated. The rotational spe ed of the rotor sail either enhances or decreases the size of the thrust force.

The Rotors use electrical power from the ship's existing electric system in order to revolve at their designated working speed, often ranging from 0 to 180 or 250 revolutions per minu te (rpm). The rotor's spinning power may fluctuate based on the dimensions of the rotor sai l, the aspect ratio, and the maximum revolutions per minute (RPM), ranging from 40 kilow atts to 160 kilowatts. The typical size of rotors ranges from 18 to 35 meters in height and 2 to 5 meters in diameter. This particular category has garnered growing interest in recent ti mes. The cylindrical sails developed by Norsepower, a company based in Finland, have be en successfully deployed on many types of vessels such as ferries, RoRo ships, and product tankers. The Rotor Sail typically functions totally automated, with the operation starting an d ceasing from the Bridge control panel. Under unfavorable wind conditions, the Rotor Sai l has the ability to either reduce its rotation speed in order to minimize drag or come to a fu ll halt (Konstantinos, 2020).

**Suction Wings**: These are wing sails characterized by their substantial thickness and an int egrated mechanical air suction mechanism. In order to manipulate the movement of air aro und the 'thick' foil-shaped object, a technique called boundary layer suction is used. This in volves the installation of one or more ventilators inside the suction wing profile. At the for emost point (referred to as the 'nose') of the egg-shaped cross section, the airflow is increas ed in speed, resulting in a significant decrease in pressure on the top-left side of the surface as well as along the suction-side.The suction wing sail is capable of generating significant l ift forces without the need for a self-rotation mechanism, despite its comparatively small si ze. These machines are completely automated and have the ability to fold up in the event of unfavorable wind conditions or when handling freight. Suction wing sails may be mounted in either a containerized form, on a flat-rack, or attached directly on the deck. When implementing a containerized system, it may be easily installed by securing the system to the hatch cover using straps and connecting it to a 400V/32A socket (Konstantinos, 2020).

**Kites:** Unlike previous wind propulsion systems, the propulsion Kite functions in the air and is located at heights of over 150m, away from the ship construction. The Kite requires a minimum wind speed to achieve lift-off, but it may continue to function at wind speeds lower than the minimum required for lift-off. During operation, the kite undergoes a dynamic figure of 8 movement, which significantly increases the apparent wind of the kite to more than 10 times that of the vessel. By flying swiftly into the oncoming wind and pulling the ship, the kite optimizes the amount of force it generates. Due to its dynamic movement, this on-deck wind propulsor may create several times the force of other propulsors, although having a comparatively smaller surface area. In addition, they function at elevations where the velocity of the wind is twice as high as it is at sea level (Konstantinos, 2020).

**Rigid wing sails**: Rigid wing sails are similar in appearance to traditional sails, but they are constructed with inflexible materials. This design ensures that the shape of the sail remains stable and closely mimics the cross-section of an aircraft wing. Wing sails are installed in a vertical position on the main deck and/or forecastle of a ship. They function based on the aerodynamic lift principles that are also used by aircraft wings. Each wing is designed with a precise aspect ratio (height/width) and wing profile shape to maximize the generation of aerodynamic lift force. During unfavorable weather or while docked, wing sails may be folded or adjusted in a telescopic manner to reduce needless resistance or air resistance. Every system is designed to operate autonomously, meaning that they modify the orientation of their wing sails based on the anemometer readings. Additionally, under unfavorable wind conditions, there is an automated feature for reducing the size or rolling up the sails (Konstantinos, 2020).

## 4.2 Solar power

Renewable energy programs are gaining significant traction worldwide, and solar power emerges as a promising solution for achieving sustainable energy for the future. The limitless nature of this resource, when coupled with advancements in technology, not only ensures a reliable supply of energy, but also plays a substantial role in minimizing the release of ca rbon dioxide and addressing the issue of climate change. In recent years, there has been a s ubstantial increase in the use of solar power in the maritime sector. Ship-owners and operat ors are increasingly aware of the advantages of using renewable energy to fuel their boats . Solar panels can be mounted on the ships deck to harness solar energy and convert it into e lectricity for powering the ship's electrical systems, lights, and propulsion systems. Harness ing solar electricity in the shipping industry not only mitigates greenhouse gas emissions a nd addresses climate change, but also provides economic advantages via decreased fuel co nsumption and operational expenses. With the increasing need for sustainable and eco-frie ndly shipping solutions, the use of solar power in the maritime sector is expected to becom e increasingly prevalent. Technological advancements and more investment in renewable e nergy are anticipated to propel the development of creative ways to capture solar power for ship propulsion, hence further mitigating environmental effects (Olga et al., 2024)

In 2020, the MS Braemar, a cruise ship owned by Fred. Olsen Cruise Lines achieved a significant milestone by becoming the first cruise ship to utilize solar panels for power generation. The ship underwent a retrofitting process that involved the installation of 28 panels. These panels have the capacity to generate up to 30 kilowatts of power, resulting in a significant reduction of the ship's emissions by 28 tons per year (Olga et al. 2024)

## 4.3 Nuclear power

The use of nuclear propulsion for ships has been in existence since 1955, mostly for militar y and submarine purposes. Nuclear propulsion operates by using an onboard nuclear power plant to heat steam, which in turn powers steam turbines and generators.

Currently, the naval fleets of the United States, Russia, China, the United Kingdom, France, and India have all implemented nuclear propulsion. Nevertheless, the implementation of n uclear power in commercial vessels intended for civilian use has progressed at a somewhat sluggish pace, with its primary use being in icebreakers. Nuclear-propelled icebreakers pro vide several technological and economic benefits in comparison to traditional icebreakers p owered by fossil fuels, particularly in polar climates. These icebreakers are capable of brea king ice that is up to three meters thick, operating without refueling for many months, and extending transportation via the Northern Sea Route for up to ten months each year (Georg e & Elias, 2021)

In 1959, the Soviet icebreaker Lenin was put into service as the first nuclear-powered ship in history for non-military operations. The power source of the system initially consisted of three OK-150 reactors; however, they were later substituted with two 171 MWt OK-900 re actors due to damage incurred during the refueling process. The ship was taken out of servi ce in 1989 because its hull was becoming thinner. Russia made significant advancements i n nuclear-powered icebreaker technology after the Lenin. This included the creation of ma ny icebreakers such as Arktika, Sibir, 50 Let Pobedy, Rossiya, Sovetskiy Soyuz, Yamal, T aymyr, and Vaygach. These developments positioned Russia as a key player in the global h istory of nuclear-powered icebreaker innovation (Quiwen et al., 2023)

However, nuclear propulsion is unlikely to become widely used in the marine sector despit e its complete absence of greenhouse gas emissions because of political factors and regulat ory requirements. Port officials will refuse to let foreign ships with a nuclear reactor on boa rd . Additional concerns about nuclear propulsion include legislative measures, training pro tocols, and safety precautions to prevent accidents, acts of terrorism, and the spread of nucl ear weapons. For example, the nuclear propulsion system must comply with the Internation al Maritime Organization's Resolution A.491-XII, which outlines safety requirements and s tandards for protecting individuals and the environment from potential radiation risks throu ghout the vessel's lifespan. Another complication associated with nuclear propulsion is the presence of radioactivity in uranium fuel and waste, which presents significant risks to the environment and human health. This implies a comprehensive redesign of cargo ships, prio ritizing safety above efficiency. Given the present emphasis on lowering greenhouse gas (GHG) emissions, nuclear energy may shift its focus in the future towards supplying ships with hydrogen.

