



# **A Comparative Study on Alternative Marine Fuels - Economic, Technology, Environmental and Safety Issues**

Master's thesis in the Master's Programme *Maritime Management*

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# A Comparative Study on Alternative Marine Fuels - Economic, Technology, Environmental and Safety Issues

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# Abstract

Transitioning to sustainable energy sources in the maritime industry is imperative for mitigating environmental impacts and achieving long-term sustainability goals. This master thesis explores the feasibility and potential of hydrogen as an alternative marine fuel, comparing it with other options such as liquefied natural gas, methanol, and ammonia. The study addresses several key questions: *What are the technological, economic, environmental, and safety implications of adopting hydrogen as a marine fuel? & How does hydrogen compare to other alternative fuels in terms of these criteria?* The authors employ a multidimensional analysis approach, incorporating methodologies such as the Analytical Hierarchy Process (AHP) and a Case Study of MV Venta Maersk to evaluate the performance of alternative fuels. The study begins by examining the technological landscape through a literature review, highlighting the challenges and opportunities associated with hydrogen production, storage, transportation, and utilization. It concludes that Carbon Capture and Storage technology, critical for blue hydrogen production, faces challenges related to stringent requirements and consistent natural gas supply. Conversely, green hydrogen production poses formidable hurdles due to cost implications and necessitates advancements in electrolysis technology and supportive governmental policies.

In assessing the environmental impact, this study emphasizes the significance of greenhouse gas emissions and marine pollution. Hydrogen emerges as a promising option, offering zero emissions during combustion and minimal environmental impact. However, the inherent characteristics of hydrogen pose technical and safety challenges. While LNG also demonstrates commendable environmental performance, generating minimal NOx and Particulate Matter emissions during use, it remains the top priority among alternative fuels due to its early adoption and relatively mature infrastructure. The AHP results from surveys have revealed a priority on safety and environmental concerns as critical criteria in the evaluation of alternative fuels. Methanol and ammonia rank lower in the comprehensive assessment due to their inherent challenges and safety considerations. Despite their potential, further research and development efforts are warranted to address technical and safety challenges and harness their full potential as viable fuel options. The study concludes by providing insights on limitations and suggests future research directions, emphasizing the need for technological innovation, supply chain optimization, and policy interventions to facilitate the adoption of alternative fuels.

**Keywords: Alternative marine fuels; Hydrogen supply chain; Analytic hierarchy process (AHP); Shipping, Maritime**

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# Abbreviations

<i>Abbreviation</i>	<i>Description</i>
AFC	Alkaline fuel cell
AHP	Analytical Hierarchy Process
BC	Black carbon
BOG	Boil-off gas
C <sub>4</sub> H <sub>10</sub>	Butane
CCS	Carbon capture and storage
C <sub>2</sub> H <sub>6</sub>	Ethane
CH <sub>4</sub>	Methane
CH <sub>3</sub> OH	Methanol
C <sub>3</sub> H <sub>8</sub>	Propane
CO	Carbon monoxide
CO <sub>2</sub>	Carbon dioxide
CBA	Cost-benefit analysis
CcH <sub>2</sub>	Cryo-compressed hydrogen
DAFC	Direct alcohol fuel cell
ECA	Emission Controlled Areas
GHG	Greenhouse gas
HFO	Heavy fuel oil
HVO	Hydrotreated vegetable oil
ICE	Internal combustion engine
LCA	Life cycle assessment
LBG	Liquid Biogas or biomethane
LNG	liquified natural gas
LPG	Liquid Propane Gas
MCFC	molten carbonate fuel cell
MCDM	Multicriteria Decision Making
MGO	Marine Gas Oil
NG	Natural gas
N <sub>2</sub>	Nitrogen
NO <sub>2</sub>	Nitrogen dioxide
NO <sub>x</sub>	Nitrogen oxide
PM	Particulate matter
ppm	Parts per million
pH	Pondus Hydrogenii
PAFC	Phosphoric acid fuel cell
PEM	Proton exchange membrane
PEMFC	Proton exchange membrane fuel cell
SOFC	Solid oxide fuel cell
SO <sub>2</sub>	Sulfur dioxide
SO <sub>x</sub>	Sulfur oxide
SECA	Sulfur Emission Control Area
\$/GJ	Gigajoule
\$/t	Monetary amount per ton



# 1 Introduction

## 1.1 Background

The most common fuel source used worldwide has been fossil fuels which have led to an annual consumption of 300 million tons (Deniz & Zincir, 2016). In recent years, there have been pursuits of finding alternative fuels that offer a mixture of efficiency, feasibility, and sustainability in their applications. Emissions from fuels range from carbon monoxide and carbon dioxide emissions (CO & CO<sub>2</sub>), sulfur oxide emissions (SO<sub>x</sub>), and nitrogen oxide emissions (NO<sub>x</sub>); all of which can vary depending on the alternative fuel (Deniz & Zincir, 2016). In the current maritime landscape, hydrogen, methanol, hydrotreated vegetable oil (HVO), FAME (biodiesel), ammonia, electricity, and liquified natural gas (LNG) have been considered as potential alternative fuels in the maritime sector (Prussi et al., 2021).

Most cargo ships are fueled with HFO (Heavy Fuel Oil) or MGO (Marine Gas Oil) because it has high economic benefits and energy efficiency (Garaniya et al., 2018). However, the environment has been deteriorating in recent years, and environmental issues have received attention from all sectors of society. The characteristics of HFO involve high viscosity, high aromatic hydrocarbon content, high sulfur content, and high hydrocarbon ratio (Garaniya et al, 2018). That means HFO has negative impacts on the environment when burned. The SO<sub>2</sub> produced during combustion causes acid rain. The high viscosity can make HFO hard to clean in the natural environment. Also, the high hydrocarbon ratio can lead to more CO and CO<sub>2</sub> production after combustion. Because of the relatively fragile and special Arctic ecosystem, HFOs carry a lot of environmental risks (PAME, 2019). Therefore, alternative clean fuels are encouraged to be used in the maritime industry.

The majority of alternative fuels can be derived from renewable sources or through biofuels which can lead to less environmental emissions compared to their fossil fuel versions. An example of this is Methanol which can either be extracted through fossil fuel or bio-derived, with the latter having a far more positive impact on the environment than its fossil fuel counterpart (Prussi et al., 2021). LNG has shown to be technically available for operational integration. However, it does not have a significant decrease in emissions compared to its bio-derived counterpart, which has a more positive impact but high costs for integration (Prussi et al., 2021). According to Prussi et al. (2021), ammonia as fuel has been a promising alternative option due to a significant amount of carbon reduction in its emissions. In particular, the bunker shipping industry has been interested in using ammonia on bunker ships. Still, the implementation costs need to be viable in the market (2021).

The use of alternative fuels is an essential path for the maritime industry to address climate change. To reduce greenhouse gas emissions, potential alternative fuels for shipping include hydrogen, ammonia, methanol, biofuels, and liquefied natural gas (LNG). The energy efficiency and emissions of biofuels depend on their production of raw materials. What is more, the high demand for shipping fuel and the currently limited supply of low-emission biofuels poses significant challenges. Large-scale utilization of biofuels could lead to the occupation of land and agricultural resources, as well as extensive deforestation, which would damage ecosystems (Basso et al., 2021). Therefore, this thesis will focus on and compare availability of hydrogen, ammonia, methanol, and LNG in the economic, environmental, technological, and safety aspects.

Previous research on alternative fuels has often been limited in scope, typically focusing on one or two

specific aspects such as economic viability or environmental benefits. For instance, many studies have extensively analyzed how these fuels can reduce costs and mitigate environmental pollution compared to conventional fossil fuels (see Deniz & Zincir, 2016). However, these studies frequently overlook critical technological developments and safety issues that are essential for a holistic understanding of alternative fuels. Conversely, other research efforts have concentrated primarily on technological advancements, providing insights into efficiency improvements and innovative technologies (see Hoang et al. 2023). Yet, these technological studies often neglect the broader economic implications and environmental consequences, thus offering an incomplete picture.

Moreover, a significant limitation of prior research is the narrow focus on a limited number of alternative fuels. Most studies investigate a single type of alternative fuel or a very small subset, restricting the generalizability and applicability of their findings (see Mandić et al, 2021, and Wojcieszuk, et al, 2019). This study addresses these gaps by examining four different alternative marine fuels — hydrogen, methanol, liquified natural gas, and ammonia—across four critical dimensions: economy, technology, environment, and safety. By adopting this comprehensive perspective, our research aims to provide stakeholders with a more robust and wide-ranging evaluation, thereby better-informing decision-making and strategic planning in the transition towards sustainable energy solutions.

## 1.2 Study Purpose

Surface-level research in the literature has shown that most studies are conducted on singular fuel types rather than several alternative fuels. The purpose and novelty of this master's thesis is to conduct a comprehensive comparative analysis of alternative fuels—specifically hydrogen, ammonia, methanol, and LNG—for their potential application in the maritime industry. The thesis aims to evaluate these alternative fuels across various dimensions including economic feasibility, environmental impact, technological readiness, and safety.

## 1.3 Purpose & Research Question

1. *How would hydrogen compare to other alternative fuels when it comes to environment, safety, technology, and economy?*
2. *What solutions to handling hydrogen fuels in shipping has the most potential in its application from a supply chain perspective (production, transport, onboard storage, and utilization)?*

## 1.4 Limitations

This study faces several limitations, including reliance on existing data, which may be limited or outdated, and the varying technological maturity of the fuels, especially hydrogen and ammonia, leading to uncertainty in their long-term viability. Economic analyses are based on current market conditions, which may change, affecting feasibility assessments. The geographic and operational specificity of fuel impacts may limit the generalizability of findings, and the focus on four specific fuels excludes others that might offer different advantages. Additionally, environmental and safety assessments are complex and may not capture all relevant factors, while regulatory changes could further influence the adoption and feasibility of these alternative fuels.

## 2 Literature Review

This thesis section constitutes the theoretical framework and provides an overview of the physical and chemical properties of HFO and several alternative fuels. In addition, it covers the relevant technology in the field of ships, serving as a foundational platform for the subsequent findings and analysis chapters.

### 2.1 Traditional Fuels

HFO is used broadly in the maritime sector because of its cost advantages till now (Abdul Jameel et al., 2019). Due to its features, HFO can only be used as fuel for ships. Speight (2011) explained heavy fuel oil as “heavy fuel oil usually contains cracked residua, reduced crude, or cracking coil heavy product which is mixed (cut back) to a specific viscosity with cracked gas oils and fractionator bottoms.” In brief, HFO is a residuum from the process of refining crude oil (Speight, 2011). As the demand for fuel increases, it promotes the development and use of these residues by marine operators. In the early stage, HFO was manufactured by simple residuals of atmospheric and vacuum distillation of crude oil (Uhler et al., 2016). However, after the first oil crisis, when crude oil imports were restricted in many countries, refineries had to adopt a more complicated thermal and catalytic cracking process. Such an approach led to worse-quality residues that were higher viscosity and harmful matter content like sulfur, metals, and inorganic residues (Uhler et al., 2016). Eventually, the fuel HFO was used extensively in the diesel engines of vessels.

#### The properties of HFO

HFO is described as a viscous liquid composed of residuals (non-distillable parts) obtained from crude oil through atmospheric or vacuum distillation, mixed with lighter distillates (Soares, 2015). The specific physical and chemical properties of HFO are determined by factors such as the origin of the crude oil, the initial content and quality of the residue, refining processes, elemental composition, and boiling range (Schüppel & Gräbner, 2024). HFO's chemical composition is exceedingly complex, making comprehensive characterization challenging. Typically, HFO consists of aromatics, saturates, resins, asphaltenes, and hybrid compounds (Garaniya et al., 2018; Schüppel & Gräbner, 2024). The primary constituents of these hybrid compounds include sulfur, nitrogen, and trace metals like vanadium and nickel, which significantly influence HFO's properties (Santos et al., 2014). Due to HFO's high molecular weight, sulfur content, and asphaltene levels, its properties are often described by their maximum allowable values (Schüppel & Gräbner, 2024). Table 2.1 presents the relevant properties of HFO.

*Table 2.1 The properties of HFO. (Source: Huth & Heilos, 2013)*

<b>Properties</b>	<i>Distillation range</i>	<i>Density</i>	<i>Lower heating value</i>	<i>Kinematic viscosity</i>	<i>Flash point temperature</i>	<i>Pour point temperature</i>	<i>Nitrogen content</i>	<i>Hydrogen content</i>
<b>Units</b>	°C	kg/L	MJ/kg	mm <sup>2</sup> /s (=cSt)	°C	°C	Mass ppm	Mass %
<b>Value</b>	350 - 500	0.85 - 0.97	39.5 - 40.9	>30 at 40°C	>60	<30	5400	var

The complexity of HFO's composition leads to a wide range of pour points, an indicator of a fuel's flow properties at low temperatures. Generally, the pour point of HFO is less than 30°C, posing challenges related to high viscosity. To improve its flow properties, the use of polymer structures with long alkyl chains or preheating methods can be employed (Schüppel & Gräbner, 2024).

Research by Schüppel and Gräbner (2024) indicates that as the distillation temperature for producing HFO increases, the content of heteroatoms such as sulfur and nitrogen also rises. Moreover, metallic elements present in crude oil remain in the HFO fraction, posing a notable source of pollution. Due to the high carbon content in the long-chain molecules of HFO, it is considered to have one of the highest carbon-to-hydrogen ratios among petroleum products, resulting in a high calorific value (Schüppel & Gräbner, 2024). In addition, HFO has a high energy density that is around 38 MJ/L (Whiteford, 2021).

## Pollutants

The threat of HFO to the environment comes from two major aspects: oil spill risk and exhaust emissions. Normal shipping operations (fueling and bilging) and marine accidents are the main reasons for ocean pollution, such as groundings, collisions, or sinking (Uhler et al., 2016). According to the historical perspective, there have been a number of severe oil spills from ships around the world. The high viscosity of HFO presents a significant challenge in terms of its effective cleaning and disposal in areas like the Arctic. What is more, the properties of HFO prevent it from emulsifying and evaporating in seawater, increasing the difficulties associated with its disposal and contributing to the negative impacts on the Arctic marine environment (Comer et al., 2020).

Apart from that, some combustion products, including gaseous and particulate emissions of HFO, also caused an environmental hazard. CO, CO<sub>2</sub>, SO<sub>2</sub>, and NO<sub>x</sub> are the primary exhaust from the combustions of HFO (Abdul Jameel et al., 2019). CO is a colorless, odorless, and toxic gas that affects the environment and human health by incomplete combustion of hydrocarbons. Hence, CO is easily inhaled without realizing it, rapidly causing death (Ernst & Zibrak, 1998). The emission of rising CO<sub>2</sub> is a primary reason for global warming. According to the European Commission (n.d.), maritime transport was responsible for 2.9% of global CO<sub>2</sub> emissions in 2018 and is estimated to increase unless adequate and effective measures are taken. Studies have shown that excessive CO<sub>2</sub> emissions can negatively impact marine environments. This is due to the fact that the emission of CO<sub>2</sub> results in changes to the ocean's carbonate system and pH, causing harm to aquatic organisms (Caldeira & Wickett, 2005). Furthermore, the use of HFO also results in the emission of another toxic gas, SO<sub>2</sub>, which causes acid rain and a wider range of impacts, including soil degradation and harm to human health (Grennfelt et al., 2020). Additionally, NO<sub>x</sub> typically referring to nitrogen dioxide (NO<sub>2</sub>) and nitrogen monoxide (NO), is a common type of air pollution that has multiple environmental consequences, such as climate change, global warming, photochemical smog, acid rain, ozone formation, and various health problems (Skalska et al., 2010).

Another typical pollutant when HFO is combusted is particulate matter (PM) emissions, which are tiny particles in smoke, ash, and ecospheres (Abdul Jameel et al., 2019). PM is a complex mixture of various components in the air; different combinations and sources decide the size of PM, which is related to toxicity and lifetime (Verma et al., 2019). In addition, Verma et al. (2019) pointed out that the physical and chemical properties of PM are influenced by many variables, such as the type of engine (load and speed), different fuels (including injection characteristics), operating environment, and natural conditions. However, due to its microscopic size, PM is difficult to filter, making it easy to inhale and causing harm to the respiratory system, even leading to severe pulmonary disease (Verma et al., 2019). In particular, black carbon (BC) is a soot particle in engine exhaust with an extremely strong greenhouse effect (Comer et al., 2020).

Consequently, there is a growing consensus among all sectors of society to mitigate the negative environmental impacts of HFO. These factors underscore the need to develop and implement alternative fuels that are more environmentally sustainable and easier to manage.

## 2.2 Hydrogen

Hydrogen is the most abundant element in nature (Momirlan & Veziroglu, 2005), comprising 75% of the universe's mass (Schlapbach et al., 2008). According to Momirlan and Veziroglu (2005), hydrogen is colorless and odorless which has a low volumetric density in its gaseous state due to its small mass and volume. As a result of the high diffusion capacity, hydrogen needs to be compressed and liquefied before it can be commercialized in the shipping industry (Basso et al., 2022). Moreover, hydrogen burns substantially faster, up to 2.65~3.25 m/s (Hammer et al., 2022), than other fuels (Schlapbach et al., 2008). However, in a natural state, hydrogen constantly forms compounds with other elements, such as water, methane (CH<sub>4</sub>), natural gas, and other hydrocarbons though the structure is simple and stable. Despite its simple and stable structure, hydrogen is considered an excellent fuel source because it produces high power output with almost no pollutants, as stated by Momirlan and Veziroglu (2005).

On the one hand, the technology of internal combustion engines is utilized widely, but these alternative fuels must modify and develop depending on their features. For instance, hydrogen as a fuel is less compatible with ships that currently have diesel engines as the power output. On the other hand, products with hydrogen-powered fuel cells are currently available on the market. However, no commercial vessels are currently powered by hydrogen fuel cells, and the life is shorter than internal combustion engines (Basso et al., 2022). Furthermore, there are various categories of hydrogen fuel cells, including the proton exchange membrane (PEM) fuel cell, the molten carbonate fuel cell, and the solid oxide fuel cell (Hoecke et al., 2021). PEM and high-temperature PEM are deemed the most promising for marine applications (PAME, 2019).

Therefore, due to its high flammability and high burning velocity, hydrogen as a marine fuel on board is probably an existing fire and explosive hazard (Schlapbach et al., 2008). Additionally, this fuel is not currently in widespread use and, as such, needs more mature regulations and experience in dealing with potential risks at sea (Basso et al., 2022).

### Production

Hydrogen is currently viewed as a promising alternative fuel in the Nordic shipping industry, as it plays a pivotal role in achieving the decarbonization goals of the industry (Basso et al., 2022). Hydrogen, when used in fuel cells or as a mono-fuel in internal combustion engines, produces no CO<sub>2</sub> emissions at the point of use, with water being the primary byproduct. This makes hydrogen a crucial alternative for ships that traditionally rely on HFOs, which are significant contributors to CO<sub>2</sub> and other harmful emissions such as SO<sub>x</sub> and NO<sub>x</sub>. Implementing hydrogen fuel technology aligns with global decarbonization goals and can significantly contribute to achieving the International Maritime Organization's (IMO) target of reducing GHG emissions from international shipping by at least 50% by 2050 compared to 2008 levels (American Bureau of Shipping, 2021). This fuel can be generated through different production methods, including blue and green hydrogen production. Basso et al. (2022) showed that blue hydrogen is produced by methane forming in natural gas coupled with carbon capture and storage (CCS) technology. However, despite using CCS technology, CO<sub>2</sub> emissions can only partially be eliminated during the production process. Moreover, methane is a potent greenhouse gas, contributing to approximately 25% of global warming forecasts (Howarth & Jacobson, 2021). Thus, blue hydrogen is not a zero-emission fuel option. On the other hand, green hydrogen is generated after the electrolysis process of renewable energy, such as wind and solar power (Basso et al., 2022). Nonetheless, it is worth noting that green hydrogen production is associated with higher costs when compared to blue hydrogen (Howarth & Jacobson, 2021). Furthermore, the lifecycle emissions of hydrogen, particularly green hydrogen produced via electrolysis using renewable energy, are markedly lower than conventional marine fuels, offering a pathway to net-zero emissions for the shipping industry (American Bureau of Shipping, 2021).

Global hydrogen production in 2019 reached approximately 70 million tons and was achieved through a variety of methodologies, encompassing the reformation of fossil fuels such as natural gas, heavy oil, coal, and naphtha, as well as the utilization of sustainable feedstocks like water and biomass. Notably, there are two predominant large-scale methods (Nikolaidis & Poullikkas, 2017), that underpin this production: steam reforming of methane and electrolysis. The former, steam reforming of methane, despite its prominence, presents a contemporary approach to hydrogen generation. However, it is crucial to acknowledge that, notwithstanding extensive endeavors, this method yields an equivalent volume of CO<sub>2</sub> emissions as the combustion of diesel for the same energy output. An alternative avenue, dry reforming of methane, involves the coalescence of greenhouse gases (GHG) and CO<sub>2</sub>, facilitating the conversion of CO<sub>2</sub> into syngas, a blend of carbon monoxide and hydrogen, which harbors applicability within the chemical industry. The second prominent technique, water electrolysis, is founded upon the fundamental principle that the application of a sufficiently robust electric current to water results in the dissociation of hydrogen and oxygen gases. This method manifests in five distinct iterations: alkaline, polymer, electrolyte membrane, solid oxide, and membrane electrolysis. Importantly, water electrolysis offers seamless integration with renewable energy sources, thereby permitting the conversion of surplus energy into hydrogen. It is pertinent to recognize that, at present, the cost of renewable hydrogen surpasses that of hydrogen stemming from steam methane reformation. For instance, one kilogram of hydrogen derived from the latter source is approximately fivefold less expensive than that produced from wind energy and roughly sevenfold more cost-effective than solar-derived hydrogen. An indispensable determinant influencing the progress of electrolysis technology is the cost of energy, given that obtaining one hydrogen molecule from another through this method incurs an expenditure approximately seven times greater than that of steam reforming (Grasu, 2023).

## Transportation

### Compressed hydrogen

The safe transport of hydrogen to the ship is the key to the realization of hydrogen-fueled ships. In the context of compressed gaseous hydrogen transportation, the main methods include pipeline trucking and shipping, but shipping is only suitable for short-distance transportation (Lovegrove, 2022). For scenarios involving long distances and substantial volumes, pipeline transit emerges as the most cost-effective way. Currently, this infrastructure predominantly repurposes existing natural gas pipelines, facilitating the transport of either pure hydrogen or a syngas mixture. However, conveying hydrogen through natural gas pipelines necessitates specialized treatment of both the gas and the infrastructure. According to DNV report, the transmission of hydrogen necessitates handling at reduced pressures within these pipelines (Lovegrove, 2022).

However, in existing polyethylene pipelines, hydrogen leakage can reach up to 4-5 times that of methane leakage. Furthermore, hydrogen permeation is even more pronounced in carbon steel pipelines compared to natural gas (Li et al., 2024). Additionally, the phenomenon of hydrogen embrittlement may occur during transportation in pipelines (Rong et al., 2023). Due to variations in the steel materials utilized across different natural gas pipelines, the susceptibility to hydrogen embrittlement differs, ultimately leading to material failure. Particularly vulnerable are the interfaces and welded components within pipelines, such as bolts and rivets, which are prone to embrittlement, resulting in reduced ductility or even rupture (Li et al., 2024). Hence, additional coatings are required within natural gas pipelines to mitigate such occurrences (Lovegrove, 2022). Although compressed hydrogen can be transported through natural gas pipelines, the compression process itself may induce hydrogen embrittlement. Presently, natural gas pipelines are capable of transporting mixed gases with relatively low hydrogen content. However, to transport higher hydrogen content or pure hydrogen, substantial investments are required to either significantly modify or reconstruct existing pipelines and infrastructure (Li et al., 2024).

Trucking represents another prevalent method for the conveyance of compressed hydrogen gas. As stated by Rong et al. (2023), in commercial applications, compressed hydrogen is transported in specially engineered high-pressure vessels housed within extended tube trailers. This technology is not only mature and secure, but such trucks are also utilized for secondary storage at hydrogen refueling stations. The loading capacity of tube trailers is directly correlated with the pressure level of compressed hydrogen, which is determined by demand and cost considerations. Typically, compression levels range from 200 to 500 bar. When transporting hydrogen using tube trailers, there is typically a loss of approximately 4% due to residual hydrogen remaining in the storage tanks (Li et al., 2024). Each truck of this kind can transport approximately 1100 kilograms of compressed hydrogen (Lovegrove, 2022), with the transportation cost per kilogram of compressed hydrogen estimated at around \$2.86 (Li et al., 2024). Consequently, tube trailers are most cost-effective for scenarios involving either short-distance (200 to 300 km) low-volume transport or long-distance low-volume transport (Li et al., 2024).

### **Liquid hydrogen**

Trucking and shipping are the two primary methods for transporting liquid hydrogen. Trucking is suitable for long-distance and large-volume transport, with a typical truck capable of carrying around 4,000 kilograms of liquid hydrogen for over 4,000 kilometers (Lovegrove, 2022). However, longer distances might increase the temperature and pressure within the tank due to heat absorption (Lovegrove, 2022). Liquid hydrogen is stored in specialized insulated tanks, and typically, the tank cannot be detached from the truck, rendering it unsuitable as a secondary hydrogen storage facility at refueling stations (Rong et al., 2023). Additionally, converting hydrogen from gas to liquid form consumes approximately 30% to 40% more energy than compressing it (Lovegrove, 2022). The technology for liquefied hydrogen not only presents significant challenges but also offers cost advantages only achievable by large-scale facilities (Li et al., 2024).

Meanwhile, shipping is apt for transporting large volumes of liquid hydrogen over even longer distances. Due to the need for low-temperature transport of liquefied hydrogen, there might be a partial loss during the journey (Lovegrove, 2022). This is primarily due to the temperature differential between the liquid hydrogen and the environment, leading to the penetration of ambient temperature into the storage tank and consequently causing boil-off gas (BOG). This phenomenon is particularly prevalent in the turbulent conditions of the open sea (Song et al., 2022). Moreover, the smaller the ratio of surface area to volume of storage tanks, the lesser the losses incurred (Li et al., 2024).

### **Ammonia and liquid organic hydrogen carrier (LOHC)**

Ammonia functions as an effective intermediary for hydrogen transportation and storage, boasting a greater energy density compared to liquid hydrogen. This allows for its economical conveyance through diverse modalities including pipelines, maritime shipping, and trucking. Nonetheless, the processes of hydrogenation and dehydrogenation of ammonia necessitate operating at elevated temperatures, approximately 300 to 350 degrees Celsius, which results in an approximate energy loss of about 30% (Lovegrove, 2022). According to Rong et al. (2023), the addition of hydrogenation and dehydrogenation units increases the transportation and storage costs, as well as the capital investment for LOHCs. These processes become most cost-effective only when the daily transport volume exceeds 20,000 kilograms, making small-scale hydrogenation stations unsuitable as endpoints for LOHC transportation.

When the transportation distance exceeds 1,500 kilometers, pipeline transportation costs are lower than maritime shipping, but the cost of conversion and energy loss must be considered. Maritime shipping's advantage lies in its ability to utilize existing infrastructure and storage facilities without incurring energy loss. Additionally, by converting hydrogen into ammonia before transport, a truck can carry about 5,000 kilograms of hydrogen (Lovegrove, 2022).

### **Bunkering for hydrogen ships**

According to Feng et al. (2021), the current methods for refueling hydrogen-powered ships include tanker bunkering, shore-based bunkering, pontoon bridge bunkering, and overall tank changing. However, due to the limited widespread use of hydrogen fuel at present, bunkering poses various challenges, such as lack of regulation and industry standards, immature technology, lack of infrastructure, and the need for pipeline integrity checks with each refueling. Currently, shore-based bunkering stands out as relatively advantageous, with its larger refueling capacity making it easier to meet the needs of vessels, and fixed refueling locations offering more manageable risks (Feng et al., 2021). But Hoecke et al. (2021) point out that refueling large cargo ships with compressed hydrogen presents challenges such as long refueling times or the need for a large number of nozzles. Since these ships have longer voyages and require more fuel, port stays are prolonged. Addressing technical issues associated with using numerous nozzles for refueling is time-consuming. Additionally, before refueling with liquid hydrogen, ports need to construct infrastructure for storing the fuel due to its high volatility. Furthermore, the liquid hydrogen in the tanks onboard tends to slosh, affecting the stability of the ship after refueling. Basso et al. (2022) also highlights similar issues, noting that hydrogen fuel bunkering currently relies heavily on a lot of bunkering vessels because of the lack of hydrogen refueling infrastructure, with most ports unable to provide refueling services.

## **Storage**

The issue of hydrogen storage is a significant challenge owing to its low density in the gaseous state, which necessitates compression or liquefaction for onboard storage (Basso et al., 2022). In a review by Hoecke et al. (2021), four distinct methods for hydrogen storage were identified: compression, liquefaction, and storage in physical or chemical carriers. However, this research only focuses on compressed and liquid forms which can be utilized as fuel on vessels as DNV's report.

### **Compressed hydrogen**

At present, compression technology is the most widely used method for storing hydrogen, with storage tanks available in various pressure ranges from 10 to 70 MPa (Hoecke et al., 2021). Based on the diverse scenarios and intended applications, compressed hydrogen storage tanks are classified into five distinct categories, denoted as Types I, II, III, IV, and V (as Figure 2.1 shows). Each kind of vessel reflects varying degrees of complexity in manufacturing processes. Type I, the most common vessel to store compressed hydrogen, is constructed entirely of metal (Hoecke et al., 2021) and operates within pressures ranging from 15 to 30 MPa. Its primary deployment is in stationary settings, such as onsite storage for industrial hydrogen production (Yang et al., 2023).

Next, Type II tanks, while still incorporating metal, also integrate composite materials, rendering them lighter than their Type I counterparts. These tanks are lined with a polymer interior, typically enduring pressures up to 20 MPa and boasting higher hydrogen storage capacity by weight than Type I tanks (Hoecke et al., 2021). Type II tanks are predominantly used in fixed high-pressure storage scenarios like hydrogen refueling stations.

Type III tanks further enhance the design of Type II by including a metal lining supported by composite fibers. Meanwhile, Type IV tanks employ a polymer lining reinforced with composite fibers. Both Types III and IV are principally utilized for transporting hydrogen in long tube trailers and containers (Yang et al., 2023). Lastly, Type V tanks, unique in their lack of internal lining, are capable of withstanding pressures exceeding 700 bar. However, their application remains significantly limited as of the current landscape (Hoecke et al., 2021). While tank-based hydrogen storage has emerged as the most widely utilized commercial method, it still faces certain limitations, such as whether the storage capacity can meet the growing demand for hydrogen utilization. Another challenge lies in safely regulating and utilizing the

hydrogen stored in tanks, as the pressure of hydrogen during actual usage is lower than that within the storage tanks (Li et al., 2024).

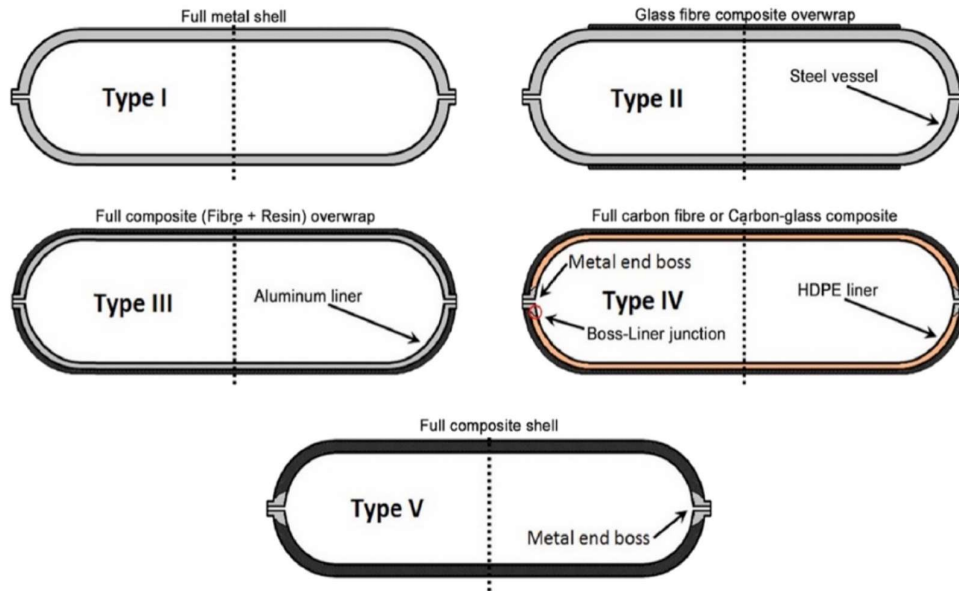


Figure 2.1 Five types of H<sub>2</sub> storage vessels. (Source: Amirthan & Perera, 2022)

### Liquid hydrogen

As illustrated in Figure 2.2, the hydrogen within the blue region is in a liquid state with a density of 70.8 kg/m<sup>3</sup>, whereas gaseous hydrogen (under conditions of 0°C and 1 bar) has a density of 0.089 kg/m<sup>3</sup> (Faye et al., 2022). Therefore, the crucial aspect of hydrogen storage lies in enhancing the volumetric energy density (Faye et al., 2022; Li et al., 2024). Figure 2.3 demonstrates the relation curves between pressure and hydrogen density at three different temperatures. Density increases with pressure and the rate of change in density decreases as pressure increases. Additionally, at the same pressure, lower temperatures result in higher hydrogen densities. Achieving higher density requires higher pressure, which can pose safety risks. Therefore, liquefied hydrogen can circumvent this issue.

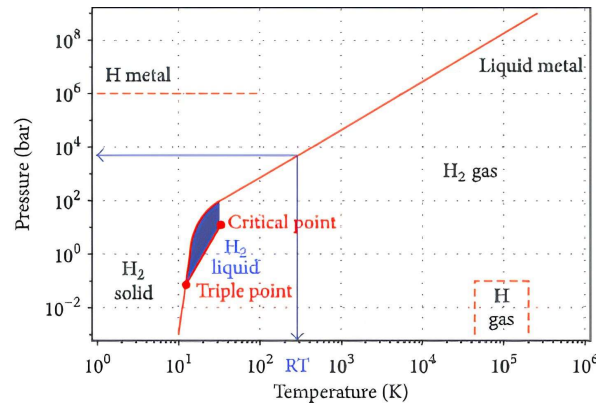


Figure 2.2 The hydrogen states at different temperature and pressures. (Source: Faye et al., 2022)

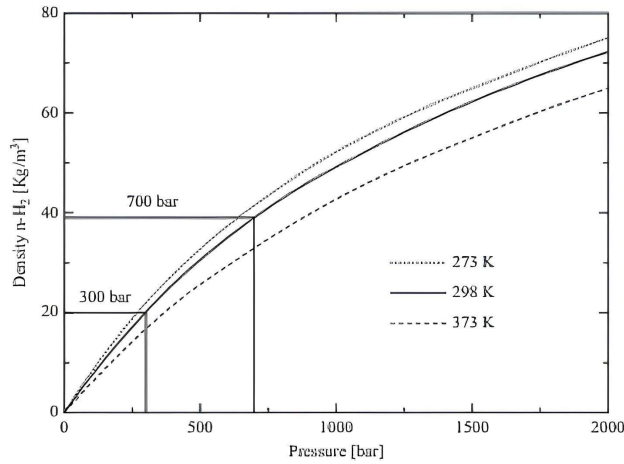


Figure 2.3 Relationship between pressure and volumetric density at three different temperatures. (Source: Faye et al., 2022)

Besides, liquefaction is another common choice that results in a volume reduction of approximately 778 times for the same mass of hydrogen. The energy density of hydrogen is 8.5 MJ/L, but diesel's energy density is 36.3 MJ/L, which means more space is needed on board to store hydrogen fuel (Hoecke et al., 2021). Storing hydrogen as a liquid requires special cryogenic tanks. This method faces a big challenge because these tanks can absorb heat from the surroundings, causing the hydrogen to evaporate. Presently, cryogenic hydrogen storage tanks experience an evaporation loss of 1% to 5% daily, whereas an ideal scenario would see this figure below 1% (Yang et al., 2023). Unlike containers designed for compressed hydrogen, these tanks cannot withstand high pressures internally, necessitating the release of evaporated hydrogen gas to maintain internal pressure equilibrium (Yang et al., 2023).

What is more, the liquefaction of hydrogen is an energy-intensive process. The task of refueling ships with liquid hydrogen introduces unique challenges, chiefly the maintenance of a consistently low temperature throughout the refueling operation. This is key to curtail the rate of hydrogen evaporation and thus reduce the associated losses. Vessels powered by liquid hydrogen, akin to LNG ships, might in the future be equipped with propulsion systems that utilize the evaporated gas (Hoecke et al., 2021). This prospective development could potentially enhance the efficiency and effectiveness of hydrogen as a marine fuel.

### Cryo-compressed hydrogen

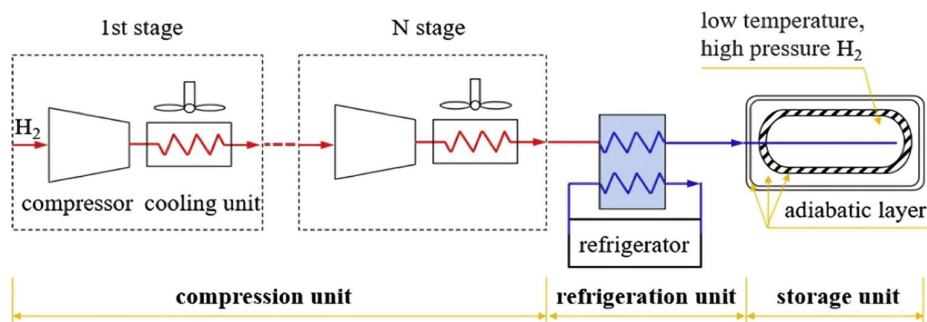


Figure 2.4 Process of cryo-compressed hydrogen storage. (Source: Yanxing et al., 2019)

The concept of supercritical cryo-compressed hydrogen storage (CcH<sub>2</sub>) was initially proposed by BMW, aiming to store hydrogen in pressure vessels capable of operating under both low and high-pressure environments (Yanxing et al., 2019). The primary objective of this technology is to address the energy losses associated with compression and liquefaction of hydrogen while providing higher volumetric energy density (Faye et al., 2022). Since the process of cryo-compressed hydrogen does not involve hydrogen liquefaction, it is anticipated to consume less energy for storage. As depicted in Figure 2.4, cryo-compressed hydrogen storage primarily consists of three stages: firstly, hydrogen is put and handled in multiple compressed and cooling units. In the second stage, the compressed hydrogen at temperatures close to ambient is cooled using refrigerators or liquid nitrogen. Finally, it is stored in specialized containers (Yanxing et al., 2019). These containers are designed to operate in environments with temperatures as low as 20K and pressures up to 35 MPa (Yanxing et al., 2019). However, such containers have yet to be commercialized in the market (Faye et al., 2022).

### **Onboard storage**

According to a 2023 report by the American Bureau of Shipping, special design considerations are essential for safely storing hydrogen fuel on ships. Firstly, hydrogen storage tanks located on the deck must be shielded from mechanical damage, and open-air fuel bays should be enclosed by bulwarks. Secondly, measures to mitigate the risk of hydrogen leakage are necessary. For instance, fuel pipelines within enclosed spaces on the ship should be housed in airtight and watertight casings to prevent hydrogen spillage from damaging the ship's structure or materials.

The hydrogen fuel supply system, including cooling and compression equipment, should be situated in a dedicated fuel preparation room. This room must be located away from airtight bulkheads and decks. Lastly, the installation of drip trays and spray shields is recommended in areas where low-temperature hydrogen might leak (American Bureau of Shipping, 2023).

## Safety and Regulations

Safety is a critical consideration in the adoption of hydrogen as a marine fuel. Hydrogen's physical properties, such as its wide flammability range and high diffusion rate, pose unique safety challenges. Hydrogen is highly flammable and can form explosive mixtures with air over a wide concentration range, requiring meticulous management to prevent leaks and accidental ignition. The rapid diffusion rate of hydrogen means that any leaks can quickly disperse, creating potentially hazardous conditions. Additionally, hydrogen embrittlement, where metals become brittle and crack when exposed to hydrogen, presents challenges for the materials used in storage and transport systems. To ensure the safe use of hydrogen, comprehensive safety measures must be implemented, including the use of specialized materials and coatings for pipelines and storage tanks to prevent embrittlement and leaks. Advanced sensor technologies are also essential for detecting hydrogen leaks and ensuring timely intervention. Moreover, stringent safety protocols and emergency response strategies must be developed and rigorously adhered to, addressing all potential scenarios involving hydrogen-related incidents on vessels (American Bureau of Shipping, 2021). Ensuring robust safety measures is vital for regulatory approval and public acceptance of hydrogen as a marine fuel.