## 4.4 Air Lubrication

This is a novel approach that minimizes the resistance between a ship's hull and the water b y using air as a lubricant. According to Barbicz, a specifically shaped underbelly of the ves sel creates an air layer between itself and the water surface. This allows the vessel to move smoothly through the water, lowering drag by 5-15%. There are three techniques for air lub rication, namely Bubble Drag Reduction (BDR), Air Layer Drag Reduction (ALDR), and Partial Cavity Drag Reduction (PCDR)

A good example of a ship using this technology is the panamax class container ship MALS - 14000CS developed by Mitsubishi Heavy Industries Ltd in Japan which has achieved a si gnificant reduction of 35% in $CO_2$ emissions. The ship is equipped with the Mitsubishi Air Lubrication System (MALS) which directs air under the bottom of the hull. This innovativ e system effectively reduces water resistance, resulting in a significant 10% decrease in CO 2 emissions compared to other types of ships (Oleg et al. 2022)

## 4.5 Vessels speed

Reducing a vessel's average speed might result in a reduction in fuel usage. Nevertheless, t he duration of the journey is extended as a consequence. Slow steaming has emerged as a widely used strategy to reduce bunker costs due to the higher fuel efficiency of maritime v essels at lower speeds. There are several solutions available for reducing emissions, includi ng the use of kite sails as previously indicated. Slow steaming might be considered as a pro mpt answer for carriers to enhance their environmental performance. The advantages of slo w steaming vary based on factors such as the kind of ship, its tonnage, itinerary, and activit ies. As previously stated, slow steaming increases the duration of journeys; yet, reducing s peed by 10% may lead to an overall average decrease in emissions of 19%. However, exte nded durations of operating at part load, as is the case with slow steaming, have the potenti al to cause damage to the engine (Muhamed et al. 2022)

## 4.6 Scrubbers

Scrubbers are probably the most suitable technology for meeting IMO criteria for SOx and PM emissions. Currently, wet scrubbers are the prevailing technology. Hybrid aqueous scr ubber systems exist, which integrate both open-loop and closed-loop systems. At long last, there are now dry flue gas scrubbers accessible. These techniques may effectively decrease SOx and PM emissions by 95% for particles bigger than 5µm and up to 80% for particles r anging from 3 to µm. Nevertheless, these installations are complex, solid, and hefty (Muha med et al. 2022)

## 4.7 Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) mitigates NOx emissions by reintroducing exhaust gases i nto the combustion chamber. Due to their elevated specific heat capacity, exhaust gases eff ectively decrease peak temperatures, resulting in a reduction in NOx emissions. The decrea se in oxygen levels inside the engine also leads to a decline in temperature. EGR, as compa red to a standard diesel engine, has the capability to decrease NOx emissions by as much a s 50%. The use of Exhaust Gas Recirculation (EGR) in combination with scrubbers may ef fectively decrease emissions of sulfur oxides (SOx) and particulate matter (PM), while also preventing the EGR cooler from getting clogged As fuel consumption increases, the use of EGR may result in challenges and higher expenses during installation. In addition, the EG R system generates waste, which has to be taken into account during the construction of su ch a system (Muhamed et al. 2022).

## 4.8 Waste Heat Recovery System

Approximately 50% of the energy is dissipated as heat, in order to comply with the principl es of the Second Law of Thermodynamics. Nevertheless, Waste Heat Recovery Systems (WHRS) have the capability to retrieve a portion of this energy from the exhaust gases, lea ding to reduced emissions and fuel use. The possible energy-generating sources are jacket water (5.2%), air cooler (16.5%), and exhaust gases (25.5%). The waste heat from the exha ust gases is used to drive steam turbines, which provide energy for auxiliary power generat ion in a waste heat recovery system (WHRS). Consequently, the auxiliary engines save gas oline. Hence, the Waste Heat Recovery System (WHRS) is most suitable for vessels that pr oduce a substantial amount of waste heat and use a significant amount of energy. The Inter national Maritime Organization (IMO) suggests a potential reduction of 8-10%. Based on p rior research, it is conceivable to achieve fuel savings ranging from 4% to 16% (George & Elias, 2021).

## 4.9 Dual-fuel technology

Wärtsila and MAN B&W have designed Dual-Fuel Engines (DEs) capable of operating on natural gas, marine diesel oil (MDO), or heavy fuel oil (HFO). The practice of using altern ative fuels or using dual-fuel technology is often known as fuel switching. Shipowners and operators may benefit greatly from the dual-fuel technology. The engine meets the standar ds of IMO Tier III without the need for additional exhaust gas purification equipment. Furt hermore, the use of dual-fuel technology not only decreases the levels of sulfur oxides (SO x) and carbon dioxide (CO2) emissions but also enables the operation of the system withou t producing smoke while operating on gas. Conversely, fuel switching enables the operator to choose the fuel type depending on changes in market prices (Muhamed et al., 2022)

## 4.10 Vessels Hull optimization

Hydrodynamic optimization is a highly efficient and reliable design approach that plays a c rucial role in optimizing hulls. Vessel design may effectively minimize hull resistance with the sea via several means, including optimizing hull size, efficient ballast operation, using l ightweight construction, including low profile hull apertures, using interceptor trim plates, shaping the skeg trailing edge, and introducing a bulbous bow (Pariotis et al., 2016).

Optimum Hull size: The hull form may be meticulously developed and fine-tuned, particul arly in the age of digital twins, to minimize the resistance encountered by the ship. Digital t wins facilitate the process of designing and testing a new product by using both 3D-CAD models and physical prototypes. This approach reduces expenses associated with research and development, production, and testing, resulting in a shorter time frame for a new produ ct to be introduced to the market. The optimal length and hull fullness (L/B) ratio may sign ificantly affect ship resistance. An increased length-to-beam (L/B) ratio may decrease resis tance, but, an excessively high L/B ratio might result in a larger wetted surface area, thereb y raising resistance. A low length-to-beam ratio (L/B) indicates that the hull lines are blunt, resulting in more resistance. Therefore, by optimizing and efficiently developing new ships while considering various design characteristics, it is possible to decrease overworking the engine. Nevertheless, the process of creating new ships is a costly alternative that requires a significant amount of time to recoup the investment (Pariotis et al., 2016)

Efficient Ballast operation: A decrease in displacement leads to a reduction in the surface area of the hull that is in contact with the water, resulting in less resistance. The ballast must be enough to maintain stability, and maneuverability (for example, to prevent the hull from slamming), and ensure that the propeller is submerged at the ideal depth. The highest decrease in fuel consumption may reach up to about 7% (Pariotis et al. 2016).

Lightweight construction: Lightweight materials, like aluminum, may be used in the construction of new ships to create lighter structures, resulting in a reduction in the overall weight of the ship. The weight of the steel construction of current ships may be decreased by 5-20% based on the level of high-tensile steel strength. According to Pariotis et al., reducing weight by 20% may potentially decrease power consumption by up to 9%. However, in most situations, a more practical reduction of 5% is expected (Pariotis et al. 2016).

Low profile hull openings: By creating hull openings that are close to the waterline, the dis ruptive impact of bow thruster tunnels may be reduced. These openings, such as sea chest openings, can effectively decrease resistance and, as a result, reduce fuel consumption. By developing and improving these openings, it is possible to obtain a reduction in power cons umption of up to 5% (Almedia, 2012).

Interceptor Trimm plate: these plates are vertical extensions located underneath at the back of the hull. They are designed to guide high-pressure flow generated by the propellers dow nward, resulting in the creation of a lift effect. This option is appropriate for vessels that ha ve reasonably fast speeds, such as RoRos and ferries. The fuel efficiency gain ranges from 1% to 5% for modest power demand and there is a 4% improvement for a typical ferry (Al media, 2012).

## 4.11 CARBON CAPTURE TECHNOLOGY

Carbon capture technology has become one of the promising ways for the reduction of GH G emissions. Carbon capture technology is the practice of capturing carbon dioxide or carb on from the main source of emissions or from atmosphere and storing it permanently or te mporarily underground or utilising it for commercial purposes. In the figure 2, the process occurs where the CO2 is captured from the emissions sources then transported through pip eline or by ships and finally it is stored or injected under rocks permanently isolated from t he atmosphere.

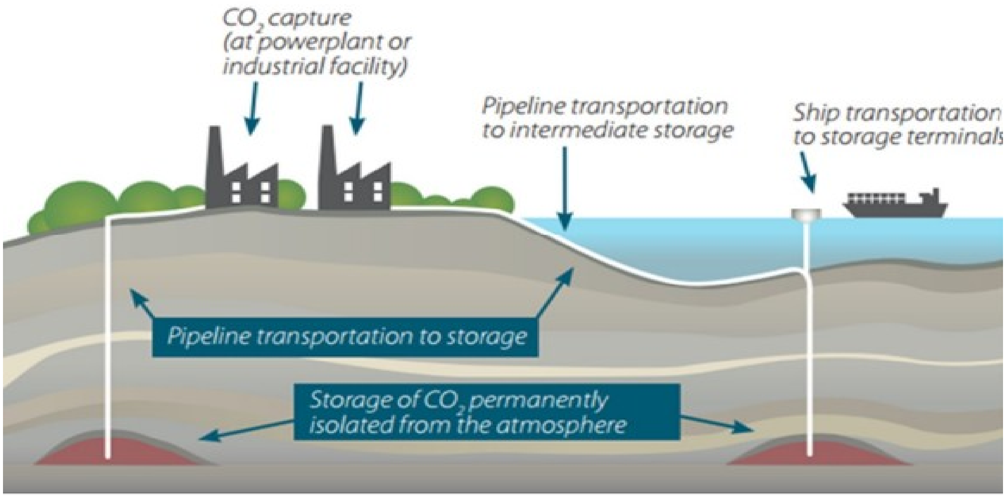


Figure 4. The basic principle for Carbon Capture and storage. CCSP research program. CLI C Innovation Oy. Source: [https://www.vttresearch.com/sites/default/files/2023-04/CCSP%20Final%20report.pdf](https://www.vttresearch.com/sites/default/files/2023-04/CCSP%20Final%20report.pdf)

According to the Finnish Funding Agency for Technology and Innovation, 2011 -2016, the
study shows that carbon capture technology leads to the reduction of 80% GHG emissions
by 2050 in Finland.

There are three types of  carbon capture technologies used on ships, industrial or power pla
nts which are post-combustion capture (PCC), pre-combustion capture, and oxyfuel combu
stions. The process of capturing Carbon dioxide from flue gases during combustion is kno
wn as post-combustion capture. Whereas pre-combustion capture is the process of converti
ng to carbon monoxide by reacting fuel with steam and oxygen which is then converted to
pure hydrogen and carbon dioxide resulting in high concentration of hydrogen fuel. Oxyfu
el combustion follows the process of fuel combustion reacting with pure oxygen resulting
in production of flue gas containing 80% of carbon dioxide. Post-combustion capture techn
ology is based on using of amine-based solvents, which is the most studied process among
the three capturing technologies. (Elfving, 2021, p.16). Due to the higher cost for changing
the ship's fuel and power generation system, pre-combustion and oxyfuel methods might n
ot be the ship's owner's first priority. However, post-combustion capture method has been f
ound to be efficiently manageable and likely to be less costly, and does not require high an
d advanced retrofitting of the ship's engine. (Baker, 2021).

### 4.11.1 Onboard Carbon Capture and Storage (OCCS)

Onboard carbon capture technology works under the principle of capturing carbon before t
he exhaust gas is emitted or released into the atmosphere. Onboard ships are integrated wit
h the vessel's fuel system by installing carbon capture systems. Pre-combustion or post-co
mbustion methods are used to capture CO2, where carbon is captured before and after the c
ombustion of fuel, respectively and stored separately. The space for installation onboard ha
s been a matter of discussion. In 2022, Hanwha Ocean collaborated with Greek shipping co
mpany Gaslog, developing and installing OCCS technology onboard four different liquifie
d natural gas (LNG) carriers.  (Hanwha, 2023).


Figure 5. Hanwha Ocean's liquefied carrier ship on display.

Source: https://www.hanwha.com/newsroom/news/feature-stories/diving-into-decarbonization-onboard-carbon-capture-and-storage-and-its-role-in-maritime-net-zero-efforts.do

Also, Wärtsilä has designed a CO2-capturing exhaust system. CCS- ready scrubbers are built and offered to ship owners for installation, ensuring profitability and efficiency. The basic principle of CCS scrubbers is based on an amine-based solvent. In Figure 5, amine solvent captures CO2 in which saturated CO2 is transferred through different processes to be stripped off. The saturated CO2 solvent is again heated, and pure CO2 is extracted and stored. The remaining solvent is again used in the CCS process. The test and experiment have demonstrated the capture rate of 70% CO2 which is under the regulation of IMO GHG emissions in shipping industries. Wärtsilä announced the world-first maritime CCS product launching by 2025. (Wärtsilä, Wärtsilä Exhaust Treatment, n.d) and (Wärtsilä, 2022).

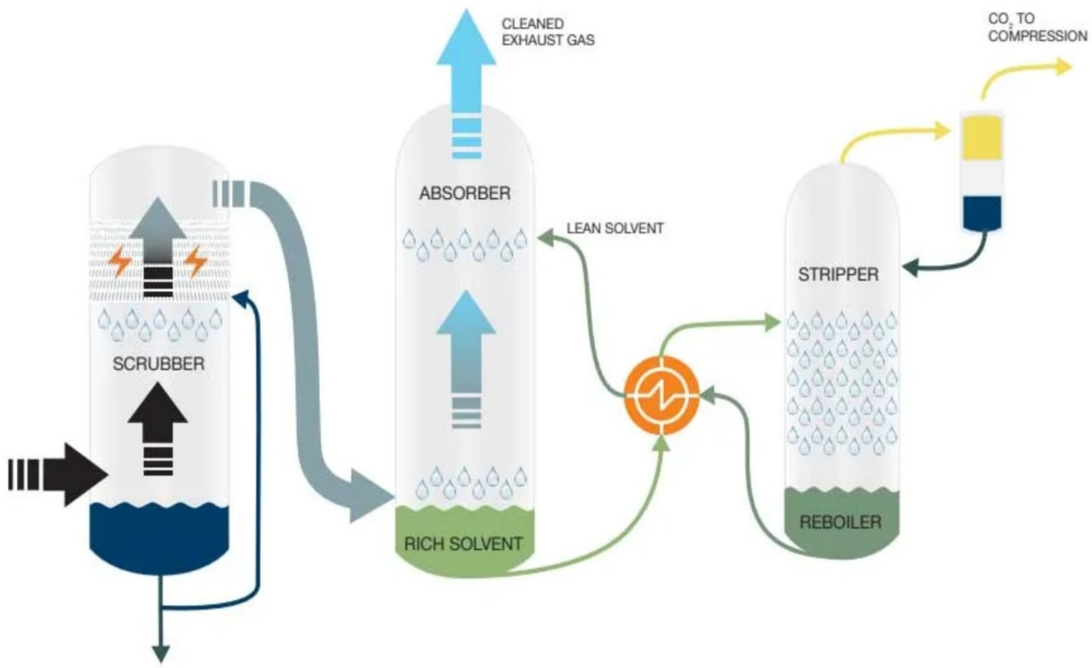


Figure 6. Wärtsilä Exhaust Treatment engineering principles.

Source: https://www.wartsila.com/marine/products/exhaust-treatment/carbon-capture-and-storage

# 5 Research Methodology

For this thesis work, the qualitative research method is adopted to assess opinions to generate quality results. According to Kothari and Garg, the qualitative research method makes it much easier to analyze people's opinions and gives participants the freedom to discuss a particular topic (Kothari & Garg 2014). A semi-structured interview is employed in this research since it is widely accepted that it is the most suitable way to conduct an interview because it is very flexible and gives room for quality data to be collected (Gilham, 2025). The data collecting method involves using a recording device to record each participant's interview. The interview took place between the 15th of March to the 5th of April 2025 and some of the interviews were held on teams and some of the participants preferred to answer the questions in written form and sent to me which was also very fine.

## 5.1 Data collection method

The purposive sampling method was employed to pick the interview participants. Purposive sampling is characterized by the researcher intentionally selecting research participants rather than employing a random selection method. The objective of purposive sampling is to select cases or participants strategically, ensuring their relevance to the research topics being addressed" (Bryman, 2016). This allows for the advantage of collecting input from readily accessible individuals and participants who have knowledge and experience that are important to the research topic

## 5.2 Challenges

Conducting interviews has drawbacks that can lead to errors and such mistakes may arise from misinterpretation of spoken or unspoken content, personal interpretation, or omission of communicated information. (Bryman, 2016). Our prior knowledge in business administration made creating the first basic plan for my thesis research simple. The degree program in marine technology lasts 4.5 years, so we had learned enough throughout our studies to be able to start with our thesis with ease. There were some minor issues, such as coordinating interview schedules with a few candidates who have busy schedules and other commitments, but these were easily resolved. This was understandable given their busy schedule, including work, travel, and meetings. Taking notes during interviews was challenging but recording them assures quality and avoids missing important information. Transcribing and listening to recordings were time consuming and tedious. It took around three to five hours to listen and write a clear transcript after an hour of recording. But however, doing the interviews was engaging and added value to the topic.

## 5.3 Interview participants

Sampling was used to pick out the right participants for this interview. Sampling is the process of using a subset of the population to represent the whole population (Will, 2022). Sampling makes it possible for research to be carried out with a more realistic cost and time frame since it uses a small number of individuals to represent the whole population. For this research, the purposive sampling method was used since in this method, participants are chosen based on their knowledge and understanding of the research questions (will, 2022)

All the participants choose for this research work have above 10 years of working experience in the maritime sector, and they all work as technical superintendents in reputable shipping companies within Finland. Their day-to-day job involves formulating ways to reduce the carbon footprint of their respective vessels. All the participants also hold degrees in maritime technology in Finland. Their vast experience within the maritime sector made them the ideal candidates for this research work.

## 5.4 Background of the Interview Participants

Respondent 1 is an experienced engineer who has been working as a technical superintendent for 10 years and manages state-of-the-art eco-friendly ships where he works, and also has a degree in maritime technology and has been sailing as an engineer for more than five years.

Respondent 2 is a professional maritime engineer who works as a technical superintendent and has more than 10 years of working experience in this role. His day-to-day job involves developing best practices to reduce $CO2$ emissions of the vessels under his control. He also has a degree in Maritime technology and has long experience sailing as an engineer.