The successful adoption of hydrogen as a marine fuel hinges on robust regulatory frameworks and sustainability verification schemes. Regulatory initiatives such as the EU CertifHy project play a crucial role in tracking and quantifying the emissions footprint of hydrogen, ensuring its environmental integrity. These

initiatives provide transparency and accountability, enabling stakeholders to verify the sustainability of hydrogen production and use. Compliance with international standards and regulations is essential for the maritime industry to transition to hydrogen fuel effectively. The IMO and other regulatory bodies are developing guidelines and standards to ensure the safe and sustainable use of hydrogen in maritime applications. Additionally, sustainability verification schemes help in fostering industry-wide best practices and encouraging investments in hydrogen technologies (American Bureau of Shipping, 2021). As the maritime industry evolves, continuous updates and adaptations of regulations will be necessary to address emerging challenges and innovations in hydrogen technology. These regulatory measures not only ensure safety and environmental compliance but also promote the broader adoption of hydrogen as a sustainable marine fuel.

## 2.3 Other Alternative Fuels

### Ammonia

According to Hammer et al. (2022), ammonia ( $\text{NH}_3$ ) is a colorless and irritative gas with a strong smell at room temperature. Unlike fossil fuels,  $\text{NH}_3$  does not contain carbon, so there is no  $\text{CO}_2$  generated as a byproduct (Basso et al., 2022). It is remarkable that ammonia, a toxic gas, can pose serious results with leakage. A spillage of just 1 liter of liquid ammonia can generate 170 cubic meters of acutely lethal toxic cloud due to the high expansion ratio. Once leaked into the ocean, ammonia gas will dissolve in water and create corrosive water that has long-lasting effects on aquatic life (Hammer et al., 2022). Moreover, ammonia is a hygroscopic compound, which means that it can absorb moisture from the air and form white clouds. The safe concentration of ammonia in the air is between 20 to 50 parts per million (ppm), while a concentration of 300 ppm or more can cause severe irritation to human organs and be fatal in a short period (exposure to an environment with an ammonia concentration of 1100 ppm for one hour poses a life-threatening risk). Besides, the boiling point of ammonia is low; thus, it will cause burns to the skin when people touch it. In addition, the burning velocity is 0.07 m/s, but there still is a hazard for fire and explosives under a specific concentration of 15% ~ 28% vol (Hammer et al., 2022).

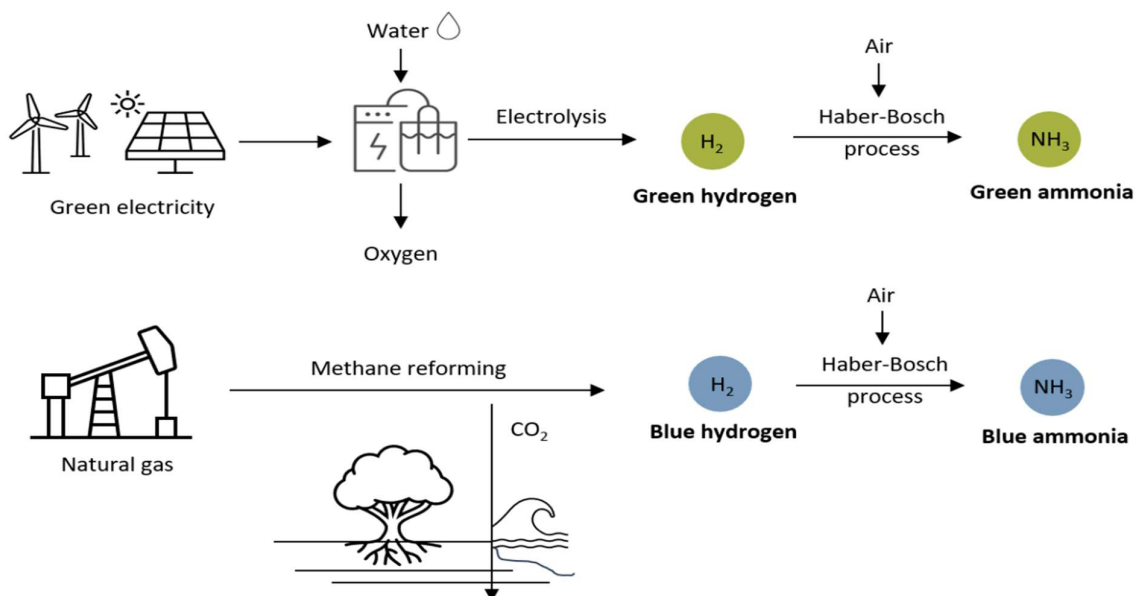


Figure 2.5 Green and blue ammonia production. (Source: Nordic Roadmap Publication No. 1-A/1/2022)

The production of ammonia is largely dependent on reforming natural gas into hydrogen. Figure 2.5 illustrates that green and blue hydrogen serve as the foundational sources for ammonia production. At present, blue ammonia is the predominant method due to its maturity, affordability, and efficiency, which surpass those of green ammonia. (Basso et al., 2022). The Haber-Bosch process of making ammonia is one of the most important reflections on industry, ammonia is formed by hydrogen and nitrogen under certain conditions. The chemical reaction (Eq. 2.1) shown below is reversible and reaction conditions are high temperature and pressure and catalysts (Schlapbach et al., 2008). Furthermore, it is an economical way to store hydrogen by ammonia (PAME, 2019). When the pressure or temperature changes, the output will also be adjusted.



As a transaction goods, it is experiential to transport ammonia onboard. Ammonia, a gas at room temperature, must be compressed and (or) refrigerated to  $-33^\circ\text{C}$  for liquefied storage. Since ammonia is corrosive, storage tanks need to be made of special materials, but the price of the specific tankers is low. Further, the energy density of ammonia is 11 MJ/L, which means more storage space onboard or frequent bunkering is necessary. The cost of ammonia fuel depends on the price of hydrogen, from which 90% of ammonia is produced. However, the transport cost of ammonia is lower than hydrogen due to the higher storage temperature and higher energy density. Combustion of ammonia produces  $\text{NO}_x$ , in particular,  $\text{N}_2\text{O}$  is a strong greenhouse gas. Despite that, the  $\text{CO}_2$  equivalent of  $\text{NO}$  is 1/30 of that of burning conventional marine fuels (Basso et al., 2022).

The development of ammonia technology is currently underway, with research indicating that ammonia can be used as a fuel in a range of prime movers, including diesel engines, spark ignition engines, gas turbines, and fuel cells (Kim et al., 2020). Basso et al. (2022) suggest that ammonia fuel is particularly suitable for internal combustion engines, and an internal combustion engine developed specifically for ammonia is expected to be available in 2025. Although ships that use this fuel may require additional fuels for ignition due to the low flammability. One such solution is to use hybrid fuel, a mixture of hydrogen and ammonia. Besides, the initial input of using ammonia fuels is high for shipowners and infrastructures that are limited by commercial scaling. There is a large investment in establishing bunkering facilities. And avoid touching the fuel while refilling ammonia. Therefore, the total initial costs are 25% ~ 30% higher than normal ships. Furthermore, current regulations related to ammonia fuel use in marine transportation are not yet fully developed (Basso et al., 2022).

## Methanol

Methanol ( $\text{CH}_3\text{OH}$ ) is a liquid substance that contains almost no sulfur oxide and has minimal  $\text{NO}_x$  emissions and is therefore considered one of the possible alternative fuels in maritime shipping due to its comparatively lessened carbon emissions. Methanol fuel is produced from synthesis gas, which comes from natural gas and coal systemization but is not solely restricted to it. The production of methanol can be expanded to come from renewable resources, namely hydrogen,  $\text{CO}_2$ , and biomass from forests, and agriculture can help produce bio-methanol, which is cleaner in emissions, but the feedstock resource is small compared to fossil biomass (Svanberg).

The flashpoint of the methanol fuel comes at  $11^\circ\text{C}$ , which can be a fire and explosion hazard if it is not contained and maintained under the right temperatures (Hammer, L. S. et al. 2022). The fuel type complies with the Sulphur Emission Control Area (SECA) regulations for sulfur oxides and can comply with most

NO<sub>x</sub> emission regulations; methanol fuel is being used in a small number of vessels but has not seen worldwide application. Methanol fuel is stored in integral fuel tanks and in a liquid state under normal conditions; the fuel should restrain from reaching a boiling point of 65°C. As Basso et al. (2022) stated, the energy density of methanol is 15.7 KJ/L, which means it requires more than 2.5 times space to store the fuel compared to diesel. According to Hammer et al. (2022), the burning velocity for methanol is 0.48 m/s, and its maximum burning velocity is 20% higher, with less oxygen required for ignition. If there is a spill, there are minimal environmental hazards as methanol is biodegradable. However, there are still health and safety risks as methanol at flashpoint temperatures is toxic when inhaled and harmful if ingested or absorbed through the skin (PAME. 2019).

According to Hammer et al. (2022), with only 10ml of ingestion of methanol, the individual can have severe effects on optical nerves and cause blurry vision or blindness, it can also include symptoms of nausea and vomiting; overexposure to methanol will eventually lead to death. For instance, staying in an environment with a concentration of 7200 ppm of methanol for one hour poses a life-threatening risk. Liquid methanol is colorless and odorless and can be mistaken for water. Methanol flames are not noticeable due to the lack of smoke and being nearly invisible under daylight (Hammer et al. 2022). In ice waters or cold temperatures, some risks may not be an issue as the onboard deck temperatures will not often reach flashpoint temperatures of 11°C. In general, the risks of methanol relate to its toxicity to human health if ingested or inhaled, and the fire hazards regarding its low flashpoint temperatures and the undetectable flames during daylight hours.

Methanol fuel is currently available in the Nordic region's ports. Also, the compatibility of methanol fuel with existing vessels is high compared to other zero-carbon fuels (Basso et al., 2022). According to Hammer, Tveit, Sverud, Leisner, and Eide. (2022), the IMO regulations, it is stated that methanol/ethanol can be used as an alternative fuel but has to follow a design framework that is mandated by the IGF code together with the Flag Administration. Currently, the maritime industry has experience in the carriage and use of methanol fuel on chemical carriers and as cargo on offshore supply vessels, methanol has been exclusively used on tankers with 11 in operation and 14 new tankers planned to be built in the near future. In 2022, it is expected that there will be an increase in container vessels that use methanol as fuel (Hammer, Tveit, Sverud, Leisner, & Eide. 2022).

## Liquefied Natural Gas

LNG has become the most significant focus in alternative energy research due to its abundance, cleaner burn, and the cost-effectiveness of its established production and usage methods (dos Santos et al., 2022). According to PAME (2019), methane (CH<sub>4</sub>) is used as the main substance for LNG which has low carbon emissions and is considered one of the main contenders for reducing CO<sub>2</sub> emissions. The composition and characteristics of LNG are comparable to natural gas which is used for generating power in residential areas and in the production industry (PAME. 2019). The boiling point of LNG is around -163°C when contained in 1 bar of pressure; due to low-temperature requirements, it has to be stored and cooled in insulated tanks to retain its liquefied state (PAME. 2019). As Basso et al. (2022) stated, the energy density of methane is 20 KJ/L, and the burning velocity is 0.37 m/s (Hammer et al., 2022). According to Tusiani & Shearer (2016), the chemical properties of hydrocarbons consist of hydrogen and carbon atoms that are interlinked, the chemical form can be seen as C<sub>n</sub>H<sub>2n+2</sub> where *n* is the number of carbon or hydrogen atoms, the higher the *n* then the molecule is heavier.

Tusiani & Shearer (2016) states that the typical composition of a hydrocarbon from the U.S. is 91% Methane (CH<sub>4</sub>), 5% Ethane (C<sub>2</sub>H<sub>6</sub>), 2% Propane (C<sub>3</sub>H<sub>8</sub>), 1% Butane (C<sub>4</sub>H<sub>10</sub>), and 1% Nitrogen (N<sub>2</sub>). According to Tusiani & Shearer (2016), the changes in composition alter the natural gas and can even lead to liquified

petroleum gas (LPG), which comes from the high liquefaction with low pressure of ethane, propane, and butane. According to PAME (2019), arctic region studies have suggested that replacing HFO with LNG will result in avoiding oil spill risks and that air emissions can be significantly reduced, LNG spills are not an environmental risk at sea due to tests showing that LNG can rapidly evaporate in open waters when spilled. PAME (2019) states that usage of LNG significantly reduces the emissions of SO<sub>x</sub>, NO<sub>x</sub>, and PM; and that depending on the engine type NO<sub>x</sub> emissions can be within the strictest IMO regulations which are required for Emission Controlled Areas (ECA).

According to Hammer, Tveit, Sverud, Leisner, & Eide, (2022), the regulations for IGF code and IMO code were built upon testing on LNG-fueled ships on a small scale, such as the Norwegian ferry “Glutra”. From thereon, decades of learning and usage of LNG have led to the better-optimized design of vessels and engines and experienced ship operations. PAME (2019) states that LNG has since been used on different types of vessels starting from the year 2000 and would be mainly used by small-sized vessels meant for short-sea transportation. In 2022, there were reported to be about 923 LNG-fueled ships in operation, and about 534 LNG ships are planned to be built from client orders (Hammer, Tveit, Sverud, Leisner, & Eide, 2022).

In the present, when it comes to accessibility, there are large volumes of LNG available and is expected to be available for the coming decades, with LNG currently making up about 10% of the natural gas market; what is currently lacking is the global infrastructure and bunkering facilities for shipping to support the LNG trade. Investments in LNG depend on the changes of gas and oil prices, and the building cost of LNG-fuelled ships is currently higher than diesel-fuelled ships (PAME. 2019). LNG does have a low carbon alternative which is Liquid Biogas or biomethane (LBG), and it can use the already existing and planned LNG infrastructures for global application therefore, it will not be difficult to enforce once its reached technological maturity (PAME. 2019).

### Physicochemical properties

Based on the description of these four alternative fuels in the above paragraphs, their physicochemical properties are summarized in the following table (Table 2.2).

*Table 2.22 Physicochemical properties of alternative fuels*

Fuel	Energy density (MJ/L)	Burning velocity (m/s)	Toxicity
Hydrogen	8.5	2.65~3.25	No
Ammonia	11	0.07	Yes (highly toxic)
Methanol	15.7	0.48	Yes
LNG	20	0.37	No

#### 2.3.1.1 Alternative fuel price

Fuel prices are constantly fluctuating due to many factors such as market conditions, supply and demand, international politics, location, inflation, etc. Therefore, the forecast of future alternative fuels is used as a measure of the economic criterion (Ait Aider et al., 2023). Table 2.3 presents the forecasted alternative fuel price.

Table 2.33 Forecasted alternative fuel price. (Source: Ait Aider et al., 2023)

Alternative fuels	Price (\$/t)	Price (\$/GJ)
Hydrogen	900	75
Ammonia	426	22.9
Methanol	593	29.8
LNG	390	7.8

### 2.3.1.2 Greenhouse gas emissions

The products resulting from the combustion of fuels are primarily influenced by the constituent elements of the fuel. Hydrogen fuel, owing to its straightforward composition, yields negligible amounts of greenhouse gases and particulate matter during combustion. Similarly, the combustion of ammonia, methanol, and LNG does not generate sulfur oxides (SO<sub>x</sub>). According to Ait Aider et al. (2023), Figure 2.6 integrated the greenhouse gas emission of four alternative fuels and two kinds of traditional fossil fuels. Therefore, for air pollutants of environmental criteria, hydrogen is considered the cleanest fuel, followed by methanol because of its low NO<sub>x</sub> emissions and lack of PM generation. Finally, the paratactic are ammonia and LNG. Due to the high amount of NO<sub>x</sub> generated by ammonia combustion, and in the case of LNG, it generates PM as a fuel.

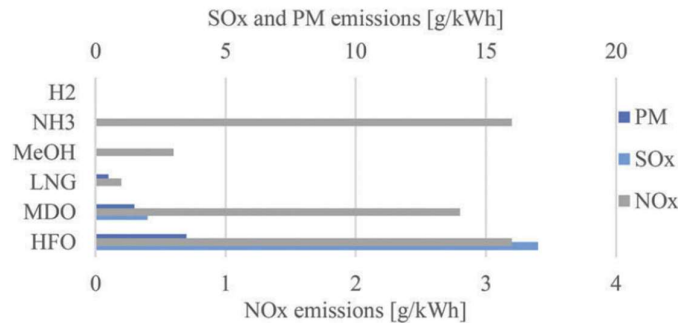


Figure 2.6 GHG from fuel combustion (Source: Ait Aider et al., 2023)

## 2.4 Technology

### Storage system

Some alternative fuels require a modification of the standard storage system in vessels or sometimes a whole new storage system that is catered to the fuel type. An article by Ait Aider, C. (2023), states that the storage system plays a crucial role in determining the feasibility and safety of adopting these fuels. The storage system must be designed and built to meet various requirements, including capacity, pressure, temperature, and compatibility with the fuel type. Additionally, the storage system must comply with statutory regulations and class rules related to safety and environmental protection. Some common types of storage systems used in ships include tanks, cylinders, and bunkers, which can be made of different materials such as steel, aluminum, or composite materials. As mentioned before in Ammonia fuels, the fuel would need to be stored

in tanks made of special material to prevent the fuel from corroding and leaking through the storage tank. The selection of a suitable storage system depends on various factors such as the ship's size, operating conditions, and the properties of the fuel. Proper maintenance and inspection of the storage system are also essential to ensure safe and efficient operation of the vessel.

## Hybrid Power System

In light of the increasing environmental challenges facing the maritime sector, recent research has proposed three primary strategies to tackle the issue, which are using new emission abatement technologies, alternative fuels, and hybrid power systems. While the implementation of new emission abatement technologies can effectively reduce pollutants, the approach does not improve the overall performance of the ship and leads to additional costs and operations, such as installation, operation, and maintenance (Inal et al., 2022). What is more, alternative fuels play an important role in decreasing emissions and enhancing the sustainability of the maritime industry. The properties of each alternative fuel vary, and the effectiveness depends on different scenarios of application. However, the use of a single alternative fuel is limited by the vessel's structural design and operating environment. For example, solar energy is limited by poor weather conditions. Lastly, the adaptation of a hybrid power system is a promising and emerging solution to provide continuously reliable power (Yuan et al., 2020). Figure 2.7 is a good illustration of the advantages of hybrid and electric propulsion by Inal et al. (2022).

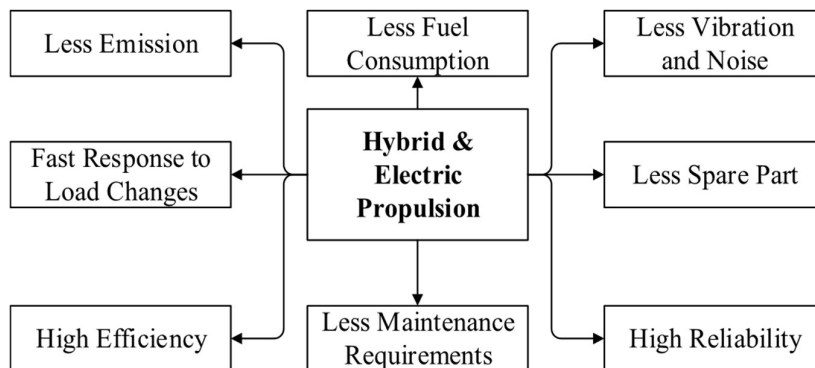


Figure 2.7 Advantages of hybrid and electric propulsion. (Source: Inal et al., 2022)

The hybrid power system integrates energy storage and power generation technologies. Energy storage systems play a pivotal role in hybrid and electric ships. The primary function of energy storage systems is to enable internal combustion engines to operate within their optimal efficiency range, thereby reducing fuel consumption and minimizing pollutant emissions. In addition, energy storage systems aid in load optimization, buffer effect during load variations, instant power supply, energy storage from renewables, backup and additional power. Onboard, the most utilized energy storage device on ships is batteries; however, supercapacitors and flywheels can also be utilized to meet specific requirements within the energy storage system configuration. (Inal et al., 2022). Power generation technologies are limited onboard, most ships are still using traditional internal combustion engines (especially diesel engines), and a few ships use fuel cells. Inal et al. (2022) pointed out that hybrid systems offer more flexibility than conventional power systems for fuel choice.