Respondent 3 is a seasoned maritime engineer who has more than 25 years of working experience as an engineer on various types of vessels and is now working as a technical superintendent in.

Respondent 4 is actively working for the last 10 years in crude oil tankers as a Chief Engineer. His career started in 1992.

Respondent 5 is a maritime chief engineer. He has been working as a seafarer since 1985.

Respondent 6 has been working in Finland and Germany. Since 2020, he has been working as a Chief Engineer.

## 5.5 The interview

Emails were sent to prospective participants who are technical superintendents of their respective companies. Some were very interested in participating and some were busy with other commitments and could not participate, and others agreed to answer the questions and sent it to me via email. For those who could participate, the interviews were held between 25.03.2025 and 05.04.2025. The interview was conducted in teams and was recorded with the permission of the participants and the interview lasted between 35 minutes to 1 hour. One of the respondents was interviewed by messenger call, and two were conducted in an in-person meeting onboard and offshore (Vantaa airport).

## 5.6 Interview Questions

These interview questions aimed to collect detailed insights and qualitative information from participants. The interview questions seek to investigate participants' thoughts, feelings and experiences concerning the subject of the research (Dovetail, 2023). Through interviews, we aimed to discover detailed viewpoints that quantitative methods might miss. The structure of these questions spans from open-ended to semi-structured formats, which provides flexibility for participant responses. The research aimed both to deepen comprehension of the topic and to support the study's comprehensive results. Seven questions were developed for this research, which are:

**Question 1:** What are the maritime industry's biggest challenges in achieving decarbonization? Or a. How will you describe the current state of sustainable shipping practices in Finland and the world?

**Question 2:** What emerging technologies, alternative fuels and policy framework do you believe hold the most promise in reducing emissions in the maritime sector?

**Question 3**: Can you share examples of successful decarbonization projects or initiatives in the maritime industry, especially in the company you currently work with?

**Question 4**: What are the key trends or developments that will shape the future of sustainable shipping, and what do you see as the most realistic timeline for achieving the IMO 2050 decarbonization target?

**Question 5:** What are the biggest misconceptions about decarbonizing the maritime industry, and how can the industry overcome resistance to change from traditional stakeholders?

**Question 6:** If you could change one thing to accelerate the decarbonization of the maritime industry, what would it be?

**Question 7:** What advice would you give to researchers or organizations looking to contribute to this field?

## 5.7 Findings

The findings of this research work will be classified under 7 different themes to ease the understanding of the outcome of this research work. These themes are derived from each of the interview questions. The various themes discussed in these findings are as follows:

### 5.7.1 Theme 1: Maritime industry challenges

This theme is derived from the interview question What are the maritime industry's biggest challenges in achieving decarbonization? Or how will you describe the current state of sustainable shipping practices in Finland and the world?". This theme examines how the maritime industry faces multiple obstacles in its decarbonization efforts as it stands at a pivotal point in reducing greenhouse gas emissions. All the respondents to this question agreed that the maritime sector needs to decarbonize, and they gave varied reasons why decarbonizing the maritime sector is proving challenging. Their reasons can be seen from their responses to the interview questions as seen below:

**Respondent 1**: he said, "Transitioning to low-emission fuels (e.g., green hydrogen, ammonia, methanol) requires significant investment in new ships, retrofitting older vessels. Alternative fuels are not yet widely available on a commercial scale. Also, the infrastructure for fuel production, storage, and distribution is not yet well developed".

Also, he again mentions that “Another issue is the lack of uniform regulations across countries. While organisations like the IMO set pollution reduction targets, uneven rules between regions can slow progress and increase compliance costs. For example, the EU is committed to decarbonisation, but other regions may not be as focused, making it difficult to implement global solutions.”

Finally, he further stated that “Shipping is a tough business with tight profits, so investing in greener technology isn’t always affordable without government support. Since ships last 20–30 years, replacing them with cleaner models takes time and money. Without incentives or subsidies, many older, high-emission ships stay in service, making it harder to cut carbon emissions quickly.”

**Respondent 2:** According to him, regarding the challenges facing decarbonisation of the maritime industry, he said that for smaller companies to adapt to all IMO regulations regarding decarbonisation is very expensive, and it is tough for these smaller companies to follow this regulation and still stay profitable. So, they turn to react more slowly to decarbonisation regulations. He also mentioned that some top politicians do not believe that climate change is a problem, thus limiting funds for green energy projects. Furthermore, he stated that since “ordinary diesel engine are still the most reliable alternative” for maritime operation, this makes decarbonising the maritime industry very challenging. Respondent 1 also emphasises the important of communication between regions so as to ensure that all the regions are following the decarbonisation regulations.

**Respondent 3:** In his view, experts in the maritime industry have “To keep finding the right technology at the same speed as the demand for shipping grows. With increasing demands on global shipping, identifying and installing sustainable technologies can prove challenging. It is hard for industry to find ways around the technicalities of managing a shift to low-emission alternatives while making sure that the new technologies can still be implemented quickly enough to satisfy the market's short-term demands.

**Respondent 4:** He stated the dependency of maritime industry in heavy fuel oil globally. New technology onboard and adaptation are the most common challenges.

**Respondent 5**: He highlighted the wide acceptance of heavy fuel oil. Common challenges are IMO policy regulation and stricter monitoring.

**Respondent 6:** He agreed with the dependency on heavy fuel oil. He stated the challenges of how regulation has been regulated and monitored in different parts of the world.

### 5.7.2 Theme 2: Sustainable Maritime Practices

This theme is formulated from the research question "What emerging technologies, alternative fuel and policy framework do you believe hold the most promise in reducing emissions in the maritime sector?". Addressing maritime sector emissions demands research into emerging technologies, alternative fuels, and policy frameworks. This theme focuses on discovering solutions that will greatly decrease the carbon footprint of maritime operations. By analyzing the connections between these aspects, this question intends to discover strategies that fulfil international emission standards while advancing economic and environmental performance in the maritime industry. The respondents all agreed that a combination of regulatory frameworks, alternative fuels and emerging technologies needs to be adopted to decarbonize the maritime sector. In their view, all options are open so long as it reduce the carbon footprint of the maritime industry. Their responses to this theme are as follows:

**Respondent 1:** In response to this question, he said, "To make shipping more sustainable, several technologies and fuels need to be explored. Wind-assisted propulsion, like rotor sails and rigid sails, utilizes wind energy to reduce fuel use. Air lubrication systems create a layer of bubbles between the ship and water to reduce friction, improving efficiency. Fuel cells and battery systems, including hydrogen and ammonia, offer zero-emission solutions for short- and medium-range shipping. AI-driven tools help optimize routes and energy use, cutting fuel consumption and emissions. Carbon capture systems onboard ships can also directly reduce $CO_2$ emissions."

Respondent 1 further stated that "Alternative fuels are a key part of the solution. Green hydrogen and ammonia are promising zero-carbon fuels but require new infrastructure and engine adjustments. Bio-based and green methanol can be used with existing engines, reducing emissions. Biofuels like biodiesel and Bio-LNG offer lower carbon intensity and are a near-term solution, while LNG, though not carbon-free, cuts down on pollutants like SOx, NOx, and particulates. There's also potential in nuclear propulsion with small modular reactors, although regulatory and public acceptance challenges remain.

He then concluded by saying that "Policy frameworks, such as the IMO's stricter regulations (CII and EEXI), are pushing for greater efficiency, while carbon pricing and emission trading schemes, like the EU's ETS, incentivize the adoption of greener fuels."

**Respondent 2:** He stated that the existing IMO and EU emissions regulations hold significant promise and are beneficial as they “exert pressure on shipping companies to decarbonize, leaving us with no choice but to adapt”. He also discussed alternative fuels such as ammonia, methanol, and biofuels, which he believes are promising options; however, substantial investment in infrastructure and adoption is still required. He emphasized the importance of wind sails for longer voyages across the Atlantic but advised that for journeys through archipelagos, a chargeable battery should be utilized due to the weaker winds in those areas. This way, the wind rotor can charge the battery, which can be used when wind conditions are unfavorable.

It can be deduced from the interview that both respondents believe that decarbonization of the maritime sector is achievable. They didn’t point out any alternative fuel, regulatory frameworks or emerging technologies as the most promising because each alternative fuel, whether it is hydrogen, biofuels, or ammonia, presents unique advantages and challenges that must be carefully evaluated. Similarly, emerging technologies such as wind-assisted propulsion and energy-efficient hull designs offer potential benefits but require further development and integration into existing systems. Regulatory frameworks also play a crucial role in shaping the industry's approach to sustainability, yet they vary significantly across regions and can sometimes hinder innovation. Therefore, an approach that combines various strategies and technologies, rather than relying on a singular alternative, is ultimately the most effective way to achieve significant reductions in carbon emissions within the maritime sector.

**Respondent 3:** In his view, “A combination of various technologies until someone invents something completely different must be applied to push forward decarbonization in the maritime sector. We are all aware that the maritime sector accounts for a large share of global GHG emissions, and thus, innovative decarbonization solutions are necessary. This challenge may be addressed through a collaborative approach of several technologies. This can be first through the adoption of new alternative fuels, such as hydrogen, ammonia, and biofuels, that can greatly decrease the carbon emitted from ships. Second, more reliance on renewable energy sources like solar and wind energy can help supplement the use of traditional fuels, thereby optimising energy efficiency. Furthermore, Technology improvements on batteries and hybrid designs will help us to adapt to energy needs and last but not the least, AI technologies to enhance routing and management processes, which leads to decreased fuel consumption. The adoption of these multiple technologies may enable the maritime industry to progress towards sustainability with reduced carbon emissions.”

**Respondent 4:** He precisely indicates the initiation of use of alternative fuels such as liquified natural gas (LNG), biofuels, green ammonia and hydrogen. He also emphasized in innovation of new technology and implementation of carbon capture technology onboard. He stated the role of IMO; ship owners and emissions trading system regulation plays a vital role in reducing carbon emissions.

**Respondent 5:** He believes the use of renewable marine fuels, hybrid vessels, LNG vessels, and carbon capture technology onboard would be better practice to reduce carbon emission in maritime sector.

**Respondent 6:** In his opinion, new and old ship engine should be converted or built where renewable fuel can be used alternatively adding scrubber system.

### 5.7.3 Theme 3: Decarbonisation in the Maritime Industry

The theme stems from the interview question 3, asking for successful decarbonization projects or initiatives within the maritime industry and specifically within the respondent's current company. The theme examines successful decarbonization projects in maritime operations by highlighting case studies from participants' current companies. The theme focuses on reviewing case studies to pinpoint successful strategies and technologies that have effectively decreased carbon emissions in maritime operations. The question aims to demonstrate the company's sustainability efforts and provide valuable insights and lessons which can benefit the entire industry.

All the respondents presented shared decarbonization projects in their respective companies, which demonstrated shared commitment to reducing greenhouse gas emissions. The respondents shared a variety of innovative sustainability practices they had implemented within their companies. Their common experiences revealed that these companies aimed to promote environmental sustainability using emerging technologies, improved energy efficiency methods and a regulatory framework while promoting corporate responsibility. Thus, they responded as follows:

**Respondent 1:** according to respondent 1, the company he works for has “introduced several successful green initiatives to cut fuel use, lower emissions, and promote sustainability in shipping.” Some of the key projects he mentions include the green newbuilding programme which involves his company investing 500 million euros in December 2023 to purchase 5 new hybrids which include three Eco-class ro-ro vessels and two Superstar ro-pax vessels. These ships are equipped with advanced technologies aimed at energy efficiency and emission reduction. These hybrid vessels have High-powered battery banks that enable zero-emission operations in ports. He goes on to say that these hybrid vessels are equipped with an "Energy Management System (EMS) that controls the control process between the Hybrid Drive System (HDS), the main engine, and the propulsion control system, allowing a constant Main engine load despite the adverse sea conditions, ensuring that engines are running at the highest efficiency level."

To further reduce their carbon footprint and improve fuel efficiency, the company makes use of advanced hull optimization by using Hull coating like "XGIT-FUEL which is a special graphene-based hull coating that doesn't contain harmful biocides. Since 2022, they've applied it to four ships, reducing fuel use and emissions by about 7% by making the hull smoother and cutting down on drag." Also he said "regular Hull Maintenance which involves cleaning of ship hulls and application of silicone anti-fouling coatings reduce water resistance and fuel consumption.

In addition to that, he expresses that the company has implemented several operational strategies to improve energy efficiency and reduce emissions such as fleet renewal and route Optimization since investments in modern vessels and optimized routing contribute to lower emissions per transported cargo unit. Furthermore, the company is currently negotiating for the new building of new green passenger ships.

**Respondent 2:** in his response to this theme question said all their ship are fitted with shore base connection which means they can now get their electricity from the shore there by reducing carbon emission when ship is at the port. All though he mentioned that not all ports have such facilities but they on their part have shore base connection installed on their vessels. He mentioned that Norway has good energy production from their hydro power electric station and provide enough electricity for ships at port. He also discusses that the company has also been investing in operational measures like having to "change and upgrade propeller blades and propeller curves on their vessels so as to get the main engine optimised." Also, vessels in their ship have optimized hull that have been painted with low-slip paint, thus reducing friction and drag, thereby increasing fuel efficiency.

**Respondent 3:** To this question, respondent 3 answered that "some decarbonisation project that we have implemented on some of our vessels includes wind-assisted power implementation as well as propeller optimization and electric motor frequency converter installation combined with underwater paint application on selected vessels in our company. Last year we outfitted the ODDA Marie vessel with Econowind  V3 VentiFoil sails together with a shore power connection which resulted in improved operational efficiency for the ship. The shore power connection minimizes emissions through harbor electrical supply connections while the VentoFoil reduces fuel consumption with rapid deployment. The MV Odda Marie uses this VentoFoil system to decrease operational emissions and support sustainable long-term maritime operations."

**Respondent 4:** According to the sustainability report 2023, the shipping company where he is working has achieved a 44.1% reduction in carbon emissions between the year 2022 and 2023 (OSM Thome Sustainability report, p.17). He mentioned the project of building green alternative fuel ship where some of the vessels have already been sailing. He stated the vessel currently working is following MRV regulation (monitoring, reporting and verification of carbon dioxide emissions).

**Respondent 5:** Based on sustainability report 2024, he stated the company has announced the target of reaching zero carbon emissions by the year 2040 (ESL shipping sustainability report 2024, p.5). The company has LNG and hybrid fleets. He mentioned that the company is building four new fleets which are run by green methanol by the year 2027 (ESL shipping sustainability report 2024, p.11).

**Respondent 6:** He indicates that the current fleet runs by heavy fuel oil. His job is to record the fuel consumption and carbon emissions data which are sent to office for further analysis and follow further instructions.

### 5.7.4 Theme 4: Decarbonisation trend

This research is adopted from interview question 4, and the theme examines how sustainable shipping is changing by identifying the primary trends and developments that will affect maritime operations in future years. This research theme seeks to find emerging technologies, evolving regulations and market trends that will be essential in determining the future direction of maritime operations. The investigation aims to develop a practical schedule to meet the International Maritime Organization's (IMO) 2050 greenhouse gas reduction goal for shipping. The research will reveal how achievable sustainability goals are while identifying obstacles that might emerge during the process through an analysis of these factors.

All participants have different views on the developments that will affect maritime operations in the future, but they were all optimistic about the future trend in maritime operations. They highlighted the potential of regulatory frameworks, cleaner fuels, emerging technologies, energy efficient vessels and improved engines technologies to continue to grow in the future. Their responses can be seen bellow.

**Respondent 1:** In anticipation of trends that will affect the future of maritime operations, he said "The IMO's 2050 decarbonization goals are ambitious but achievable with the right steps. From 2025 to 2030, we'll see rapid growth in ships powered by methanol, ammonia, and biofuels, alongside large-scale testing of hydrogen and fuel cell technologies. Ports will expand shore power and electrification, and regulatory pressures, like carbon pricing, will increase."

He further stipulated that "Between 2030 and 2040, alternative fuels will become more widely adopted as costs fall, and hydrogen and ammonia will become commercially viable for large vessels. Digital technologies like AI will help further reduce emissions, and carbon-neutral shipping routes will start to take shape."

He also believes that "By 2040 to 2050, most new ships will run on zero-emission fuels, and older vessels will be retrofitted for cleaner operations. Stricter regulations will push out the remaining fossil-fuel ships. While the 2050 target is realistic, delays in infrastructure or fuel development could push full decarbonization beyond that date."

**Respondent 2:** In his view, he expects rapid development in alternative fuels like Methanol, Biofuel, ammonia and hydrogen and stricter regulation on carbon emissions. He also noted that sail technology used with powerful chargeable batteries will pick up and shore base power connection will be set up at port facilities to reduce emissions at port. Huge investment will be made in the decarbonization effort and government support to maritime operator will also grow since the burden for decarbonization should not fall on ship operators alone. He believes that "shipping companies will follow trends and change if there are value in the changes and of course from shipping company point of point of view it's all down to costs."

**Respondent 3:** In this theme, he responded that "crucial developments in technology through improvements in engine efficiency and energy-saving devices as well as digital route optimization solutions will drive future progress. The use of artificial intelligence along with machine learning techniques will improve operational efficiency, which will result in lower fuel usage and decreased emissions. The IMO 2050 decarbonization goal demands combined actions from shipowners, manufacturers and governments although the timeline remains ambitious. Broad implementation of sustainable practices and technologies by 2050 remains uncertain because nobody knows when those advancements will become widespread."