According to Yuan et al. (2020), the multi-energy hybrid power system can be categorized into two types based on the characteristics of energy mixing: hybrid mechanical propulsion and hybrid electrical propulsion. However, the integration of these different energy sources increases the complexity of the power system, which ultimately results in a higher incidence of faults. Thus, it becomes imperative to conduct a thorough risk assessment and implement effective control measures to enhance the safety of hybrid power systems.

## Internal combustion engine

The most common form of propulsion engine is the internal combustion engine which has been used in various vessels (Ait Aider et al. 2023). According to Hammer et al (2022), The engine comes in 2-strokes and 4-strokes, and the recent developments of alternative fuels has made the internal combustion engine more versatile than ever. There have been developments of altering the engines to be able to use fuels such as methanol, ammonia and especially hydrogen. Unlike conventional fossil fuels, hydrogen combustion yields only water vapor as a byproduct, making it an attractive option for addressing climate change concerns. The use of hydrogen as a primary fuel in ICEs involves injecting hydrogen into the combustion chamber, where it mixes with air and ignites, driving the engine's pistons and producing mechanical work; this is further demonstrated in Figure 2.8 (Hoang et al., 2023). Hammer et al (2022) further explains 4-stroke engines are having the most predominant developments alongside fuel cells compared to other hydrogen energy converters making internal combustion engines highly viable for integrating hydrogen fuels into deep-sea and short-sea chartering routes.

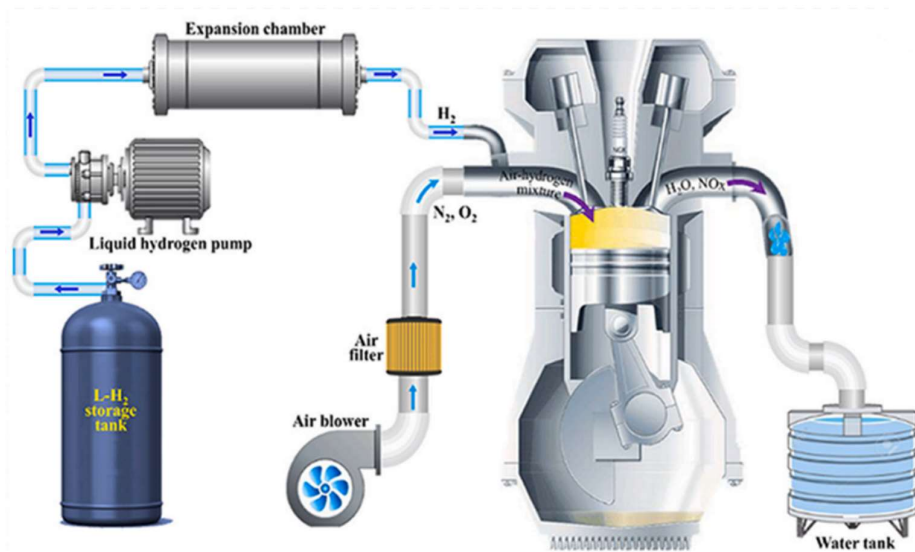


Figure 2.8 The scheme of diesel engines fueled with pure liquid hydrogen. (Source: Hoang et al., 2023)

According to Hoang et al (2023), a range of alternative fuels, such as ammonia, methanol, LNG, and LPG (Liquid Propane Gas), are being evaluated for use in ICEs. These fuels offer varying degrees of environmental benefits and challenges. Ammonia, for instance, presents a carbon-free option with potential for reducing greenhouse gas emissions in the shipping industry. Methanol, derived from renewable sources, holds promise as a low-carbon fuel for marine and automotive applications. LNG and LPG, while still fossil fuels, produce fewer emissions compared to traditional gasoline and diesel when used in ICEs (Hoang et al., 2023).

Hydrogen fuels have many merits to being used in ICEs as both a standard direct fuel and alongside another fuel in a dual fuel engine which has been accepted as an ease of approach to integrating hydrogen as fuel. However, Hoang et al (2023) mentions that the biggest drawbacks for hydrogen fuel have been its need for

bulk storage capacity and the strict safety regulations behind the applications of hydrogen storage. The article by Hoang et al (2023) brings up a study examining the compressed hydrogen bunkering system employed on the Orkney Island ferries has shed light on potential safety considerations. The 16-passenger shuttle used for the study has been certified as the first of its kind to utilize hydrogen to power a diesel engine, employing a hybrid system enabling operation on both diesel and hydrogen fuel (Hoang et al., 2023). The utilization of hydrogen as a secondary power source has been found to increase brake thermal efficiency by 1.2%. Regarding liquid hydrogen storage, cryogenic tanks have been proposed as a viable storage method, facilitating the capture of CO<sub>2</sub> and its direct feeding to fuel cells, thereby enhancing energy efficiency without requiring precious metal electrodes. However, challenges remain in the combustion of hydrogen, primarily due to its high volatility and susceptibility to self-ignition. Studies have drawn divergent conclusions regarding optimal injection pressures for diesel engines utilizing hydrogen. Efforts are underway to overcome these challenges, with the introduction of wet and dry low-emission gas turbine models aiming to mitigate water consumption and minimize corrosion issues associated with hydrogen combustion (Hoang et al., 2023).

## Fuel Cells

According to Van Biert et al. (2016), ships often use generators such as diesel generators to produce electricity through the process of chemical reactions, which creates thermal and mechanical energy, this is then converted to electricity to be used for auxiliary power and for propulsion. Fuel cells are able to convert chemicals into electric energy without the need for thermal energy from chemical reactions, therefore, avoiding the formation of NO<sub>x</sub> emissions (Van Biert et al., 2016). According to Van Biert et al. (2016), fuel cells work similarly to batteries, and the power produced from fuel cells can be distributed across all systems within a vessel without needing to increase fuel consumption. Fuel cells have already been successfully applied as backup power systems, and in data centers, but in maritime applications, the technology is still being tested before it is seen in widespread use. Essential components of a fuel cell comprise the cathode, anode, and electrolyte. Diverse varieties of fuel cells are distinguished by the nature of the electrolyte, including solid oxide fuel cells (SOFC), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), direct alcohol fuel cells (DAFC), alkaline fuel cells (AFC) and proton exchange membrane fuel cells (PEMFC) which can be seen in Figure 2.9. While fuel cells operate akin to traditional batteries, they diverge in their lack of necessity for charging and energy storage; rather, they sustain continuous electricity generation when provided with a steady supply of fuel and air. This operational trait endows fuel cells with a notable energy conversion efficiency surpassing 60% and enhanced reliability, particularly when juxtaposed with batteries, particularly amidst inclement weather conditions (Muhammed et al., 2023).

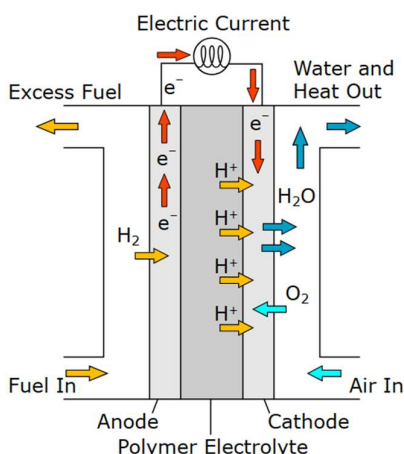


Figure 2.9 "Proton Exchange Fuel Cell Diagram" [Image], by Mattuci, 2015, OpenVerse.

The article by Hoang et al (2023) elaborates that hydrogen stands as the primary energy source for fuel-cell systems, necessitating the installation of onboard hydrogen storage systems for such vehicles. Despite the potential for vehicles equipped with fuel-cell systems to achieve twice the efficiency compared to those with conventional internal combustion engines, they encounter limitations due to their low hydrogen storage capacity, accommodating approximately 500 km of travel. Van Biert et al. (2016), seems to agree with this as it is mentioned in the article as well that fuel cell systems can generate electricity efficiently with few hazardous emissions, making them an ideal solution for ships with short-sea voyages. However, for longer sailing times, the limited hydrogen storage density can result in larger system volumes compared to alternative energy-dense logistic fuels like diesel. High-temperature fuel cell systems, on the other hand, can achieve high overall efficiency using hydrocarbon fuels and can be reasonable for ships with mission requirements of several days. For ships that require a longer independent operation, owners may need to balance smaller fuel tanks with a more energy-dense fuel, such as diesel, or fuel savings with a less energy-dense gaseous fuel, like natural gas (NG) (Van Biert et al., 2016).

Concerning electrical efficiency, fuel cells outperform open-cycle gas turbines by a significant margin, ranging from 32% to 70% (Hoang et al., 2023). Importantly, fuel cell technology signifies a green alternative, as it only produces water as a byproduct of electricity generation. Given the maturity of this technology, extensive research is ongoing for electricity production from hydrogen. Although hydrogen is not the exclusive fuel compatible with fuel cells, its utilization can enhance overall system synergy, leading to improved energy efficiency, heightened security, and reduced  $CO_2$  emissions. Moreover, fuel cell technology finds diverse applications, encompassing the fulfillment of power demands for commercial and residential buildings, as well as fuel cell-powered vehicles. Currently, various types of fuel cells are available in the market, each possessing distinct technical characteristics (Hoang et al., 2023).

Despite being more expensive than conventional generators, fuel cell systems offer several benefits, including avoiding exhaust gas cleaning for vessels operating in ECA zones (Van Biert et al., 2016). While environmental benefits from LNG as a logistic fuel may be debatable, NG-fueled fuel cell systems are in an advanced development state. Van Biert et al. (2016) predict that the developing LNG infrastructure and NG-fuelled fuel cell systems will facilitate the introduction of gaseous fuels and fuel cell systems on ships. Van Biert et al. (2016) suggest further research is needed on fuel cell combined cycles, hybridization with auxiliary electricity storage components, and classification standards for distributed electricity generation.

## 2.5 Impact of Fuel Spills

An article by Zhang et al (2019b), HFO fuel emissions have a large impact in open waters due to its air pollutant chemicals such as CO<sub>2</sub> and SO<sub>x</sub> but the most prominent air pollutant is black carbon particles. BC particles have a significant impact on the Arctic regions due to their influence on the albedo properties of ice and snow. BC darkens the coloration of ice and snow which leads to ice/snow absorbing more solar radiation rather than reflecting it back into space, leading to warmer temperature increases. The article claims that even a small amount of BC particle emissions can disproportionately affect the thawing of arctic ice and global warming.

According to Methanex. (2021) methanol is biodegradable and can dissolve quickly in water, but it still has minimal impact in marine waters. Methanol could possibly affect marine wildlife and the rapid evaporation of methanol can lead to the formation of toxic fumes, which can harm human health. Generally, the impact of methanol fuel spill is generally low compared to a diesel oil spill, methanol has developed to be biodegradable and the fast diluting of chemicals in bodies of water can lower the risk of harming wildlife depending on the amount of fuel spilled. According to Lloyd's Register (2022), ammonia is a toxic and corrosive substance that can have severe impacts on the environment if it spills. Ammonia fuel spills could have significant negative effects on the fragile ecosystems and wildlife that rely on the delicate balance of these areas. Ammonia can rapidly disperse and contaminate surrounding water and soil, potentially leading to significant ecological damage. Ammonia can also evaporate quickly, potentially leading to air pollution and adverse effects on human health.

## 3 Methodology

### 3.1 Mixed method research

Mixed method research is described as combining different methods, often qualitative and quantitative, to aid in the research. Bazeley, P. quotes “*I just say it's a combination of either different types of data, different types of data sources, or different kinds of analyzes in order to develop an outcome that is integrative so that they have to be interdependent with a common purpose-- and the integration is critical*” (2015). The mixed method approach does not have to be limited to qualitative and quantitative methods but can be broader in its application. This method will be used for research as assessing alternative fuels is determined through qualitative and quantitative data.

#### Qualitative research

Qualitative research is a primary methodology for academic study that reveals the nature of things (Berg, 2009). According to Merriam and Tisdell (2015), researchers are usually focused on people’s cognition and experiences of the world in qualitative research. Further, qualitative research is to understand and explain phenomena, indeed, expose the relations and connections between certain phenomena through the definition of things. Hence, qualitative research is descriptive and flexible. The data (non-numeric) in the form of text or images are from different research methods, such as interviews, documents, observations, and primary instruments (Merriam & Tisdell, 2015).

#### Quantitative research

According to O'Reilly et al. (2013), the Quantitative research method is used for collecting and analyzing data that is numerical and/or can be measured. Quantitative data can often come from sources such as surveys, questionnaires, and observations; once the data is collected, it can be analyzed and presented through statistical charts (O'Reilly et al., 2013).

#### Secondary Data Analysis

DEVINE (2003) states that “Secondary data analysis involves the analysis of an existing dataset, which had previously been collected by another researcher, usually for a different research question.” This methodology is used due to ease of access to existing data by other researchers; the research is mainly conducted through literature review; therefore, secondary data analysis will also be used on quantitative data.

### 3.2 MCDM and AHP

Multicriteria Decision Making (MCDM) is a subfield of operational research (Ramanathan, 2004) that aims to handle, manage, and access multiple criteria in a complicated environment and then make the optimal choice (Kumar et al., 2017). According to Kumar et al. (2017), MCDM has been employed in a wide range of applications and has proven to be one of the most effective and appropriate tools for the analysis of energy resources.

The Analytical Hierarchy Process (AHP) is a widely used and popular algorithm for multi-criteria decision-making that is both qualitative and quantitative (Satty, 1980). AHP is based on a hierarchical structure, which captures the relationship and dependencies between criteria and alternatives. Therefore, creating the hierarchical model is the primary task. Next, give a nominal value to each element in the model that

represents the importance in relation to the decision problem. Then, utilize the matrix based on the pairwise comparison to aggregate each element's weight and provide an overall ranking for decisions (Taherdoost, 2017).

### 3.3 Research Design

The procedures of AHP calculation after determining the problem and knowledge foundations are as follows.

#### Step 1: Build Hierarchical Model

Taherdoost (2017) demonstrated that the hierarchical model is a valuable framework to reflect and facilitate decision-making through indicators and choices. The model is designed to decompose complex problems into smaller, independent, and measurable parts, which are then placed each criterion into the different layers of the hierarchical model. Such a method can be beneficial in determining weights and priorities when having a holistic view and consideration of the problem. It is crucial to construct a hierarchical tree to ensure the effective adaptation of objectives, criteria, and issues in order to support goal achievement (Zuraidi et al., 2018).

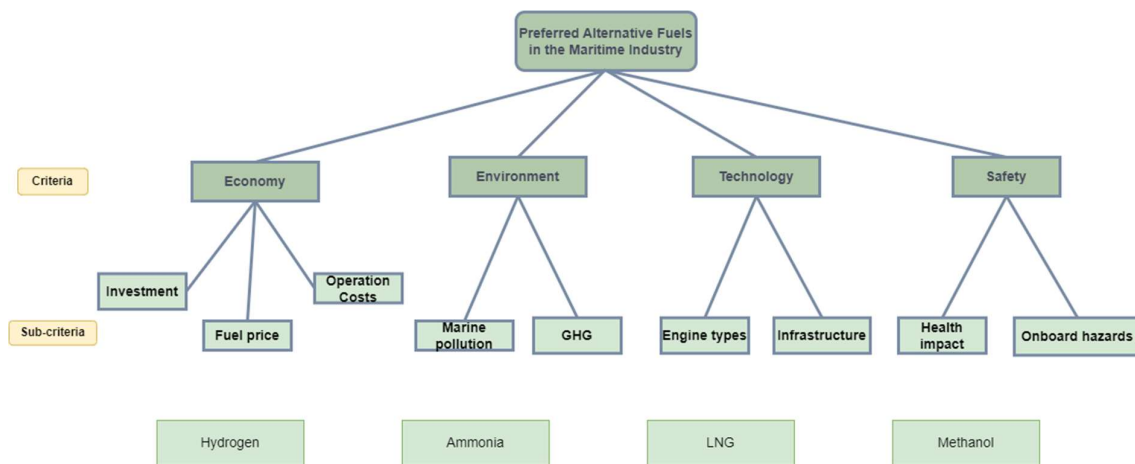


Figure 3.1 Hierarchical model for evaluating marine alternative fuels

As illustrated in Figure 3.1, the hierarchical tree used in this case involves selecting the most preferred alternative fuels in the marine sector. According to the purpose of the thesis, the criteria consist of four main aspects: economy, environment, technology, and safety. Further, below each criterion, several sub-criteria are divided: investment (retrofitting of existing vessels to support the use of alternative fuels), fuel price, operation costs for economy; marine pollution, GHG for environment; engine types, infrastructure for technology; crew health issues, and onboard accidents for safety. The selection of these sub-criteria was based on literature and Table 3.1 shows the display and analysis of the relevant literature. The judgment matrix can be obtained by dividing the hierarchy and performing pairwise comparisons.

Table 3.1 Analysis of Literature Supporting the Selection of Sub-Criteria.

No.	Author	Title	Publication year	Importance	Note
1.	Basso, M. N., Abrahamoglu, S., Foseid, H., Spiewanowski, P., Winje, E., & Jakobsen, E.	Nordic Roadmap Publication No. 1-A/1/2022	2022	High	Core literature, in-depth exploration of the characteristics of these four alternative fuels, which can reflect performance in terms of economy, technology, environment and safety. In particular, this paper emphasizes the economic aspects of <i>fuel prices, investment, and operating costs</i> ; and the technological aspects of <i>Infrastructure</i> .
2.	Hammer, L. S., Tveit, O., Sverud, T., Leisner, M., & Eide, M. S.	Nordic Roadmap: Fuel properties and their consequences for safety and operability.	2022	High	This literature describes in detail the nature of these four alternative fuels regarding economic, environmental and safety hazards, which supports the sub-criterias for <i>investment, marine pollution, safety impact &amp; onboard hazard</i> .
3.	Ait Aider, C., Roß, L., Ehlers, S., Kaeding, P., & Lindemann, T.	Integration of a tank storage solution for alternative fuels on a RoRo ship	2023	High	<i>GHG</i> was chosen as a sub-criterion for the environment because this literature emphasizes the significance of GHG emissions for the study of alternative fuels and how this is closely related to the research question of this thesis.
4.	Inal, O. B., Charpentier, J.-F., & Deniz, C.	Hybrid power and propulsion systems for ships: Current status and future challenges	2022	Medium	The literature dives into various propulsion systems and hybrid powered engines using criterias to measure the progress and potential of alternative engines instead of relying solely on ICE. This is what helped provide the chosen sub-criteria for <i>Engine Types</i> in Technology.
5.	Hermann, R. R., Lin, N., Lebel, J., & Kovalenko, A.	Arctic transshipment hub planning along the Northern Sea Route: A systematic literature review and policy implications of arctic port infrastructure.	2022	Medium	The <i>Infrastructure</i> sub-criteria is supported by the referred literature which covers the planning and challenges when it comes to developing port infrastructures in the northern sea route.

The sub-criteria within this hierarchical model are delineated based on the specific purpose and scope of the study. Firstly, the fuel price is characterized as the monetary amount per ton (\$/t) or gigajoule (\$/GJ) required to procure the fuel. Secondly, the investment factor pertains to the modifications necessary to retrofit the existing vessel for the utilization of alternative fuels. Another essential consideration in this model is the operational cost, which is influenced by the energy density of various alternative fuels. For instance, alternative fuels with higher energy density enable longer distances to be covered per unit volume, resulting in enhanced economic efficiency. Consequently, these criteria serve as the basis for discerning the most economically advantageous alternative fuel option.

When evaluating the environmental aspects of alternative fuels, two important sub-criteria come into play: marine pollution and greenhouse gas (GHG) emissions. Marine pollution focuses on the potential toxicity of the fuel and its impact on delicate polar ecosystems in the event of accidental leakage into the oceans. On the other hand, the GHG sub-criterion assesses whether the combustion products of alternative fuels contribute to climate issues. Together, these two sub-criteria play a pivotal role in determining the overall environmental friendliness of the four alternative fuels.

Technology sub-criterion investigates the feasibility of implementing alternative fuels within existing technological frameworks by examining the dimensions of engine type and infrastructure. The engine type is delineated into two powertrains: diesel engines and fuel cells, in order to assess the applicability of these alternative fuels. However, at present, most commercial ships are still driven by internal combustion engines, thus, this study will focus more on this driving method. Furthermore, the notion of infrastructure pertains to the determination of whether the adoption of alternative fuels necessitates the construction of novel supporting facilities, such as refueling stations. The study aims to elucidate whether alternative fuels can seamlessly integrate into current technologies, with particular emphasis on their compatibility with established engine types and the potential infrastructural prerequisites they may entail. The analysis of these factors will contribute to a comprehensive understanding of the viability and sustainability of alternative fuel utilization in the existing transportation and energy landscape.