**Respondent 4:** He stated the serious concern on IMO zero carbon emission target by 2050. In his opinion, the vigorous development of using alternative fuel oil, carbon capture technology onboard are the promising trend of future sustainable shipping. He mentioned a neutral position in achieving zero carbon emissions by 2050.

**Respondent 5:** He stated a huge hope and positiveness towards achieving net zero carbon emissions by 2050. He believes in innovation and use of varieties of alternative fuel as a key trend in decarbonization in maritime industry.

**Respondent 6:** He noted the introduction of alternative fuel, green fuel engine, and carbon capture technology onboard are the key factors in decarbonization in maritime industry. However, he stated that he is not fully convinced in achieving net zero carbon emission by 2050. He believes the big obstacle could be the acceptance of new technology and the huge cost by ship owners.

### 5.7.5 Theme 5: Misconception of decarbonization practices in shipping

This research question is derived from interview question 5 and it investigates common misunderstandings about maritime industry decarbonization while developing methods to reduce traditional stakeholders' resistance to change. This research question identifies and clarifies misunderstandings that obstruct sustainable practices in maritime operations.

All respondents highlighted that misconceptions surrounding the maritime sector still exist and must be addressed. Some respondents pointed out the myth that decarbonization is expensive while others pointed out the importance of education and awareness of stakeholders to the dangers of climate change. Their opinions can be seen from their responses below:

**Respondent 1:** He stated that, "There are several common misconceptions about decarbonizing the maritime industry. One is the belief that it's too expensive to switch to alternative fuels and new technologies. While the upfront costs can be high, the long-term savings from fuel efficiency, carbon tax reductions, and meeting regulatory requirements make it economically worthwhile. Financial incentives and subsidies can help ease this transition."

He also mentioned that "Another misconception is that alternative fuels like green ammonia, hydrogen, and biofuels aren't scalable yet due to production and infrastructure challenges. However, investments in fuel production and global infrastructure can speed up their adoption.

In addition to that, he talked about "resistance to emissions regulations, with some seeing them as unnecessary red tape. However, clear and phased policies, created with industry input, can drive innovation and long-term sustainability instead of just adding extra costs.

Finally, "Finally, many assume older ships can't be made more sustainable, thus slowing down the process. Retrofitting existing vessels with technologies like air lubrication, wind-assisted propulsion, and carbon capture can significantly reduce emissions without needing to replace the whole fleet."

**Respondent 2:** with fuels that are still harmful to the climate. He believes that until these loopholes are stopped, effective decarbonization will continue to be evasive. In his views, some loopholes still exist in some regulations for example, the IMOs Carbon Intensity indicator (CII) regulation and the Eu Emissions trading system that requires company to pay for their emission is being taken advantage of by some company thus allowing their vessels to operate

He also talks about some top stakeholders and politicians who still don't believe climate change is real and is just unnecessarily expensive, thus they tend not to want to invest in clean energy alternatives. But he believes this will change in the future with stricter regulations being put in place. Again, in his opinion, since decarbonization is a global issue and not a regional issue, some regions still believe they are not responsible for the damage done to the environment and don't accept being signatories to important emission regulations, which is not good for the fight against climate change.

**Responded 3:** According to him, "Many people wrongly believe shipowners alone must lead sustainability transitions when in fact technology manufacturers, governments and international organizations must join forces with shipowners to achieve sustainable practices. People often believe technological progress happens rapidly, but widespread, sustainable technological adoption takes more time than expected. Also, the industry can diminish stakeholder resistance to change by initiating open communications and educating about decarbonization benefits while showcasing the sustainable practices' economic benefits over time.”

**Respondent 4:** He noted that IMO and ship owners are not the only responsible parties for decarbonization. He emphasized global cooperation and the wide acceptance of new technology.

**Respondent 5:** He believes decarbonization can be overcome, but at the same time he has a concern about the development of infrastructure, cost, and the regulation of policy. In his opinion, IMO, ship owners, the global market, and the individual person are responsible. He mentioned that the future global decarbonization in the maritime sector depends upon the development of technology by 2035.

**Respondent 6:** He stated a clear set of open minds towards new technology and innovation regardless of cost.

### 5.7.6 Theme 6: Personal Decarbonization Strategies

Developed from the “interview question 6”, this study utilizes this research question to pinpoint essential factors or technologies perceived by participants as capable of achieving major greenhouse gas emission reductions. Through this question, we aim to obtain various viewpoints from our interviewees, which will help us identify the most effective changes that can be implemented.

The respondents were willing to share their personal strategy, which they believe could fast-track the decarbonization process. They highlighted their commitment to adopting cleaner technologies and innovative solutions that not only address environmental concerns but also enhance operational efficiency. Their responses were as follows:

**Responded 1:** In his response to this theme question, he declared that “If I could change one thing to speed up the shift to cleaner shipping, it would be investing heavily in alternative fuel infrastructure—things like green hydrogen, ammonia, methanol, and biofuels.

Also, Governments need to play a bigger role in helping shipowners make this transition.

In addition to that, decarbonizing the industry requires huge investments in new fuels, technology, and infrastructure—costs that shouldn't fall entirely on shipping companies or be passed down to consumers.

Finally, Policymakers should implement subsidies, tax incentives, and funding programs to ease the financial burden on shipowners. With the right support, we can cut shipping emissions faster without hurting global trade or the economy."

**Respondent 2:** For him, he will "like to see fair and universal implementation of emission regulation around the globe and better economic incentives for shipping companies". He believes that shipping companies should be able to decarbonize and still be able to continue business, and it should be worth making these changes economically because it's very expensive to decarbonize. Also, he said he will "push for tax breaks, grants and subsidies to shipping companies that invest in fuel-efficient vessels or cleaner technologies."

**Respondent 3**: In his opinion, "If i could change something, it would be to develop advanced fuel and combustion engine technologies because the development of new ship propulsion technologies stands as a primary method to achieve fuel efficiency. New fuels combined with advanced engine designs will lead to significant reductions in greenhouse gas emissions and better energy efficiency."

**Respondent 4:** His opinion on decarbonization strategies could be building new greener technology ship. He stated that the cost of building a new technology ship might be costly. However, he mentioned that in the beginning, new choices are always difficult to accept.

**Respondent 5:** He emphasizes stricter regulation on building hybrid vessels, the use of renewable energy, and promoting promising carbon capture technology onboard.

**Respondent 6:** He pointed out stricter regulation of IMO policy, huge compensation fines for carbon emissions, and investment in new technology.

### 5.7.7 Theme 7: Advice for Researchers and Organizations

The question to this theme is "What advice would you give to researchers or organizations looking to contribute to this field?". This question seeks to collect valuable insights and recommendations from our knowledgeable participants. This question seeks to discover effective practices while identifying challenges and new approaches which aim to improve research quality and outcomes.

All the participants agreed that communication, collaboration and teamwork need to be encouraged between the various stakeholders involved in the maritime sector. The following answers represent how the respondents reacted to this question

**Respondent 1:** "To make shipping more sustainable, we need practical, affordable solutions like cleaner fuels, wind-assisted propulsion, and upgrades to existing ships. Real progress comes from teamwork—fuel producers, shipbuilders, technological companies, and policymakers all need to work together. Researchers in this field need to work to build a bridge that fosters communication and collaboration between the various stakeholders in the maritime sector."

**Respondent 2**: According to him, "to accelerate the decarbonisation of the maritime industry, shipping companies, stakeholders, technology providers and international maritime bodies, and fuel producers must work together strategically. Cooperation and teamwork need to be encouraged."

**Responded 3:** In his view, "Firstly, cooperation with other researchers, institutions, and industry partners can lead to innovative solutions and broaden the impact of research work and ensure that research has real-world applications. It is also very good to consider how findings can be translated into practice and how they can benefit the maritime industry.

Finally, researchers should be aware that by collaborating with other researchers and industry partners, they can create innovative solutions which expand the influence of their research and enable it to solve real-world situations. Researchers and organisation should also evaluate the practical application of their findings and their potential advantages to the maritime industry."

**Respondent 4:** He has some advice on support and funding for R&D, international collaboration, and investing in innovation for affordability of green technology.

**Respondent 5:** He stated the importance of study and investment in new technology for future sustainable shipping practice.

**Respondent 6:** He noted the study and more research in alternative fuel, new technology, and policy enforcement.

## 5.8 Outcome of the Research

The outcome of this research on the available pathways to decarbonize the maritime industry has revealed great insight into the decarbonization effort in the maritime industry. Our respondents are actively implementing strategies to integrate sustainable practice into their operations. This study sought to investigate the available pathways to decarbonisation in the maritime industry, thus highlighting important results that show possibilities as well as challenges.