Finally, safety considerations are crucially evaluated with respect to crew health issues and on-board accidents. The toxicity of the alternative fuel serves as a pivotal indicator for potential crew health issues. In the event of a safety incident, such as a fuel leak, or inadvertent contact between crew members and the fuel, adverse health effects may arise. Furthermore, onboard accidents, particularly fires, are examined with a primary focus on burn rates. Understanding the burn rate of the alternative fuel is imperative in comprehending its potential impact on fire hazards and the degree of severity in the event of a fire-related incident.

## Step 2: Pairwise Comparisons

In this phase, the questionnaire is designed to gather opinions from relevant respondents to complete the pairwise comparison process (Taherdoost, 2017). As outlined in the hierarchical tree of the previous step, the pairwise judgmental comparison is conducted within every two criteria at the same level. The assessment is the core of the AHP approach because it determines the priority of each element and decides the final decision subsequently (Zuraidi et al., 2018). In order to compare the importance of elements, a scale of numbers is necessary, as Table 3.2 shows (Saaty, 2008). For instance, if criterion A is moderately more important than criterion B, then it is assigned an intensity value of 3. Based on the reciprocal axiom, B is 1/3 times more important than A. Further, the intensity value 1 means two elements have the same importance. Nevertheless, to simplify the understanding of respondents, the questionnaire employs a 1-3-5-7-9 scale for comparing the importance of the two criteria (Table 3.3). After that, the data collected from questionnaires are subsequently rearranged and placed into a pairwise comparison matrix for further analysis (Zuraidi et al.,

2018). However, it is worth noting the need to convert individual inputs into collective judgments before output by using the geometric mean method since multiple respondents were involved (Taherdoost, 2017).

Table 3.2 The fundamental scale of absolute numbers. (Source: Saaty, 2008)

<i>Scale</i>	<i>Definition</i>	<i>Explanation</i>
<b>1</b>	Equal importance	Two activities contribute equally to the objective
<b>3</b>	Moderate importance of one over another	Experience and judgment strongly favor one activity over another
<b>5</b>	Essential or strong importance	Experience and judgment strongly favor one activity over another
<b>7</b>	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
<b>9</b>	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
<b>2,4,6,8</b>	Intermediate values between the two adjacent judgments	
<b>Reciprocals of above</b>	If activity $i$ has one of the above non-zero numbers assigned to it when compared with activity $j$ , then $j$ has the reciprocal value when compared with $i$	

Table 3.3 Example of the Questionnaire

<b>Criterion A</b>	<b>9</b>	<b>7</b>	<b>5</b>	<b>3</b>	<b>1</b>	<b>3</b>	<b>5</b>	<b>7</b>	<b>9</b>	<b>Criterion B</b>
Economy	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Environment
Economy	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Technology
Economy	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Safety
Environment	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Technology
Environment	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Safety
Technology	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Safety

### Step 3: Data Analysis

To facilitate a clear and simple explanation of the calculation process involved in the AHP, an illustrative example is demonstrated in Table 3.4. The objective is to identify the most critical factor for selecting the optimal alternative fuel in the marine industry. To accomplish this, the elements in the first column are compared to those in the first row, as prescribed by Saaty (2008). In this specific case, the environment criterion is regarded as very strongly more important than the economy criterion, thus, is given a value of 7. On the other hand, the economy criterion is deemed to be less important than the environment criterion, in relative terms, the value is calculated to be 1/7, as determined by the matrix.

*Table 3.4 An example of a pairwise comparison matrix*

	Economy	Environment	Technology	Safety
Economy	1	1/7	1/3	1/9
Environment	7	1	7	1
Technology	3	1/7	1	1/9
Safety	9	1	9	1

Next, this table can be organized in the form of a matrix, such as A. Let A be a  $n \times n$  comparison judgment matrix (Eq 3.1 and 3.2).

$$A = \begin{pmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{pmatrix} \quad (3.1)$$

$$A = \begin{pmatrix} 1 & \frac{1}{7} & \frac{1}{3} & \frac{1}{9} \\ 7 & 1 & 7 & 1 \\ 3 & \frac{1}{7} & 1 & \frac{1}{9} \\ 9 & 1 & 9 & 1 \end{pmatrix} \quad (3.2)$$

### Three calculating approaches in AHP

To calculate the weight of criteria, there are three approaches to use: mean of the normalized value method, geometric mean method (also called the logarithmic least squares method), and eigenvector method (Ishizaka & Lusti, 2006). Since there are slight differences in the calculation results of each method, the weights will be calculated by these three methods separately and then averaged.

#### Method 1: The mean of the normalized value

It is the simplest method, but there is no mathematical approach to handling the inconsistency matrix (Ishizaka & Lusti, 2006). To simplify the subsequent calculations, the normalization of this matrix results in

the following (Table 3.5). The normalization process (Eq 3.3 and 3.4) is the sum of each column, then dividing each element from the column with the sum of each (Cahyapratama & Sarno, 2018).

$$a_{ij} = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}} \quad (3.3)$$

$$a_{11} = \frac{a_{11}}{\sum_{i=1}^n a_{i1}} = \frac{1}{1 + 7 + 3 + 9} = 0.050 \quad (3.4)$$

*Table 3.5 Normalization of the pairwise comparison matrix.*

	Economy	Environment	Technology	Safety
Economy	0.050	0.063	0.019	0.050
Environment	0.350	0.438	0.404	0.450
Technology	0.150	0.063	0.058	0.050
Safety	0.450	0.438	0.519	0.450

Next, the approach entails the synthesis weight by the sum of each row after normalized processing (Eq 3.5).

$$\text{Economy: } (0.050 + 0.063 + 0.019 + 0.050) \div 4 = 0.045 \quad (3.5)$$

Follow the same method to calculate the synthesis weights for other criteria (Table 3.6).

*Table 3.6 The synthesis weight of the AHP criterion.*

Criterion	Synthesis Weight
Economy	0.045
Environment	0.410

Technology	0.080
Safety	0.464

**Method 2: Geometric mean**

Geometric mean is also a common approach applies to calculate AHP (Ishizaka & Lusti, 2006). Based on the normalized table above, the geometric mean is calculated in the following equations 3.6 and 3.7:

$$w_i = \frac{(\prod_{j=1}^n a_{ij})^{\frac{1}{n}}}{\sum_{i=1}^n (\prod_{j=1}^n a_{ij})^{\frac{1}{n}}} \tag{3.6}$$

Economy:

$$\begin{aligned} w_1 &= \frac{(\prod_{j=1}^4 a_{1j})^{\frac{1}{4}}}{\sum_{i=1}^4 (\prod_{j=1}^4 a_{ij})^{\frac{1}{4}}} \tag{3.7} \\ &= \frac{(a_{11} \cdot a_{12} \cdot a_{13} \cdot a_{14})^{\frac{1}{4}}}{(a_{11} \cdot a_{12} \cdot a_{13} \cdot a_{14})^{\frac{1}{4}} + (a_{21} \cdot a_{22} \cdot a_{23} \cdot a_{24})^{\frac{1}{4}} + (a_{31} \cdot a_{32} \cdot a_{33} \cdot a_{34})^{\frac{1}{4}} + (a_{41} \cdot a_{42} \cdot a_{43} \cdot a_{44})^{\frac{1}{4}}} \\ &= \frac{(1 \cdot \frac{1}{7} \cdot \frac{1}{3} \cdot \frac{1}{9})^{\frac{1}{4}}}{(1 \cdot \frac{1}{7} \cdot \frac{1}{3} \cdot \frac{1}{9})^{\frac{1}{4}} + (7 \cdot 1 \cdot 7 \cdot 1)^{\frac{1}{4}} + (3 \cdot \frac{1}{7} \cdot 1 \cdot \frac{1}{9})^{\frac{1}{4}} + (9 \cdot 1 \cdot 9 \cdot 1)^{\frac{1}{4}}} \\ &= 0.042 \end{aligned}$$

The weights of each criterion calculated by the same method are shown in the following table (Table 3.7):

*Table 3.7 The geometric mean of the AHP criterion.*

Criterion	Geometric mean
Economy	0.042
Environment	0.408

Technology	0.072
Safety	0.463

### Method 3: Eigenvalue

Satty (1980) proposed to obtain the weight vector of pairwise comparison matrices by calculating the eigenvalues (Ishizaka & Lusti, 2006). The specific calculation process is as follows (Eq. 3.8):

$$A \cdot w = \lambda_{max} \cdot w \quad (3.8)$$

Where

A: pairwise comparison matrix

w: the principle right eigenvector of the matrix A

$\lambda_{max}$ : the dimension of the matrix

The specific calculation process is completed by MATLAB, and the results of the case shown as follows (Eq 3.9):

$$\lambda_{max} = 4.1624 \quad (3.9)$$

The eigenvector (Eq. 3.10) which corresponds to the largest eigenvalue ( $\lambda$ ) is:

$$w = \begin{pmatrix} -0.0684 \\ -0.6534 \\ -0.1205 \\ -0.7442 \end{pmatrix} \quad (3.10)$$

This eigenvector is normalized, which gives the weights as the following table (Table 3.8):

*Table 3.8 Eigenvalue-based weight for the AHP criterion.*

Criterion	Weight
-----------	--------

Economy	0.043
Environment	0.412
Technology	0.076
Safety	0.469

The weights of each criterion are obtained by three calculation methods, however, there are some slight differences in the results obtained with these three methods. Therefore, the average of the weights obtained by these three methods will be calculated at the end to get a more precise answer (Table 3.9).

*Table 3.9 The final weights of the AHP criteria*

Criterion	Method 1	Method 2	Method 3	Weight (Avg)
<b>Economy</b>	0.045	0.042	0.043	<b>0.043</b>
<b>Environment</b>	0.410	0.408	0.412	<b>0.410</b>
<b>Technology</b>	0.080	0.072	0.076	<b>0.076</b>
<b>Safety</b>	0.464	0.463	0.469	<b>0.465</b>

#### Step 4: Consistency Test

In order to validate the results of the AHP method, a consistency test is often necessary (Eq. 3.11 and 3.12). The consistency ratio indicates the level of consensus among decision-makers in assessing judgments about the relative importance of different criteria or alternatives. If the consistency ratio is equal to or less than 0.1, the result of the calculation can be acceptable (Taherdoost, 2017). The index random consistency is related to the dimension of the matrix, in other words, the complexity of a decision problem tends to increase with the size of the decision matrix. Moreover, the specific values are shown in the following Table 3.10 (Cahyapratama & Sarno, 2018).

$$CR = \frac{CI}{RI} \quad (3.11)$$

(3.12)

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

Where:

CR is Consistency Ration

CI is Consistency Index

IR is Index Random Consistency

Table 3.10 The value of Index Random Consistency (Source: Cahyapratama & Sarno, 2018)

Matrix Dimensions	RI
1	0
2	0
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51
12	1.48

The maximum eigenvalue has been obtained in method 3, thus, consistency ration calculations as shown below (Eq. 3.13 3.14 and 3.15):

$$\lambda_{max} = 4.1624 \tag{3.13}$$

$$CI = \frac{4.1624 - 4}{4 - 1} = 0.0541 \tag{3.14}$$

$$CR = \frac{0.0541}{0.9} = 0.06 < 0.1, \text{ consistent} \tag{3.15}$$

After passing the consistency test, the individual weights are utilized in the analysis of results. The attributes of each category of the four alternative fuels, hydrogen, LNG, ammonia, and methanol are initially ranked and scored according to the objective of the thesis, which is to assess the most viable alternative fuels based on environmental, technical, economic, and safety considerations. The purpose of this research serves as a

rating scale for each alternative fuel. Ultimately, the scores are multiplied by the weights and summed up to derive the outcomes.

### 3.4 Case Study

The Venta Maersk, a prominent ship built in 2018, serves as an ideal candidate for this study because it operates in polar waters and is categorized by the Polar Code as FS Ice Class 1A. The properties of the vessel can be seen in Table 3.11. By evaluating the potential of alternative fuels, namely hydrogen, ammonia, LNG, and methanol, this study seeks to analyze the technical, economic, and environmental aspects associated with retrofitting Venta Maersk with each fuel type. It is worth highlighting that in terms of technology this case study focuses on its internal combustion engine as a propulsion system. The findings of this case study will contribute valuable insights into the feasibility and suitability of alternative fuels for reducing carbon emissions and increasing safety in maritime transportation.

*Table 3.11 Properties of the vessel*

<b>Character</b>	<b>Symbol</b>	<b>Value</b>
Length over all (meters)	LOA	200
Breadth moulded (meters)	B	35.2
Main engine (kiloWatts)	MCR	17279
Service speed (knots)	At: 0.9 MCR 15% sea margin	19.000
Fuel consumption (t)	tonnes per day	65.000

*Table 3.12 Density and energy content/LHV (Source: Brynolf et al., 2023)*

<b>Unit</b>	<b>HFO/MGO</b>	<b>Liquid Hydrogen</b>	<b>Compressed Hydrogen</b>	<b>Methanol</b>	<b>LNG</b>	<b>Ammonia</b>
Density (kg/m <sup>3</sup> )	855	70.8	42	791.4	468.1	682.6
Energy Content / Lower heat value (MJ/kg)	42.7	120	120	19.9	48	18.6
Energy Density (MJ/m <sup>3</sup> )	36508.5	8496	5040	15748.86	22468.8	12696.36

Table 3.13 Engine type from Venta Maersk ship information and tank-to-wake efficiency.  
(Source: Brynolf et al., 2023)

Engine efficiency 2-stroke engines	Efficiency (80% load)
HFO/MGO	50%
Hydrogen (Liquid and Compressed)	50%
Methanol	50%
LNG	50%
Ammonia	46%

Some properties of the vessel are lacking in MV Venta Maersk ship specifications, particularly the fuel type and fuel capacity of the vessel which is needed to compare and contrast the feasibility of the alternative fuels in the ship. Without comprehensive data, rough estimate assumptions become necessary to approximate the vessel's fuel storage capabilities. While this approach provides a basic approximation, it is important to acknowledge its limitations and uncertainties. Vessel-specific factors, including fuel efficiency measures, operational profiles, and voyage durations, can significantly impact the actual fuel storage capacity.

To estimate the fuel storage capacity, we can consider the typical fuel consumption rate for a vessel of this size and operational profile. However, it's important to note that actual fuel storage capacity can vary depending on factors such as the ship's design, fuel efficiency measures, voyage duration, and fuel consumption rates.

As an approximation, the fuel consumption rate is around 65 metric tons per day based on data given by the ship specifications of MV Venta Maersk (See Table 3.11). For this case study, the consumption rate is assumed to be consistent for all fuel types. Given this estimated fuel consumption rate, a calculation can be made on the potential fuel storage capacity of MV Venta Maersk based on a typical voyage duration. Using data given by Brynolf et al (2023), tank-to-wake propeller efficiency for 2-stroke engines is 50% (Table 3.13), for the sake of consistency an assumption is made that the fuel efficiency is 50% for all fuels besides Ammonia which is 46%. The article also includes data regarding the density of the fuels as well as Lower Heat Value (LHV) which is then used to find the energy density for each fuel (Brynolf et al, 2023).

With this data, the main goal of the calculations is to determine the fuel storage capacity of each fuel that would be required for a 4-day voyage. 4-days were chosen as an assumption for the average amount of days ships would spend sailing polar waters.

Calculations for Energy density was found by multiplying LHV with Density (Eq. 3.16) (Results shown in Table 3.12)

$$\text{Energy Density} = \text{Lower Heat Value} \times \text{Density} \quad (3.16)$$

Step 1: Start by calculating Total Energy Consumption for 4-Day Voyage for Each Fuel

The formula for this calculation follows as such (Eq. 3.17):

$$Total\ Energy\ Consumption = (65\ tonnes/day \times 4\ days \times 1000\ kg) \times LHV \quad (3.17)$$

Since fuel consumption is “ton/day”, it will need to be converted to kilograms (1000 kg) for further calculations regarding storage. The calculations for each fuel's results are shown in Table 3.14 below.

*Table 3.14 Total energy consumption over 4 days for all alternative fuels*

Fuel	Total energy consumption over 4 days (MJ)
HFO/MGO	11102000
Liquid Hydrogen	11102000
Compressed Hydrogen	11102000
Methanol	11102000
LNG	11102000
Ammonia	12067391

Step 2: Calculate Volume and Mass for Each Fuel Type

Now, let's calculate the volume and mass of each fuel required for the voyage.

For volume, the calculation is done by dividing the total energy consumption of a fuel over 4 voyage days by the energy density of the same fuel (Eq. 3.18). This will lead to the results showing the volume required for the fuel in meters cubed (m<sup>3</sup>)

$$Volume = \frac{Total\ Energy\ Consumption\ over\ 4\ days}{Energy\ Density\ (MJ/m^3)} \quad (3.18)$$

To find the mass of the fuel, the volume from the previous calculation is taken and multiplied with Density from Table 3.12, then divided by 1000 kg to convert the mass into tons (Eq. 3.19). This is due to the consumption rate of the Venta Maersk ship being measured as Tons per Days.

$$Mass = \frac{Volume \times Density}{1000\ kg} \quad (3.19)$$

The two formulas will be used for each fuel to achieve the theoretical results on storage requirements needed for a 4-day voyage on a Venta Maersk ship.



## 4 Results and Analysis

### 4.1 Hydrogen supply chain

#### Production

*Table 4.1 Comparison table of blue and green hydrogen production methods. (Source: Grasu, 2023)*

<b>Production Method</b>	<b>Key Characteristics</b>	<b>Environmental Impact</b>	<b>Cost Considerations</b>
<b>Blue Hydrogen (Methane reforming with CCS)</b>	Partial elimination of CO <sub>2</sub> emissions; reliance on methane; moderate cost-effectiveness	Residual CO <sub>2</sub> emissions; concerns about methane as a potent greenhouse gas	Moderate cost efficiency compared to green hydrogen; potential for cost reduction with advancements in CCS technology
<b>Green Hydrogen (Water Electrolysis)</b>	Produced from renewable energy; minimal environmental impact	Zero direct emissions; reliance on renewable energy sources	Higher production costs compared to blue hydrogen; potential for cost reduction with advancements in electrolysis technology

Insights from Grasu (2023) provide a comprehensive overview of hydrogen production methods and their relevance in maritime applications (shows in Table 4.1). Blue hydrogen, utilizing methane reforming with CCS, leverages established technologies, but persistent concerns center around environmental impact due to residual CO<sub>2</sub> emissions and methane usage. In contrast, green hydrogen, produced through water electrolysis, reflects ongoing technological evolution, offering a promising zero-emission alternative with integration capabilities into renewable sources. Grasu (2023) underscores economic considerations, noting that, despite the environmentally friendly attributes of green hydrogen, it currently entails higher production costs compared to blue hydrogen. The economic feasibility of hydrogen applications in shipping is a focal point, emphasizing the need for ongoing advancements in technology and potential regulatory shifts to enhance cost competitiveness.

#### Transportation

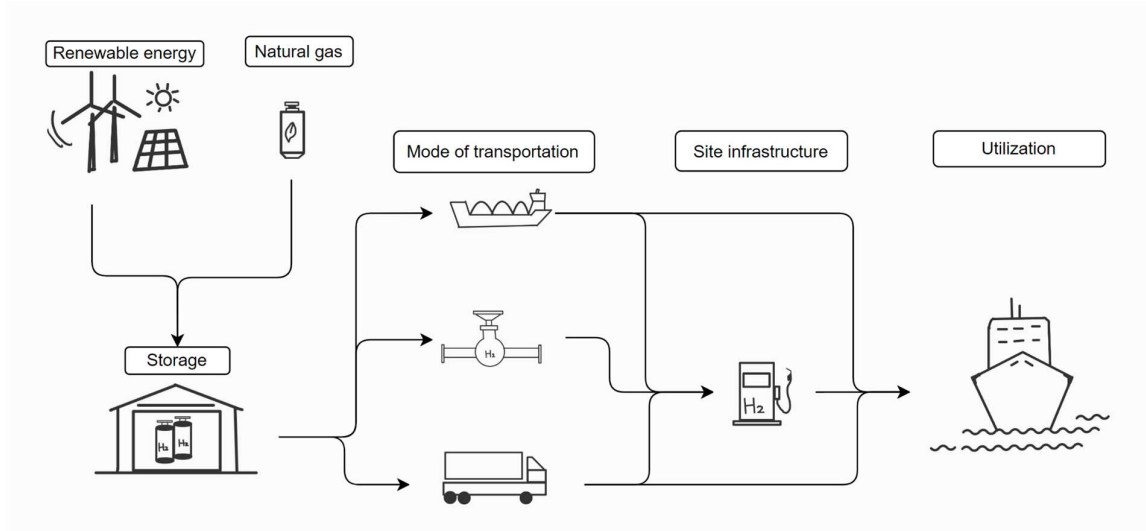
According to Lovegrove's report (2022), Table 4.2 delineates the various transportation methods for different forms of hydrogen fuel, along with the scenarios each method is best suited for. Beyond considering distance and volume requirements for hydrogen transport, both Rong et al. (2023) and Lovegrove (2022) highlight the impact of infrastructure on the choice of transportation method. Rong et al. (2023), in particular, provide detailed insights into the compatibility of transportation tools with existing infrastructure. For instance, using extended tube trailers for transporting compressed hydrogen, their characteristic high-pressure hydrogen storage tanks can be utilized as secondary storage devices at refueling stations. Moreover, in the study by Rong et al. (2023), cost-effectiveness is also considered as a vital factor in selecting a transportation method.

Table 4.2 Transportation methods and applicable scenarios of different forms of hydrogen fuel. (Source: Lovegrove, 2022)

<b>Compressed hydrogen</b>	
<b>Mode of transportation</b>	<b>Application scenario</b>
Pipeline	Long distances and substantial volumes
Trucking	Short distance and low volumes or long distance and low volumes
Shipping	short distance transportation
<b>Liquid hydrogen</b>	
<b>Mode of transportation</b>	<b>Application scenario</b>
Trucking	Long distance (4000 km) and large volume (4000 kg)
Shipping	Large volumes and over even longer distances
<b>Ammonia &amp; LOHC</b>	
<b>Mode of transportation</b>	<b>Application scenario</b>
Pipeline	Distance exceeds 1500 km & a large volume
Shipping	Long distance and large volume; transoceanic transport
Trucking	Short distance and low volumes

## Storage

In the literature by Yang et al. (2023), and Hoecke et al. (2021), there is a detailed classification of compressed hydrogen storage tanks, ranging from Types I to IV. Hoecke et al. (2021) also mention the existence of Type V tanks, which are capable of withstanding higher pressures, a detail not covered in Yang et al. (2023). The likely reason for this omission could be the currently limited application scenarios for Type V hydrogen storage tanks. Regarding the storage of liquefied hydrogen, Hoecke et al. (2021) point out that it is not yet a common maritime cargo, primarily due to unresolved issues with evaporation during refueling and storage processes that have not yet reached an ideal standard. This challenge is similarly emphasized in Yang et al. (2023), where it's noted that tanks for storing liquefied hydrogen cannot withstand high pressure, necessitating the venting of hydrogen gas that evaporates due to the absorption of ambient heat. Furthermore, considering hydrogen storage scenarios on ships, only the report by the American Bureau of Shipping (2023) details the need for specific designs and modifications on vessels using hydrogen as fuel, to ensure safety.



*Figure 4.1 Hydrogen supply chain as marine fuel.*

Based on the literature review in Chapter 2.2, Figure 4.1 has been developed to illustrate a simplified hydrogen fuel supply chain process, encompassing production, storage, and transportation. Hydrogen production considers two environmentally friendly methods: blue hydrogen produced from natural gas and green hydrogen produced from alternative energy sources. In comparison, the production process of green hydrogen is cleaner, albeit approximately 5-7 times more costly than blue hydrogen (Grasu, 2023). For vessels engaged in extended voyages, there is potential to produce hydrogen fuel on board by harnessing wind and solar energy to electrolyze water.

In the realm of hydrogen fuel storage, storing compressed hydrogen gas in tanks stands as the most economically viable and widely employed method at present (Li et al., 2024). However, both Li et al. (2024) and Hoecke et al. (2021) have cited concerns regarding the low volumetric energy density and safety issues associated with compressed hydrogen, posing challenges to hydrogen storage. Conversely, storing liquid hydrogen in cryogenic tanks boasts a higher volumetric energy density than compressed hydrogen. Yet, liquid hydrogen storage demands stricter environmental requirements and encounters issues of energy-intensive refueling processes and evaporative losses (Hoecke et al., 2021). Although cryo-compressed hydrogen storage shows promise in addressing the shortcomings of compressed and liquid hydrogen storage, its maturity level requires enhancement, with storage tanks not yet applied commercially. Consequently, for vessels necessitating long-distance travel and substantial cargo capacity, liquid hydrogen emerges as a fitting choice, offering higher energy density within limited storage space. Looking ahead, cryo-compressed hydrogen storage holds potential, as it not only provides higher energy density but also minimizes fuel loss during storage.

Transporting hydrogen fuel stands as a critical link within the supply chain. Compressed hydrogen primarily undergoes transportation via pipelines and trucks, while liquid hydrogen is primarily transported by trucks and ships (Lovegrove, 2022). Given the current scarcity of infrastructure such as hydrogen refueling stations, pipeline transportation cannot directly facilitate refueling for ships, thus affording trucks and hydrogen refueling ships a competitive advantage in hydrogen fuel transportation. Furthermore, for large vessels with greater fuel demands, hydrogen refueling ships offer unique advantages as they can refuel at sea during voyages, distinguishing them from trucks.

In summary, the most promising application for handling hydrogen fuel in maritime shipping involves the production of hydrogen from renewable sources, storing it as liquid hydrogen or cryo-compressed hydrogen,

and transporting it to vessels via hydrogen refueling ships. Such an approach enables zero emissions, efficiency, and sustainability, facilitating the transition of the maritime sector towards hydrogen fuel.

## Hydrogen Technical Application

The utilization of Hydrogen in both internal combustion engines (ICEs) and fuel cells represents two distinct pathways toward decarbonizing various sectors. This section aims to compare the utilization of hydrogen fuel in internal combustion engines and fuel cells, focusing on key aspects such as efficiency, emissions, infrastructure, and costs as seen in Table 4.3.

*Table 4.3 Comparison of hydrogen fuel cell and hydrogen internal combustion engine technologies.*

<i>Applications</i>	<i>Internal Combustion Engine (ICE) using Hydrogen</i>	<i>Fuel Cells using Hydrogen</i>
<i>Efficiency</i>	Lower efficiency compared to fuel cells	Higher efficiency, typically 40%-60%
<i>Infrastructure</i>	Minimal changes to existing infrastructure required. High accessibility, only requires modifications of existing ICE on vessels	Can be expensive. Significant infrastructure development needed for hydrogen production, distribution, and refueling stations
<i>Cost</i>	Relatively lower initial cost compared to fuel cells	Higher initial cost and ongoing challenges with cost reduction
<i>Emissions</i>	Much lower emissions compared to conventional ICEs	Zero emissions, only water vapor

Internal combustion engines powered by hydrogen typically exhibit lower efficiency compared to fuel cells. While ICEs offer familiar technology and relatively simpler integration into existing vehicle platforms, their thermal efficiency tends to be lower, resulting in less effective utilization of hydrogen energy (Van Biert et al., 2016). In contrast, fuel cells, known for their electrochemical conversion of hydrogen into electricity, achieve higher efficiency levels, typically ranging from 40% to 60% (Muhammed et al., 2023). This superior efficiency of fuel cells contributes to reduced energy consumption and greenhouse gas emissions during vehicle operation.

Hydrogen utilization in both ICEs and fuel cells offers environmental benefits compared to conventional fossil fuels. Internal combustion engines powered by hydrogen produce lower emissions, contributing to improved air quality and reduced carbon footprint. However, fuel cells stand out for their truly zero-emission operation, as they only emit water vapor during hydrogen conversion (Hoang et al., 2023). These characteristic positions fuel cells as a compelling solution for achieving carbon neutrality and mitigating climate change impacts.

The infrastructure requirements for hydrogen utilization vary significantly between internal combustion engines and fuel cells. Hydrogen-powered ICEs generally necessitate minimal changes to existing infrastructure, as they can utilize conventional refueling stations with minor modifications. In contrast, fuel cells require more extensive infrastructure development, including hydrogen production, distribution, and refueling stations equipped with specialized storage and dispensing systems. This substantial investment in infrastructure presents a notable challenge for the widespread adoption of fuel cell technology.

Technological considerations play a crucial role in determining the viability and scalability of hydrogen utilization in both ICEs and fuel cells. Internal combustion engines offer a familiar and mature technology, enabling easier integration into existing vehicle fleets (Hoang et al., 2023). However, challenges such as hydrogen storage and combustion efficiency limit their long-term sustainability. In contrast, fuel cells represent a more advanced and promising technology with higher efficiency and zero-emission operation. Despite their higher initial cost and infrastructure requirements, fuel cells hold significant potential for transforming the transportation sector towards a sustainable future.

While hydrogen utilization in both internal combustion engines and fuel cells offers benefits in terms of efficiency and environmental impact, fuel cells stand out for their superior performance and zero-emission operation. However, addressing infrastructure challenges and advancing technological developments are crucial for realizing the full potential of hydrogen as a clean and sustainable energy carrier in transportation.

## 4.2 Case study -Venta Maersk

Table 4.4 Fuel storage required for operating 4 days (Volume)

Fuel storage required for operating 4 days (Volume)	
Fuels	Volume (m <sup>3</sup> )
HFO/MGO	304.09
Liquid hydrogen	1,306.73
Compressed Hydrogen	2202.78
Methanol	704.94
LNG	494.11
Ammonia	950.46

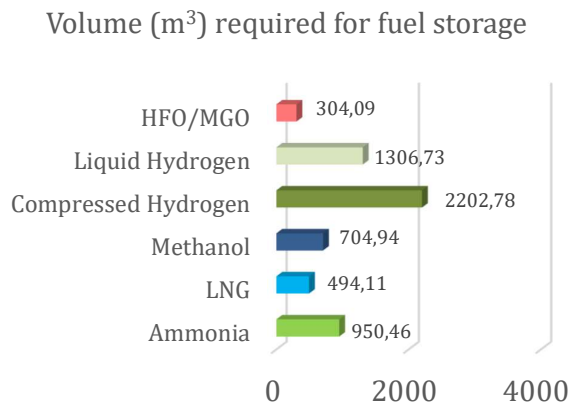


Figure 4.2 Volume (m<sup>3</sup>) required in fuel storage for 4 days voyage.

Table 4.5 Fuel storage required for 4 days (Mass)

Fuels	Mass (ton)
HFO/MGO	260.00
Liquid Hydrogen	92.52
Compressed Hydrogen	92.52
Methanol	557.89
LNG	231.29
Ammonia	648.78

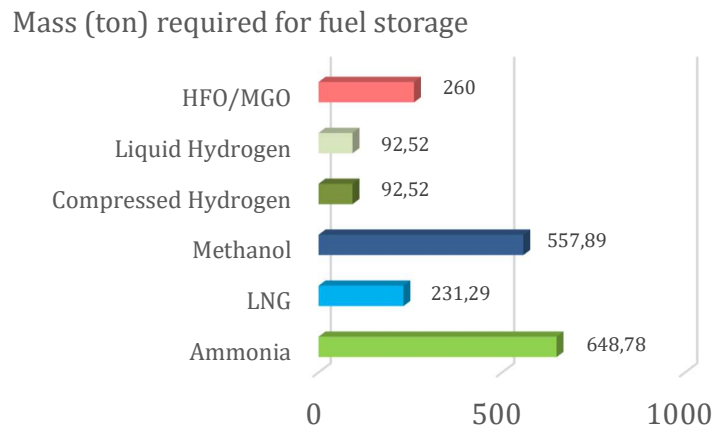


Figure 4.3 Mass for fuel storage for each alternative fuel.

### Case Study Analysis

In evaluating the feasibility of alternative fuels for Venta Maersk, several factors must be considered, including volume, mass, energy consumption, and engine efficiency. The calculations provide insight into the potential practicality and challenges associated with each fuel option. Here, we analyze the implications of the volume and mass requirements for each alternative fuel, focusing on their feasibility and suitability for Venta Maersk.

#### Volume and Mass Considerations

**HFO/MGO:** Results for HFO/MGO show volume and mass being relatively lower than other alternative fuels apart from liquid & compressed hydrogen, and LNG when it comes to Mass (Tons). HFO has had a long withstanding high density of energy as shown in Table 3.12 but proves that it is difficult to simply replace it with another fuel unless it can match or overcome the benefits that HFO/MGO provides while removing the drawbacks that come with using traditional fuels, namely carbon emissions.

**Hydrogen (Compressed Gas):** Despite its high energy density per unit mass, hydrogen requires significant storage volume due to its low density. The calculated volume and mass for hydrogen (compressed gas) indicates substantial storage requirements, posing challenges in onboard storage space and logistics. Moreover, ensuring safe handling and containment of hydrogen under high pressure adds complexity to its implementation.

**Liquid Hydrogen:** Liquid hydrogen exhibits even higher volume requirements compared to compressed gas due to its extremely low density. While offering high energy content, the necessity for cryogenic storage and insulation further complicates its practicality for maritime use. The substantial volume and mass underscore the logistical and engineering challenges associated with liquid hydrogen storage and distribution.

**Methanol:** Methanol demonstrates relatively moderate volume and mass requirements compared to hydrogen, making it a more practical option for onboard storage. While offering lower energy density per unit volume, methanol's ease of handling and compatibility with existing infrastructure enhance its feasibility for Venta Maersk. However, concerns regarding methanol's toxicity and flammability necessitate safety precautions and regulatory compliance.

**LNG (Liquefied Natural Gas):** LNG presents favorable volume and mass characteristics, striking a balance between energy density and storage efficiency. The calculated volume and mass for LNG indicate manageable storage requirements, supported by established infrastructure and operational experience in the maritime sector. LNG's cleaner combustion profile and relative abundance make it an attractive transitional fuel option for Venta Maersk.

**Ammonia:** Ammonia exhibits moderate volume requirements but comparatively higher mass due to its denser nature. While offering potential as a carbon-neutral fuel, ammonia's toxicity and corrosive properties pose challenges in handling, storage, and infrastructure compatibility. Addressing safety concerns and developing ammonia-specific engine technology are crucial for its successful adoption.

Feasibility Assessment:

**Hydrogen vs. Other Alternatives:** Among the alternative fuels considered, hydrogen (compressed gas and liquid) presents the greatest challenges in terms of storage volume and infrastructure requirements. While offering zero-emission potential, the practicality of hydrogen for maritime use remains limited by storage constraints and safety considerations. In comparison, methanol, LNG, and ammonia offer more feasible options, balancing energy density, storage efficiency, and operational considerations. Methanol emerges as a promising transitional fuel, leveraging existing infrastructure and offering relatively straightforward handling and storage requirements.

While hydrogen holds promise as a zero-emission fuel, its feasibility for Venta Maersk is limited by significant storage volume and safety challenges. Methanol, LNG, and ammonia present more practical alternatives, balancing energy density, storage efficiency, and operational considerations. Further research and technological advancements are necessary to overcome the challenges associated with alternative fuels and facilitate the transition towards sustainable maritime transport.

### 4.3 The Result of the Analytic Hierarchy Process

Based on the statistics and organization of all the questionnaires, the results of averaging the data provided by all the participants are shown in the tables below (Table 4.6 - Table 4.10).

*Table 4.6 Pairwise comparison matrix.*

Criteria				
	Economy	Environment	Technology	Safety
Economy	1	31/175	127/525	223/1575
Environment	175/31	1	31/15	117/175
Technology	525/127	15/31	1	163/315
Safety	1575/223	175/117	315/163	1

*Table 4.7 Pairwise comparison matrix for economy subcriteria.*

Economy sub-criteria			
	Investment	Fuel price	Operation cost
Investment	1	143/75	41/25
Fuel price	75/143	1	5/3
Operation cost	25/41	3/5	1

*Table 4.8 Pairwise comparison matrix for environment subcriteria.*

Environment sub-criteria		
	Marine pollution	GHG
Marine pollution	1	537/175
GHG	175/537	1

*Table 4.9 Pairwise comparison matrix for technology subcriteria.*

Technology sub-criteria		
	Engine type	Infrastructure
Engine type	1	37/25
Infrastructure	25/37	1

*Table 4.10 Pairwise comparison matrix for safety subcriteria.*

Safety sub-criteria		
	Health impact	Onboard hazard
Health impact	1	31/25
Onboard hazard	25/31	1

By conducting a comprehensive pairwise comparison matrix analysis, the weights assigned to each criterion are graphically presented in the accompanying figure (shown in Figure 4.4). In the first level of the hierarchical model, the criterion of safety emerges as the most prominent and crucial consideration, signifying its paramount importance in the assessment. Following safety, the environment is identified as

the second most significant factor in the decision-making process. On the other hand, technology and economic factors are depicted as the last two influential in this particular context, indicating their relatively lower priority in comparison to the other criteria. On top of that, the economy is way less important than technology.

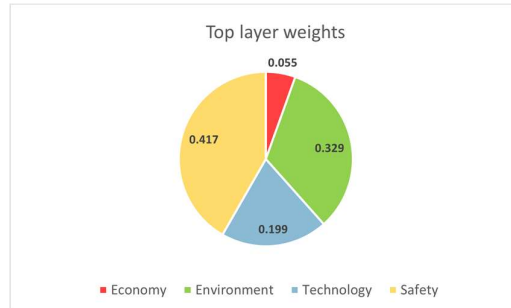


Figure 4.4 The mean average weights of the top layer criteria in the hierarchical model.

Upon evaluating the weights of the pairwise comparison matrices in Tables 4.6 - 4.10 using each of the three designated approaches: arithmetic averaging, geometric averaging and eigenvalue methods, (the specific computational demonstration is elucidated in Chapter 3.3.), the ultimate weights are derived through the process of mean averaging the outcomes obtained from the three methods. Detailed records of the weight results obtained from each calculation method and the consistency test can be found in Table A.1 to Table A.5 of Appendix A. Figure 4.4 shows the categorization of criteria, with sub-criteria within each category being distinctly identified by varying shades of color. For economic sub-criteria (shown in Figure 4.5), stakeholders placed paramount importance on the investment criterion as the primary indicator, with fuel price ranking second while operating costs had a comparatively marginal influence. Figure 4.6 illustrates that the types of engines suitable for alternative fuel utilization received greater emphasis in the technology sub-criterion. In the domain of environmental sub-criteria (shown in Figure 4.7), marine pollution emerged as the central consideration among stakeholders when evaluating the adoption of alternative fuels, closely followed by greenhouse gas emissions. Lastly, within the safety sub-criterion (shown in Figure 4.8), the potential impacts on crew health resulting from the use of alternative fuels were accorded a slightly higher priority than onboard accidents.

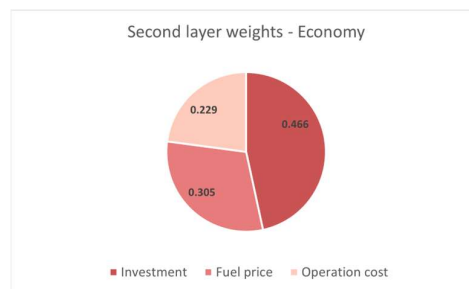


Figure 4.5 Pie chart of the second layer weights of economy.

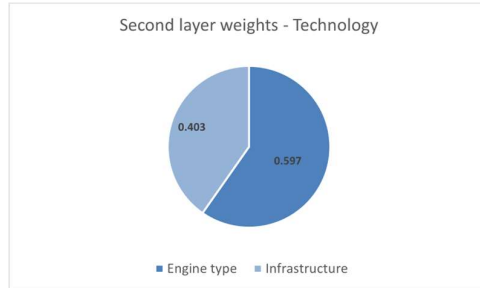


Figure 4.7 Pie chart of the second layer weights of technology.

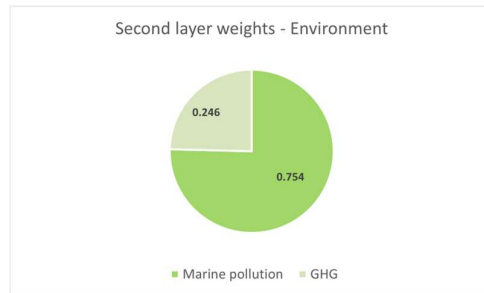


Figure 4.6 Pie chart of the second layer weights of the environment.



Figure 4.8 Pie chart of the second layer weights of safety.