Based on individual respondent views, the target set by IMO to achieve net-zero carbon emissions by 2050 is found to be positive and challenging. However, IMO regulation, shipping companies, ship owners, and global common effort and initiation lead the path of decarbonization. The study shows that the use of alternative fuel such as LNG, methanol, the implementation of carbon capture technology onboard, and hybrid fleets are the common methods suggested in decarbonizing the maritime industry. The initial common solution found to be use of alternative fuel instead of regular heavy fuel oil. All the respondent has mentioned carbon capture technology solution onboard, which seems to be a promising technology in the future. The interview reveals that individual companies like OSM Thome Shipping and ESL Shipping have contributed huge success in decarbonizing the maritime industry.

It was also found out that the most effective pathway available at the moment to decarbonise the maritime industry is a multifaceted approach to decarbonisation. As seen by the decarbonisation project carried out on the vessels from most of our of respondents' respective companies. Respondent 1 mention a combination of Hybrid systems, hull optimisation, solar panels, air lubrication systems and route optimisation as solutions chosen by their companies to decarbonise. Meanwhile, respondent 2 mentions shore-based electric connection and operational measures like hull optimization, propeller blade upgrade as methods for decarbonisation use on their vessels. Respondent 3 mentions the use of VentoFoils V3 sails together with a shore-based electric connection to curb carbon emissions on one of their vessels. Also, the theoretical material of this thesis mentions various pilot projects that have been carried out by various companies on their vessels to reduce their vessels' carbon footprint. For example, the ULSTEIN SX190 Zero Emission DP2 construction support vessel is powered by hydrogen, utilizing a cutting-edge Nedstack fuel cell power system in combination with an electric diesel engine. When in zero-emission mode, no greenhouse gases are emitted, thereby minimize the environmental impact of its offshore projects.

Secondly, this study revealed that regulatory framework plays a significant role in enhancing the right pathway to decarbonisation by establishing guidelines that regulate emissions and promote sustainable shipping. Respondents 1 mention that “The IMO's 2050 decarbonization goals are ambitious but achievable with the right steps”. He further stated that with a universal enforcement of IMO emission regulations in all regions, decarbonising the maritime industry will be achieved quicker. This view is strongly supported by all respondents in the interview. The theoretical material of this thesis also discusses several regulations that set legal and operational boundaries for ship owners and operators, ensuring compliance with international and regional agreements such as the IMO's emission reduction regulations, the Paris agreement and the EU Fit for 55 initiatives.

Furthermore, it was also discovered that collaboration amongst stakeholders, including ship operators, fuel suppliers, international organisations and technology developers, is very vital in promoting innovations and accelerating the transition to cleaner fuels in the maritime sector. All respondents in the interview encouraged collaboration and teamwork between stakeholders in the maritime sector since it will foster the decarbonisation of the sector.

In addition to that, it was also discovered that the government offering financial incentives like tax cuts and subsidies can encourage companies to decarbonise their operations. These measures greatly reduce the overall tax burden for companies and also make it more economically viable to transition to renewable energy sources and implement energy-efficient processes. This view was strongly brought forward by respondent 1 when he said, “Policymakers should implement subsidies, tax incentives, and funding programs to ease the financial burden on shipowners. With the right support, we can cut shipping emissions faster without hurting global trade or the economy”. This viewpoint is further supported in the theoretical framework of this thesis, where it explains national and regional efforts in decarbonising the maritime industry. For instance, Norway has developed a comprehensive strategy to provide subsidies and tax incentives for companies that acquire eco-friendly vessels. In 2019, Norway's national budget established a dedicated fund to facilitate the implementation of low-emission and zero-emission initiatives for high-speed passenger ships.

Finally, it was also found out that infrastructural developments play an important role in reducing carbon emissions. Modernisation of port facilities, for instance, implementing a shore power connection, or bunkering facilities for different alternative fuels in all ports, will eliminate the need to use auxiliary engines, which normally use fossil fuel, thus curbing carbon emissions. All our respondents mention that they already have shore electric connections on their vessels, but some ports still don't have the facilities. This is a very big challenge to decarbonisation, which is also mentioned throughout the theoretical material of this thesis. For example, the Ulstein's SX190 Zero Emission Offshore Service Vessel can only operate in zero emission mode for 4 to 5 days due to infrastructural limitations of hydrogen bunkering facilities in most ports.

## 5.9 Conclusions

In conclusion, decarbonizing the maritime industry offers substantial opportunities alongside numerous challenges. The maritime sector needs to adopt innovative solutions like renewable energy systems and advanced propulsion technologies while improving operational efficiencies due to the growing global emphasis on climate change. Regulatory frameworks need to become a central focus for future efforts so they can promote sustainable practices while supporting the shift towards low-carbon technologies. Industry stakeholders, government bodies, and research organisations must collaborate to provide funding for green technology developments while establishing sustainable practices. Through strict adherence to these pathways, the maritime industry can attain sustainable economic viability while improving environmental responsibility, which will lead to a cleaner future for global shipping.

## 5.10 List of References:

Hui Xing, Charles Stuart, Stephen Spence, Hua Chen. 2021, Alternative fuel option for low carbon maritime transport: Pathways to 2050. Online: https://www.sciencedirect.com/science/article/abs/pii/S0959652621008714

Mohamad Issa, Adrian Ilinca, and Fahed Martini. 2022, Ship Energy Efficiency and Maritime Sector Initiatives to Reduce Carbon Emissions. Online: https://www.mdpi.com/1996-1073/15/21/7910

Junjie Dong, Jia Zeng, Yanbin Yang, Hua Wang. 2022, A review of law and policy on decarbonization of shipping. Online: https://www.frontiersin.org/articles/10.3389/fmars.2022.1076352/full

George Mallouppas and Elias Ar. Yfantis, 2021, Decarbonization in Shipping Industry: A Review of Research, Technology Development, and Innovation Proposals.Available Online: https://www.mdpi.com/2077-1312/9/4/415?trk=public_post_reshare-text

UNCTAD, 2023, A review of maritime transport 2023. Available Online: https://unctad.org/system/files/official-document/rmt2023ch3_en.pdf

Pariotis, E.G. and Zannis, T.C.; Yfantis, E.A.; Roumeliotis, I.; Katsanis, J.S. Energy Saving Techniques in Ships—Technical and Operational Measures. In Proceedings of the International Conference Green Transportation, Athens, Greece, 4 June 2016. [Google Scholar]

Lindstad E. and Rialland A. LNG and cruise ships, an easy way to Fulfil regulations—Versus the need for reducing GHG emissions. Sustainability 2020, 12, 2080. [Google Scholar] [CrossRef] [Green Version]

S. Brynolf et al. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and biomethanol (2014)

J. Hua et al. Alternative fuel for sustainable shipping across the Taiwan Strait Transport. Res. Transport Environ. (2017)

Maritime forecast to 2050 DNV Gl, S SAFER, G DNV - Energy transition outlook, 2018 - certifiedportexecutive.com PORTCON 2019 LA Long Beach - Annual Update Conference of the Certified Port Executive Program … www.dnvgl.com The trademarks DNV GL®, DNV®, the Horizon

European Commision (2021) Fit for 55. Available at: https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/.

Kothari C.R & Garg G 2013, Research Methodology: Method and techniques (3rd ed.) India, Heinemann

Balcombe, P.; Brierley, J.; Lewis, C.; Skatvedt, L.; Speirs, J.; Hawkes, A.; Staffell, I. How to decarbonise international shipping: Options for fuels, technologies and policies. Energy Convers. Manag. 2019, 182, 72–88. [Google Scholar] [CrossRef]

Hsieh, C.-W.C.; Felby, C. Biofuels for the Marine Shipping Sector; IEA Bioenergy: Paris, France, 2017. [Google Scholar]

Dr Prapisala Thepsithar, Alternative Fuels for International Shipping, published2020, Available Online: https://www.indonesiawaterportal.com/storage/eb/articles/263/mesd-afis-report-140420-spreads-low-res.pdf

Issa, M.; Beaulac, P.; Ibrahim, H.; Ilinca, A. Marinization of a Two-Stage Mixed Structured Packing Scrubber for Sox Abatement and CO2 Capture. Int. J. Adv. Res. 2019, 7, 73–82. [Google Scholar] [CrossRef]

John Kilner, HYDROGEN PRODUCTION METHODS AND ITS COLOURS, 2022, Available Online: https://cicenergigune.com/en/blog/hydrogen-production-methods-colours