For each fuel, attributes were assessed, and ranked in the following analysis. The fuel that most effectively aligned with the study's objectives received a rank of 1, while the one that least aligned received a rank of 4. Finally, by factoring in the assigned weights, the ranked outcomes are aggregated, and the lowest numerical value signifies the most optimally balanced result across all aspects.

## Economic impacts assessment

According to Chapter 3.3, the evaluation process involved four alternative fuels, each of which was assessed across various criteria.

### Fuel Price

Initially, as presented in Table 4.11, the pricing of alternative fuels stands as the primary economic factor. The four fuels have been ranked for the comparison, facilitating a clear observation of the most economically favorable option.

*Table 4.11 Fuel price rank of alternative fuels.*

<b>Alternative fuels</b>	<b>Price (\$/t) <sup>1</sup></b>	<b>Price (\$/GJ)<sup>2</sup></b>	<b>Rank</b>
Hydrogen	900	75	4
Ammonia	426	22.9	2
Methanol	593	29.8	3
LNG	390	7.8	1

### **Investment**

Presently, the predominant propulsion systems utilized in most ships rely on diesel engines. To adopt alternative fuels for these vessels, substantial modifications to the engines and massive investment are imperative to accommodate the unique characteristics of each fuel type. According to Basso et al. (2022), the incorporation of hydrogen fuel in diesel engines necessitates noteworthy adaptations. Moreover, hydrogen exhibits the potential for compatibility with diesel-electric and battery-electric systems, albeit extensive vessel modifications are essential to enable such integration. However, there is no existing vessel that presently possesses the capability to solely utilize hydrogen fuel cells as a standalone power system. In addition to substantial investments required in the advancement of maritime propulsion system technologies, the adequacy of infrastructure in both technical capabilities and quantity to meet the escalating demands is equally crucial for the utilization of hydrogen fuel. Ammonia is considered suitable for use in internal combustion engines and fuel cells, however, its compatibility with existing vessels is considerably limited, necessitating comprehensive modifications or even the development of entirely new engines (Basso et al., 2022). The utilization of ammonia as a propulsion source for maritime vessels is presently in its nascent stage of development. There is relatively extensive experience with the use and transport of methanol as a fuel and cargo at sea, and the number of vessels fueled by methanol is on the rise (Hammer, Tveit, Sverud, Leisner, & Eide. 2022). Methanol can be used in retrofitted internal combustion engines, and the technology is mature and commercially available. Currently, methane stands out as a prevalent alternative fuel utilized in LNG vessels. Nonetheless, its application in other types of vessels necessitates either engine modifications or the adoption of new engines (Basso et al., 2022).

In summary, the use of ammonia and hydrogen as fuels would necessitate substantial investment in thoroughly re-building and intricately modifying a ship's internal combustion engine. On the other hand, the engines of methanol and methane are presently accessible in the market with relatively well-established technology. However, implementing methane as a fuel in other pre-existing vessels would demand more extensive engine modifications and reconstructions. As a consequence, the investment prioritization for these four fuels is outlined in the Table 4.12 below:

---

<sup>1</sup>Based on Basso et al. (2022)

<sup>2</sup>Based on Basso et al. (2022)

Table 4.12 Investment rank of alternative fuels

Alternative fuels	Investment description <sup>3</sup>	Rank
Hydrogen	Redesign or extensively retrofitted engine	2
Ammonia	Redesign or extensively retrofitted engine	2
Methanol	Commercially available in ICE	1
LNG	Commercially available in LNG vessels; extensively retrofitted engines in other existing vessels	1

### Operational cost

The final sub-criterion within the economic category is the operating cost, which correlates with the energy density of the fuel. This is since greater energy density results in a reduced volume of fuel needed for the vessel to cover the same distance. Therefore, the high energy density of the fuel means lower operating costs and better economics. The table below (Table 4.13) shows the energy density and ranking of each alternative fuel:

Table 4.13 Operational costs rank of alternative fuel

Alternative fuels	Energy density (MJ/L)	Rank
Hydrogen	8.5 <sup>4</sup>	4
Ammonia	11 <sup>5</sup>	3
Methanol	15.7 <sup>6</sup>	2
LNG	20 <sup>7</sup>	1

## Environmental impacts assessment

### Greenhouse Gas emissions

Referring to Greenhouse Gas emissions in 2.2.5, the 4 fuels have been demonstrated to have varying levels of emissions depending on all of them having low CO<sub>2</sub> emission or none at all. Methanol has been considered to almost eliminate carbon emissions, but it can still release NO<sub>x</sub> emission but in significantly smaller amounts compared to fossil fuels, there are also different variants of methanol that all have differing potentials but such as E-methanol having the most potential due to harnessing renewable energy. Ammonia is a gas that does not contain any CO<sub>2</sub> meaning it can fully eliminate carbon emissions during its use, however, currently technology has not been able to prevent the high amounts of NO<sub>x</sub> emissions that are

<sup>3</sup> Based on Basso et al. (2022)

<sup>4</sup> Based on Hoecke et al. (2021)

<sup>5</sup> Based on Basso et al. (2022)

<sup>6</sup> Based on Basso et al. (2022)

<sup>7</sup> Based on Basso et al. (2022)

released which can still have climate impact. LNG has resulted in no CO<sub>2</sub> emissions but there are still low PM and NO<sub>x</sub> emissions. Hydrogen has been shown to have negligible number of emissions and pollution during its combustion and does not release any CO<sub>2</sub>, SO<sub>x</sub>, NO<sub>x</sub> and PM emissions, making it one of the cleanest fuels with the least amount of GHG impact.

When ranking the individual fuels, the most obvious was to rank Hydrogen as number 1, however, it is the rest of the fuels where it starts to get difficult. LNG, Methanol and Ammonia all have varying benefits and drawbacks. When doing our research and conducting interviews, we have seen that methanol has great potential as an accessible green fuel in the future and overtake LNG as the 2nd best fuel but in our current time, methanol would have to be ranked 3rd place as it is slightly outperformed by LNG for its cleaner emissions. Ammonia is also tied at 3rd place however, this fuel could have also been placed higher due to the fact that it does not contain any CO<sub>2</sub> emissions, the only aspect that is seen as a drawback is the high amount of NO<sub>x</sub> emissions, if this fuel was mass produced and used by all vessels, the GHG impact would still exist with the atmosphere being covered in high amount of NO<sub>x</sub> instead of CO<sub>2</sub>.

*Table 4.14 Impact of Greenhouse Gas for each alternative fuel*

<b>Alternative fuels</b>	<b>GHG emissions (CO<sub>x</sub>, NO<sub>x</sub>, SO<sub>x</sub> and PM)</b>	<b>Rank</b>
Hydrogen (Liquid)	Clean emissions	1
Ammonia	No CO <sub>2</sub> emissions, High NO <sub>x</sub>	3
Methanol	Significantly less CO <sub>2</sub> emissions, Low NO <sub>x</sub> emissions	3
LNG	No CO <sub>2</sub> emissions, low NO <sub>x</sub> and PM emissions	2

**Marine Pollution**

According to (Hammer et al., 2022), leaks or spillage of Ammonia fuel result in toxic fumes in the air and create long-lasting corrosive damage to aquatic life which can have significant impact to marine pollution. In comparison, Methanol fuel is considered a marine pollutant that has several cases of being dangerous to marine life and can dissolve quickly which leads to toxic fumes, however, due to its biodegradability and technology that has developed the fuel to be fast-diluting, it has significantly less impact than a regular oil spill and may potentially be removed of all potential as a marine pollutant in the near future. Hydrogen and LNG have been shown to have no impact as marine pollutants and are completely safe to marine life and ecology in the case of a leakage or spillage. LNG is needed in a liquid state which is in negative temperatures but can rapidly evaporate when exposed to outside temperatures leaving no trace of pollution.

*Table 4.15 Marine pollution rank of alternative fuels*

<b>Alternative fuels</b>	<b>Marine Pollution</b>	<b>Rank</b>
Hydrogen	No impact	1
Ammonia	Significant impact	3
Methanol	Minimal Impact	2
LNG	No impact	1

## Technological impacts assessment

### Engine type

The primary sub-criterion for evaluating technology is regarded as the engine type and infrastructure, specifically with regard to their applicability within diverse power systems and their compatibility with existing infrastructures.

In the specific case of hydrogen as a fuel source, it is imperative to acknowledge that it remains in the nascent phases of development, lacking current compatibility with marine internal combustion engines. Extensive engine modifications would be necessitated for its application in the marine business. It is noteworthy that despite the existence of hydrogen fuel cells, the deployment of this technological paradigm has not yet attained a state of widespread commercial realization (Basso et al., 2022). Therefore, within the current developing circumstance, the technological maturity of hydrogen fuel remains conspicuously low. According to Kim et al. (2020), ammonia has emerged as an applicable fuel for powering internal combustion engines and fuel cells. Both two-stroke and four-stroke internal combustion engines engineered to run on ammonia are anticipated to reach a state for practical deployment by 2023. Furthermore, retrofitting of existing ships' engines is planned for 2025 (Basso et al., 2022). Nevertheless, it is not yet known when this technology will be able to support commercialization. Since 2015, methanol has been accessible for utilization in both two-stroke and four-stroke internal combustion engines. Furthermore, its applicability will extend to fuel cells, while in a developmental stage with expectations of reaching technological maturity by the year 2040 (Basso et al., 2022). Among the four fuels, methane is the longest-used fuel and there are commercial LNG vessels that are fully compatible with this fuel. However, retrofitting existing vessels for LNG utilization necessitates the installation of specialized storage systems and LNG-capable engines (Basso et al., 2022). The development of methane fuel cells is presently in progress, as outlined by Van Biert et al. in 2016.

The utilization of methanol and LNG fuels in the maritime sector shows a higher level of maturity compared to hydrogen and ammonia alternatives. This maturity is exemplified by the existing commercial availability of technologies that enable the retrofitting of internal combustion engines to accommodate methanol and dedicated ship designs for LNG. In contrast, employing hydrogen and ammonia in internal combustion engines would necessitate extensive modifications or even complete engine research and development. Therefore, there are higher priorities of engine types for methanol and LNG.

*Table 4.16 Engine types rank of alternative fuels.*

Alternative fuels	Engine types	Rank
Hydrogen	<ul style="list-style-type: none"> <li>● Internal combustion engine: extensive modifications</li> <li>● Fuel cell: under developing</li> </ul>	2
Ammonia	<ul style="list-style-type: none"> <li>● Internal combustion engine: extensive modifications</li> <li>● Fuel cell: under developing</li> </ul>	2
Methanol	<ul style="list-style-type: none"> <li>● Internal combustion engine: accessible for two-stroke &amp; four-stroke</li> <li>● Fuel cell: under developing</li> </ul>	1

LNG	<ul style="list-style-type: none"> <li>• Internal combustion engine: dedicated ship designs for LNG</li> <li>• Fuel cell: under developing</li> </ul>	1
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### Infrastructure

According to Basso et al (2022), hydrogen is the least developed in terms of infrastructure which in this case would be the lack of proper fuel storage and refueling facilities for the purpose of supply and distribution of the fuel, and this is mainly due to lack of regulation in regard to safety and handling of hydrogen chemicals. Hydrogen-fuelled ships are currently limited to small-sized vessels such as ferries that are meant for shortsea operations but there is a lack of experience or research in hydrogen fuels in larger vessels and therefore, the development of a proper infrastructure to support hydrogen fuels is very far behind. The same applies for Ammonia fuel which is also in early stages of development due to lack of research and experience, the current challenges of Ammonia fuel are related to the toxicity of the chemical and its safety regulation as well as how relatively the fuel type is in the shipping industry (Basso et al., 2022). Methanol and LNG are the most developed in terms of infrastructure, methanol as a fuel has been one of the most technological mature in terms of infrastructure and has been developed as a vessel fuel for a long time with production and distribution facilities already existing for many years, however methanol still lacks dedicated storage and bunkering infrastructure due to its flammability and still needs some development (Hammer, Tveit, Sverud, Leisner, & Eide. 2022). LNG is by far the most technologically mature and its infrastructure has been developed over decades to be technologically feasible. Infrastructure for liquefaction, storage and bunkering of the fuel is already well-established in some areas (PAME. 2019).

*Table 4.17 Infrastructure rank of alternative fuels*

Alternative fuels	Infrastructure	Rank
Hydrogen (Liquid)	Least feasible and developed infrastructure	4
Ammonia	Lacking feasibility and development of facilities and regulations	3
Methanol	High feasibility, already established infrastructures	2
LNG	Most feasible infrastructure with well-established facilities	1

## Safe impacts assessment

### Health impacts

Ensuring safety is critical when selecting alternative fuels. The first criterion is a thorough evaluation of the toxicity of the alternative fuels, in particular the potential risks to the health of the crew in the event of a safety incident such as a fuel spill. Based on the data provided in Table 4.18, two alternative fuels - hydrogen and LNG - stand out and receive high ratings because of their non-toxicity. As for ammonia and methanol,

they are both toxic, but their mechanisms of toxicity vary and are related to the degree of potential hazard to the health of the crew and the duration of exposure. Ammonia exhibits potent corrosiveness, posing a significant risk of severe damage to the skin, eyes, and respiratory system tissues when individuals are exposed to concentrations of ammonia exceeding safety thresholds. Moreover, methanol is inherently non-toxic; its toxicity to the human body primarily stems from highly toxic metabolites generated through metabolic processes. According to the report by Hammer et al. (2022), concentrations of 1100 ppm and 7200 ppm of ammonia and methanol, respectively, can be fatal within one hour. Under these conditions, methanol needs to be approximately 6.5 times more concentrated than ammonia to pose a life-threatening risk to humans. Consequently, the toxicity of ammonia exceeds that of methanol, thus ranking methanol higher than ammonia.

*Table 4.18 The rank of human impacts of alternative fuels.*

Alternative fuel	Toxicity <sup>8</sup>	Rank
Hydrogen	Non-toxic	1
Ammonia	Toxic	3
Methanol	Toxic	2
LNG	Non-toxic	1

### **Onboard hazards**

The connection between the burning velocity of alternative fuels and onboard hazards lies in the fact that a faster burning velocity can increase the potential risks associated with combustion, including fires, explosions, and other safety hazards on board. By comparing the combustion velocities of the four alternative fuels in Table 4.19, it is clear that ammonia has the lowest combustion rate. In contrast, hydrogen burns at a significantly higher velocity compared to the remaining three fuels. The faster burning of hydrogen means that in the event of a safety accident involving hydrogen on board a ship, the flame will spread considerably faster than with the other fuels. Therefore, hydrogen could be the most unsafe of the four fuels in such a situation.

*Table 4.19 The rank of onboard hazards of alternative fuels.*

Alternative fuel	Burning velocity <sup>9</sup> (m/s)	Rank
Hydrogen	2.65~3.25	4
Ammonia	0.07	1
Methanol	0.48	3
LNG	0.37	2

<sup>8</sup> Based on Hammer et al. (2022)

<sup>9</sup> Based on Hammer et al. (2022)

## The final score of alternative fuels in AHP

*Table 4.20 The final score of alternative fuels*

<b>Fuel</b>	<b>Economy</b>	<b>Environment</b>	<b>Technology</b>	<b>Safety</b>	<b>Final score</b>
Hydrogen	0.169	0.329	0.558	0.975	<b>2.031</b>
Ammonia	0.123	0.987	0.478	0.879	<b>2.467</b>
Methanol	0.101	0.739	0.279	1.020	<b>2.139</b>
LNG	0.055	0.410	0.199	0.603	<b>1.267</b>

Finally, the ranking of each criterion was multiplied by its respective weight to gain its score as detailed in Tables A.6 through A.9 in the Appendix. By utilizing these weights and rankings, Table 4.20 was formulated, and lower scores mean higher priority. In this table, LNG emerges as the top choice when considering the comprehensive criteria.

# 5 Discussion

## 5.1 Hydrogen

The production, transportation, storage, and utilization of hydrogen present multifaceted challenges that demand nuanced solutions for the advancement of hydrogen as a viable energy carrier. Carbon capture and storage technology presents stringent requirements alongside the need for a consistent natural gas supply to facilitate blue hydrogen production effectively. Conversely, the cost implications associated with green hydrogen production pose a formidable developmental hurdle. This expense stems from the substantial electricity demand of electrolysis, coupled with the necessity for advancements in electrolysis technology and substantial facility investments. Consequently, the facilitation of large-scale green hydrogen production is rendered more feasible and cost-effective through the implementation of supportive policies by governments and affiliated organizations.

Transportation logistics constitute another critical facet, entailing considerations of infrastructure compatibility and cost-effectiveness. Compatibility with existing infrastructure is paramount in determining the viability of transportation methods, with cost optimization emerging as a central concern. Challenges arise particularly in scenarios involving high-pressure storage tanks, such as Type V tanks, which necessitate infrastructure modifications. However, innovative approaches like extended tube trailers offer promising avenues for leveraging pre-existing infrastructure, thereby streamlining transportation operations and enhancing cost efficiency.

Storage poses further challenges, with issues like evaporation during storage and refueling processes warranting meticulous attention to optimize efficiency and safety. Therefore, the development of hydrogen storage container materials is crucial. Moreover, ensuring maritime safety entails bespoke vessel designs and adherence to regulatory mandates, underscoring the imperative for strategic planning in hydrogen storage implementations. The classification framework for compressed hydrogen storage tanks (Types I to IV) serves as a utility tool in guiding stakeholders toward judicious storage methods selection. This framework facilitates informed decision-making within the burgeoning hydrogen economy, empowering stakeholders to make choices that align with their specific needs and priorities.

Technical applications of hydrogen have demonstrated that while ICEs offer familiarity and relatively straightforward integration into existing vehicle platforms, they suffer from lower efficiency levels compared to fuel cells. Despite producing lower emissions than conventional fossil fuels, hydrogen-powered ICEs still fall short of achieving truly zero-emission operation. In contrast, fuel cells display superior efficiency and emit only water vapor during hydrogen conversion, positioning them as a compelling solution for mitigating environmental impacts and advancing carbon neutrality goals. However, the infrastructure requirements for fuel cells are more extensive, posing a notable challenge for widespread adoption. Addressing these infrastructure challenges alongside advancing technological developments remains pivotal for harnessing the full potential of hydrogen as a clean and sustainable energy carrier in transportation. Thus, while both ICEs and fuel cells offer benefits in terms of efficiency and reduced emissions, fuel cells emerge as a more promising avenue for achieving long-term sustainability and environmental stewardship within the transportation sector.

## 5.2 Case Study

Hydrogen emerged as an intriguing alternative fuel due to its zero-emission potential and abundance as the most abundant element in the universe. The feasibility of hydrogen stems from its potential to significantly reduce greenhouse gas emissions and contribute to achieving decarbonization goals in the maritime sector. However, several limitations hinder the widespread adoption of hydrogen as a marine fuel. One primary limitation is the challenge of hydrogen storage and distribution. Hydrogen's low volumetric density necessitates either high-pressure compression or cryogenic liquefaction for onboard storage, posing logistical complexities and requiring significant infrastructure investment. Additionally, the production of hydrogen, particularly green hydrogen from renewable sources, remains energy-intensive and costly, hindering its economic viability compared to conventional fuels.

Furthermore, safety concerns surrounding hydrogen storage, handling, and potential for combustion hazards necessitate stringent safety protocols and regulatory frameworks to mitigate risks effectively. The lack of established infrastructure and operational experience with hydrogen as a marine fuel further exacerbates the challenges, requiring collaborative efforts from industry stakeholders, policymakers, and research institutions to address.

While hydrogen presents promising environmental benefits, alternative fuels like LNG and methanol offer more immediate and practical solutions for reducing greenhouse gas emissions in the maritime sector. LNG, characterized by its lower emissions profile and established infrastructure, provides a transitional pathway towards cleaner maritime operations. The widespread availability of LNG infrastructure and proven operational experience make it a feasible option for existing vessels like the *Venta Maersk*.

Similarly, methanol offers advantages in terms of energy density, storage, and engine compatibility, making it a viable alternative to conventional fuels. Methanol can be produced from renewable sources, further enhancing its environmental credentials and contributing to sustainable shipping practices. However, challenges such as flammability, safety concerns, and infrastructure development require careful consideration for successful integration into maritime operations.

In addition to energy density and storage considerations, economic factors play a critical role. The cost of alternative fuels and the associated infrastructure investment for storage and distribution need to be factored into the decision-making process. For instance, while LNG is relatively well-established and cost-effective, hydrogen and ammonia may require substantial upfront investment in new technologies and safety protocols. Moreover, regulatory compliance and environmental regulations are becoming increasingly stringent, pushing the maritime industry toward cleaner fuels. Methanol and LNG, with their lower carbon footprints and established safety records, align better with current regulatory trends compared to HFO/MGO.