Alireza Abbaspour, Nasrin Parsa and Mohammad Sadeghi, A New Feedback Linearization-NSGA-II based Control Design for PEM Fuel Cell, 2014. Available Online: https://www.researchgate.net/publication/271156635_A_New_Feedback_Linearization-NSGA-II_based_Control_Design_for_PEM_Fuel_Cell

Ulstein, Zero emissions operation in offshore Market. 2019. Available Online: https://ulstein.com/news/zero-emission-operations-in-offshore-construction-market

IRO, Ulstein`s road map to Hydrogen future. 2020. Available Online: https://iro.nl/news-and-press/roadmap-to-hydrogen-future/

Heather Thomson, James J. Corbett, and James J. Winebrake, "Natural Gas as a Marine Fuel," Energy Policy, Vol. 87, 2015,

S&P Global, Next big growth spurt for global LNG import demand to come in 2020s, report says, 2018. Available: https://www.spglobal.com/marketintelligence/en/news-insights/trending/rAbXm34iYK5ql1dwzYCN2w2

Man, LNG gas supply and bunker system, 2020. Available: https://www.man-es.com/docs/default-source/document-sync/lng-gas-supply-and-bunker-systems-eng.pdf?sfvrsn=b32d2eb5_0#:~:text=The%20LNG%20supply%20system%20consists%20of%20a%20vacuum,supply%20natural%20gas%20to%20engines%20on%20a%20ship.

Meryer Werft, AIDAnova, 2018, Available: https://www.meyerwerft.de/en/ships/aidanova.jsp

Shell, Decarbonising shipping: Setting shells course, 2024

Mr. Pradeep Nayyar, The Use of Biodiesel Fuels in the U.S. Marine Industry, 2010. Available: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=7616a20c5ebbe71f69877d75a4c6c39fd8958f22

Anouk Van Grinsven, Emiel Van Den Toorn, Reinier A. C. van der Veen, Bettina Kampman, Used Cooking Oil (UCO) as biofuel feedstock in the EU, 2010. Available: https://www.researchgate.net/publication/359135504_Used_Cooking_Oil_UCO_as_biofuel_feedstock_in_the_EU_Used_Cooking_Oil_UCO_as_biofuel_feedstock_in_the_EU

CSL, Biodiesel as an effective decarbonization transition solution for existing ships, 2021. Available at:
https://cslships.com/wp-content/uploads/2023/05/csl_biofuel_case_study_0.pdf

Konstantinos M. Fakiolas, Wind Propulsion Principles, ed 3, 2000.

Olga Petrychenko , Maksym Levinskyi , Sergey Goolak , Vaidas Lukoševičius , Solar Energy: Revolutionizing Shipping Industry Towards Sustainability and Environmental Stewardship, 2024. Available:
file:///C:/Users/Steph/Downloads/preprints202402.0154.v1.pdf

George Mallouppas & Elias Ar. Yfantis, Decarbonization in Shipping Industry: A Review of Research, Technology Development, and Innovation Proposals, 2021, Available:
https://www.mdpi.com/2077-1312/9/4/415?trk=public_post_reshare-text

Qiuwen Wang, Hu Zhang and Puxin Zhu, Using Nuclear Energy for Maritime Decarbonization and Related Environmental Challenges: Existing Regulatory Shortcomings and Improvements, 2023. Available at :
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9966280/#:~:text=Researchers%20have%20found%20that%20nuclear,31%2C32%2C33%5D.

Almedia Rob, Part 1: How to Design a More Efficient Ship, 2021. Available at:
https://gcaptain.com/part-design-efficient-ship/#:~:text=Finding%20the%20optimum%20length%20and,negative%20effect%20on%20total%20resistance

Hua, sha, Zhang & Cao 2023. Ocean Engineering. Volume 281. Available Online: https://doi.org/10.1016/j.oceaneng.2023.114929

CLIC Innovation OY, the Finnish Funding Agency for Technology and Innovation, 2011 -2016. Carbon Capture and Storage Program (CCSP). Available Online: https://www.vttresearch.com/sites/default/files/2023-04/CCSP%20Final%20report.pdf

Kujanpää, Reznichenko, Saastamoinen, Mäkikouri, Soimakallio, Tynkkynen, Lehtonen, Wirtanen, Linjala, Similä, Keränen, Salo, Elfving & Koponen, 2023. Carbon dioxide use and removal. Publication of the Government's analysis, assessment and research activities 2023: 19. Finnish Government. Available Online: https://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/164795/VNTEAS_2023_19.pdf https://urn.fi/URN:ISBN:978-952-383-197-1

Jere Elfving, 2021. Direct capture of CO2 from air using amine-functionalized resin- effec t of humidity in modelling and evaluation of process concepts. Available Online: https://lutpub.lut.fi/bitstream/handle/10024/163524/Jere%20Elfving_A4.pdf?sequence=1&isAllowed=y

Baroudi, Awoyomi, Patchigolla, Jonnalagadda & Anthony, 2021. A review of large-scale C O2 shipping and marine emissions management for carbon capture, utilisation and storage. Centre for Thermal Energy and Materials (CTEM), School of Water, Energy. Available Online: https://www.sciencedirect.com/science/article/pii/S0306261921000684?ref=pdf_download&fr=RR-2&rr=8bfd956d780f8dda

(Elfving et al, 2021). Elfving, Kauppinen, Jegoroff, Ruuskanen, Jarvinen & Sainio, 2021 E xperimental comparison of regeneration methods for CO2 concentration from air using ami ne-based adsorbent. Chemical Engineering Journal. https://doi.org/10.1016/j.cej.2020.126337 Retrieved from https://www.sciencedirect.com/science/article/pii/S1385894720324657?via%3Dihub

(Tavakoli et al., 2024) Tavakoli, Gamlem, Kim, Roussanaly, Anantharaman, Yum &Valland, 2024. Exploring the technical feasibility of carbon capture onboard ships. Journal of Clenaer Production. Retrieved from https://www.sciencedirect.com/science/article/pii/S095965262401480X https://doi.org/10.1016/j.jclepro.2024.142032

Baker, 2021. Can carbon capture technologies helps the shipping industry cut GHG emissi ons? Access on 11th September 2024. Retrieved from https://www.potterclarkson.com/insights/can-carbon-capture-technologies-help-the-shipping-industry-cut-ghg-emissions/

Government.no, Longship project, 2021. Climate, Industry and Technology Department. C an we guarantee that CO2 is safely stored? Access on 11 September 2024. Retrieved from https://www.regjeringen.no/en/topics/energy/landingssider/ny-side/sporsmal-og-svar-om-langskip-prosjektet/id2863902/?expand=factbox2864134

Hanwha, 2023. Diving Into Decarbonization: Onboard Carbon Capture and Storage and Its Role in Maritime Net Zero Efforts. Access on 11 September 2024. Retrieved from https://www.hanwha.com/newsroom/news/feature-stories/diving-into-decarbonization-onboard-carbon-capture-and-storage-and-its-role-in-maritime-net-zero-efforts.do

Wärtsilä, Wärtsilä Exhaust Treatment, “n.d”. Onboard carbon capture anstorage. Access on 11 September 2024. Retrieved from https://www.wartsila.com/marine/products/exhaust-treatment/carbon-capture-and-storage

Wärtsilä, 2022. How much could carbon capture help shipowners meet CO2 targets? Access on 12 September 2024. Retrieved from https://www.wartsila.com/insights/article/how-much-could-carbon-capture-help-shipowners-meet-co2-targets

Malmgren, E., Brynolf, S., Fridell, E. et al (2021). The environmental performance of a fossil-free ship propulsion system with onboard carbon capture - a life cycle assessment of the HyMethShip concept. Sustainable Energy and Fuels, 5(10): 2753-2770. http://dx.doi.org/10.1039/d1se00105a. Access on 12 September 2024. Retrieved from https://research.chalmers.se/publication/524139/file/524139_Fulltext.pdf

Dovetail Editorial Team, What is a semi-structured interview?, 2023. Available Online: https://dovetail.com/research/semi-structured-interview/

Will Webster, Sampling methods, types & techniques, 2022, Available online: https://www.qualtrics.com/experience-management/research/sampling-methods/#:~:text=There%20are%20two%20major%20types,zero%20chance%20of%20being%20selected.

OSM Thome Sustainability report 2023. Retrieved from https://osmthome.com/wp-content/uploads/06292024_OSM-Thome-Sustainability-Report-2023.pdf

ESL shipping Sustainability report 2024. Retrieved from https://www.eslshipping.com/hubfs/Documents/Sustainability%20reports/ESL%20Shipping%20Sustainability%20Report%202024%20lowres.pdf?hsCtaTracking=50fd281d-a5ad-4487-b176-889655c1b6af%7C7a064de6-0554-4cfc-9c99-f2a223f5a0a3