This alignment can potentially reduce compliance costs and enhance the sustainability profile of shipping operations. Finally, the transition to alternative fuels must consider the readiness of the maritime industry. Existing vessels and ports are primarily designed for HFO/MGO and retrofitting them for new fuels can be complex and costly. Therefore, a phased approach leveraging transitional fuels like LNG and methanol, which require less drastic changes, could be more pragmatic in the near term.

The case study had some limitations that should be acknowledged and addressed in future research. First, the case study was based on a single ship and a single voyage, which limited the generalizability and representativeness of the results. Second, the case study relied on secondary data sources, such as reports, interviews, and articles, which might have introduced some biases or inaccuracies in the data collection and analysis. Third, the case study did not consider some factors that might have influenced the performance and feasibility of the alternative fuels, such as the weather conditions, the ship design, the crew training, and the stakeholder preferences.

### 5.3 Analytical Hierarchy Process

#### The weight of the criteria

The questionnaire elucidates that safety criteria certainly stand paramount in the contemplation of alternative fuel adoption, a reasonable stance given the intricate connection between fuel properties and the crew's health and safety. An incident compromising fuel safety on board not only poses immediate danger but also potentially unleashes catastrophic repercussions. This concern is particularly amplified in icy waters where the prompt arrival of rescue vessels in response to a safety incident is markedly challenging.

Second, in the hierarchy of considerations is the environment, which is a consensus unanimously regarded as pivotal across various societal sectors, with the maritime industry being no exception. Despite the economic efficiency and technological maturity had by HFO, the industry persistently explores feasible alternative fuels to alleviate environmental detriments. Utilizing alternative fuels is particularly crucial to circumvent harmful impacts on the delicate ecology of polar regions, mitigating risks such as those associated with HFO leaks.

Under environmental considerations, greenhouse gas emissions and marine pollution emerge as significant sub-criteria. Intriguingly, the questionnaire results accord a higher weight to marine pollution compared to greenhouse gas emissions. Several reasons can be postulated for this weighting discrepancy. Primarily, fuel leaks wield a direct, substantial, and enduring impact on marine ecosystems. For instance, research on HFO delineates its high viscosity and challenging emulsification and evaporation in aquatic environments, as highlighted by Comer et al. (2020). Such characteristics render the removal of HFO exceedingly difficult, culminating in the gradual erosion of marine biodiversity and ecological equilibrium. Consequently, marine pollution necessitates priority in the deliberation of alternative fuels. In contrast, the deleterious effects of greenhouse gases on the environment are indirect, unfolding over a longer time through the intricate dynamics of climate change. This reason why marine pollution is a more palpable, immediate concern in the evaluation and prioritization for alternative fuel adoption.

Technology emerges as the third criterion in the hierarchical ranking, presenting a significant intersection with the other considerations: safety, environment, and economy. The advanced technological frameworks invariably amplify ship performance and foster fuel efficiency, thereby indirectly buttressing both safety and environmental objectives elucidated above. The term 'technology' in this context extends to include compatibility with existing engines and the availability of supporting infrastructure. For instance, selecting alternative fuels that seamlessly integrate with current engine configurations can engender substantial economic savings, thereby enhancing the overall economic feasibility of maritime operations.

The economy, while positioned last in prioritization, nonetheless commands attention as an important determinant. Within its domain, three subordinate criteria warrant consideration in the selection process

of alternative fuels: price, operational costs, and investment. Amongst these, investment was the foremost consideration in economic criterion. This importance of investment can be elucidated by adopting a long-term analytical view. While this initial investment might inflate the short-term financial outlays, it possesses the potential to unlock considerable future savings. Indeed, the short-term fiscal burden is counterbalanced, and potentially overshadowed, by the prospective long-term economic value that such technological innovations are poised to deliver.

In short, these rankings underscore the necessity of considering a multitude of factors within the maritime transport sector. Safety and environmental protection are widely regarded as paramount due to their direct implications for human safety and sustainability. Technical and economic considerations, while important, serve a complementary role in maintaining a balance between the former two. Given the complicated interplay among these factors, decision-makers must navigate trade-offs and strive for a synthesis of multiple needs to make optimal choices.

### Impact assessments of alternative fuels

In assessing the impact derived from the AHP analysis, it is discernible that LNG consistently emerges as the top priority. Firstly, fuel prices, perpetually oscillating, are influenced by many factors, thereby necessitating evaluations to be grounded in predictive data concerning future prices. Subsequently, the quantitative assessment of investment into alternative fuels proves to be inherently intricate, defying simplification into a single, digestible data set that cogently encapsulates the performance of each alternative fuel. The decision for organizations to invest in alternative fuels is invariably bound to a complex and protracted planning process, within which only the investment costs related to modifying existing vessel engines are considered in the present study. It is predicated on the premise that only through genuine modification or reconstruction of existing engines can alternative fuels be comprehensively incorporated into commercial utilization on a substantive scale, thereby reducing their respective fuel prices. LNG, having been utilized the longest among these four fuels, demands relatively the lowest investment due to its mature technology, which has been broadly employed on ships. Hence, it also possesses the most advantageous fuel pricing.

In this study, factors influencing the environmental assessment include GHG emissions and marine pollution. Hydrogen fuel neither generates any greenhouse gases nor inflicts damage upon the marine ecosystem, signifying its crucial role in the maritime industry's realization of decarbonization and other environmental objectives. While hydrogen does not exhibit prominent performance in other aspects, its further in-depth research remains warranted based on environmental protection objectives. Additionally, LNG also demonstrates commendable environmental performance, generating only minimal NO<sub>x</sub> and PM during use. Due to its competitive edge in various other aspects, LNG has already been acknowledged by maritime sectors as a primary low-carbon alternative fuel (dos Santos et al., 2022).

Evaluation pertaining to technological aspects tends to be comparatively subjective, with fuel rankings deriving from an overview of the pertinent literature. When assessing engine types, this research prioritizes internal combustion engines, attributing to their status as the most ubiquitously employed propulsion systems. LNG and methanol exhibit higher maturity in this context, potentially signifying an expedited path toward commercialization, since technology fundamentally underpins economic, environmental, and safety objectives. Moreover, compared to the technology of alternative fuels applied to internal combustion engines, the weight of infrastructure has demonstrated that this criterion is not determinative. Possible stakeholders might contemplate that the technical difficulty of infrastructure, as opposed to engine modification, is minimal and, supported by adequate financial backing, is not sufficient to impede the utilization of alternative fuels.

In the assessment of safety criteria, it is obvious that the present research considers two attributes of the fuels regarding their impact on crew health and onboard hazards. The non-toxic characteristics of hydrogen and LNG potentially render them more desirable in certain applications, particularly in contexts where frequent human interaction is prevalent. These fuels do not cause health issues related to toxicity. However, the toxicity of ammonia and methanol implies that their utilization necessitates additional safety cautions to safeguard crews and other individuals who may come into contact with these fuels. Such safety measures might encompass specialized transportation, storage, and handling procedures, as well as dedicated training for the crew. What is more, when considering the onboard hazard potentiality of alternative fuels, ammonia with the low combustion velocity is the least hazardous option, therefore occupying the top rank. Conversely, while hydrogen exhibits the highest combustion velocity, it introduces the most significant potential onboard perils. This could imply that, when deploying hydrogen as an alternative fuel, additional safety measures need to be implemented to mitigate related risks.

### The final ranking of alternative fuels

According to the AHP analysis in chapter 4.3, the final rank was shown in Table 5.1. Undoubtedly, LNG stands as the top-ranking alternative fuel by multifaceted evaluations. This outcome aligns with the theory proposed by dos Santos et al (2022), positing LNG as the predominant focal point among current alternative fuels. Not only does it epitomize environmental friendliness, but its supply chain and associated technologies also exhibit paramount cost-competitive advantages. Firstly, LNG boasts historical precedence among the four alternative fuels under scrutiny, which has led to the development of dedicated vessels and supporting infrastructure tailored to its utilization. In terms of economic, technical, and safety considerations, LNG has superior benefits compared to the other three alternative fuels that have yet to reach widespread commercialization. From an environmental perspective, LNG exhibits environmental friendliness by producing low emissions on marine ecosystems though it generates a minor of NO<sub>x</sub> and PM during combustion. Particularly in polar regions, the adoption of LNG mitigates the ecological devastation arising from HFO (PAME, 2019).

*Table 5.1 The final rank of AHP assessment.*

<b>Alternative fuel</b>	<b>Final rank</b>
Hydrogen	2
Ammonia	4
Methanol	3
LNG	1

Based on the findings in 4.3.4, the three alternative fuels under consideration exhibited performance variations. A somewhat unexpected outcome was the elevated ranking of hydrogen fuels following LNG. While hydrogen fuel occupies the lowest positions in terms of economic and technological priorities, its noteworthy environmental benefits significantly bolster its standing in the overall ranking. This aligns with the assertion made by Momirlan and Veziroglu (2005) that hydrogen fuel, when used for high-energy output applications, emits minimal pollutants. The third alternative fuel in the analysis is methanol, which demonstrates a slight advantage in economic, environmental, and technological aspects compared to ammonia. Such an outcome is not surprising; the economy often depends on the maturity of technology. However, despite ammonia surpassing methanol in safety considerations, this factor also presents challenges in securing a higher overall priority for ammonia.

Despite LNG being ranked as the top fuel in AHP studies, research by Basso et al. (2021) indicates that LNG is not an absolute zero-carbon fuel, although it is more environmentally friendly compared to HFO. However, achieving the goal of utilizing cleaner energy in the industry is challenging when relying solely on a single alternative fuel. The production and use of LNG may release methane, a potent greenhouse gas. Therefore, hydrogen, ammonia, and methanol, especially hydrogen produced from renewable resources, are considered ideal zero-carbon fuels. In the transition towards zero-carbon fuels like hydrogen, LNG plays a significant role in the shipping industry by reducing carbon emissions from maritime operations in the short term. Additionally, LNG serves as a bridge while infrastructure for other alternative fuels is being developed and their technologies are improved. This multi-fuel strategy provides greater resilience and flexibility for the shipping industry.

## 5.4 Comparison of HFO to alternative marine fuels

*Discussion comparisons between HFO to Alternative fuels is divided into two segments. Emissions of the fuels and how it affects the environment; and Accessibility which covers a broad range of topics such as costs, technology, infrastructure, etc.*

### **Accessibility**

The accessibility of marine fuels is critical in determining their feasibility for widespread adoption. This section compares HFO with alternative marine fuels, including LNG, hydrogen, ammonia, and methanol, focusing on various accessibility factors such as cost, technology, infrastructure, and supply chain logistics.

HFO has historically been favored in the maritime industry due to its low cost and high energy density. Its production is well-established, benefiting from economies of scale. However, the environmental regulations and the need for cleaner fuels are driving up the costs associated with HFO due to required investments in emission control technologies. According to Table 4.11 of the thesis, the price ranking of alternative fuels places LNG at a competitive position relative to HFO, while hydrogen, ammonia, and methanol are generally more expensive due to production and handling complexities.

In contrast, alternative fuels such as LNG, hydrogen, ammonia, and methanol often come with higher initial costs. For example, the production of hydrogen, especially green hydrogen, is expensive due to the energy-intensive electrolysis process. Similarly, ammonia production is costly, particularly when derived from renewable resources. Methanol and LNG, while cheaper than hydrogen and ammonia, still face higher costs compared to HFO, especially when considering the need for infrastructure development and conversion of existing vessels.

The technological readiness and the existing infrastructure for HFO are well-developed, with extensive bunkering facilities worldwide. Ships using HFO do not require significant modifications, making it the default choice for many operators. Alternative fuels, however, require substantial technological advancements and infrastructure development. LNG has the most developed infrastructure among the alternatives, with established bunkering facilities and LNG-powered ships in operation. However, it still requires significant investment for global adoption (See Table 4.17).

Hydrogen and ammonia face even greater technological and infrastructure challenges. Hydrogen storage and handling require advanced technologies due to its low energy density and the need for cryogenic or high-pressure systems. Ammonia, while easier to store than hydrogen, is highly corrosive and toxic, necessitating stringent safety measures and specialized storage solutions. Methanol, being a liquid at ambient conditions, presents fewer challenges in terms of storage and handling compared to hydrogen and ammonia. However,

the infrastructure for methanol bunkering is not as widespread as for LNG or HFO, requiring new investments to facilitate its use (See Table 4.20).

HFO benefits from a well-established global supply chain, with refineries and bunkering stations positioned in major ports around the world. Its logistics are streamlined, reducing operational complexities for shipping companies.

Alternative fuels present varied challenges in supply chain logistics. LNG has a relatively mature supply chain compared to other alternatives, but its availability is still limited to specific regions. Hydrogen and ammonia, on the other hand, require the development of new supply chains, from production facilities to specialized transportation and bunkering infrastructure. This adds complexity and cost to their adoption. Methanol, while easier to transport than LNG, hydrogen, or ammonia, still requires the establishment of dedicated supply chains. The production of bio-methanol from renewable resources adds another layer of complexity, as it involves integrating agricultural or waste processing sectors with maritime fuel supply chains (See Table 2.3).

To summarize, while HFO remains the most accessible marine fuel in terms of cost, technology, and infrastructure, alternative fuels are gradually catching up, driven by environmental regulations and technological advancements. LNG is currently the most accessible alternative, offering a balance of lower emissions and existing infrastructure. Hydrogen and ammonia, although promising from an emissions standpoint, face significant technological and infrastructural challenges. Methanol presents a middle ground with better availability and infrastructure than hydrogen and ammonia but higher costs and less maturity than LNG.

## **Emissions**

HFO has long dominated the global marine industry due to its high energy density and low cost. However, the extensive use of traditional fuels has significantly polluted and damaged the ecosystem. Firstly, the combustion of HFO produces CO<sub>x</sub>, SO<sub>x</sub>, and NO<sub>x</sub>. Besides the emitted gases, PM and black carbon cause threats to human health and the environment. What is more, HFO spills are challenging to emulsify and evaporate in the ocean, causing further harm to marine ecosystems. Therefore, the development of alternative fuels aims to address the growing environmental issues caused by traditional fuels, especially greenhouse gas emissions.

Hydrogen is one of the cleanest fuels, producing almost no pollutants when burned. However, hydrogen production currently relies heavily on fossil fuels. Although green hydrogen produced by water electrolysis is clean, it requires substantial electricity, making this method expensive. Achieving widespread water electrolysis for hydrogen production is key for reducing carbon emissions in the future.

Ammonia is also a zero-carbon fuel, but its combustion produces NO<sub>x</sub> due to its chemical composition. Ammonia has a slightly higher energy density than hydrogen, allowing ships using ammonia fuel to travel longer distances or reduce refueling frequency. However, ammonia is highly corrosive and toxic, posing severe risks if leaked into the ocean or handled by crew members. Hence, strict regulations must be followed during its transportation, storage, and use.

Methanol, a low-carbon fuel, significantly reduces CO<sub>x</sub> and NO<sub>x</sub> emissions compared to HFO. As a sulfur-free fuel, it avoids the SO<sub>x</sub> and PM emissions associated with HFO. Methanol can be sourced from fossil fuels and renewable resources. Promoting the production and use of bio-methanol is key to realizing its low-carbon potential.

Compared to HFO, LNG significantly reduces CO<sub>x</sub>, SO<sub>x</sub>, and PM emissions. LNG has been used for the longest time among these four alternative fuels and boasts the highest energy density, making it highly cost-effective. Nevertheless, both LNG and HFO are sourced from non-renewable resources, positioning LNG as a transitional fuel from traditional to alternative energy sources as more reasonable. While methane, the main component of LNG, can quickly evaporate in open waters if leaked, it is a potent greenhouse gas.

In short, hydrogen, ammonia, methanol, and LNG each have distinct advantages and disadvantages as alternatives to HFO. Hydrogen and ammonia excel in environmental friendliness but face technical and economic challenges. Methanol and LNG offer more mature emission reduction solutions but still have carbon footprints and methane leakage issues. Comparing these fuels' emissions can clarify how to mitigate the environmental impact of marine fuels. Lastly, increasing HFO restrictions will encourage new policies and technological advancements in alternative fuels, ultimately improving public health and societal well-being.

## 6 Conclusion

Research on hydrogen fuels in academic articles has shown carbon capture and storage (CCS) technology, while pivotal for blue hydrogen production, confronts challenges regarding stringent requirements and consistent natural gas supply. Conversely, the cost implications associated with green hydrogen production pose formidable hurdles, necessitating advancements in electrolysis technology and supportive governmental policies. Transportation logistics demand meticulous consideration of infrastructure compatibility and cost-effectiveness, with innovative approaches such as extended tube trailers offering promising solutions. Storage presents further challenges, necessitating the development of efficient and safe hydrogen storage container materials, alongside adherence to regulatory mandates for maritime safety. Technical applications highlight the trade-offs between ICEs and fuel cells, with the latter displaying superior efficiency and emission reduction potential. However, the extensive infrastructure requirements for fuel cells pose challenges for widespread adoption. Addressing these challenges and advancing technological developments are imperative for realizing the full potential of hydrogen as a sustainable energy carrier. Hence, while both ICEs and fuel cells offer benefits, the latter emerges as a more promising avenue for achieving long-term environmental stewardship and sustainability within the transportation sector.

The case study is based on theoretical assumptions and scenarios, many factors are left out in the calculations as it requires more knowledge and time to consider all known factors that were in play. However, this case study has provided insights in the possible feasibility of hydrogen fuels based on storage volume and mass. Despite its potential to significantly reduce greenhouse gas emissions and contribute to decarbonization efforts, hydrogen faces substantial hurdles related to storage, distribution, safety, and economic viability. In comparison, alternative fuels like LNG offer more immediate and practical solutions, leveraging established infrastructure and operational experience. However, recognizing hydrogen's long-term potential and environmental benefits, concerted efforts are needed to enhance its feasibility. Key strategies include advancing hydrogen storage and distribution technologies, reducing production costs through innovation and scale-up, implementing robust safety protocols, fostering collaboration among industry stakeholders, policymakers, and research institutions, and incentivizing investments in hydrogen infrastructure and adoption. Addressing these challenges and leveraging synergies with existing initiatives will be instrumental in realizing the full potential of hydrogen as a sustainable marine fuel.

In the master thesis, the AHP methodology is utilized to evaluate how hydrogen compares to other three alternative fuels across the dimensions of economy, technology, environment, and safety. Through the analysis conducted using the AHP, it is determined that LNG stood out among the four alternative fuels considered. This is primarily attributed to its early adoption in maritime transportation, resulting in a wealth of practical experience and consequently affording it a relatively mature infrastructure and competitive pricing. Hydrogen fuel ranks second, demonstrating significant potential, particularly in contributing to the maritime industry's emission reduction objectives owing to its environmental advantages over other alternative fuels. However, inherent characteristics of hydrogen pose technical and safety challenges. In this study, stakeholders have identified safety and environmental concerns as the two most critical criteria. Consequently, methanol and ammonia rank lower in the comprehensive evaluation. Therefore, further research and development efforts are warranted for methanol and ammonia to address respective challenges and harness their potential as viable fuel options.

In conclusion, this research aims to identify the most promising options that balance economic viability with environmental sustainability. The results of the thesis have some implications for policymakers, industry stakeholders and researchers to construct decision-making frameworks from different perspectives to select the most appropriate alternative fuels. The study provides a comprehensive assessment of alternative fuels

based on multiple criteria, providing valuable insights for informed decision-making and strategic planning for the transition to sustainable energy systems in the maritime sector.

## 6.1 Future Research Suggestions

Looking ahead, future research endeavors should focus on addressing the uncertainties and technical challenges associated with the adoption of hydrogen and other alternative fuels involves strategies such as technological innovation, supply chain optimization, and market development. Furthermore, governments and relevant organizations should actively promote policy interventions and economic incentives to encourage the use of alternative fuels and address the energy challenges facing the maritime industry.

Based on the findings and limitations of the case study, we recommend some directions and actions for future research and practice in this field. For future research, we suggest conducting more case studies on different ships, routes, and fuels, to obtain a more comprehensive and comparative understanding of the impacts and implications of alternative fuels in different waters. We also suggest using more primary data sources, such as surveys, experiments, and observations, to collect and analyze more reliable and accurate data on the alternative fuels and their associated technologies and infrastructures. We also suggest applying more advanced and robust methods, such as life cycle assessment (LCA), cost-benefit analysis (CBA), and risk analysis, to evaluate and compare the alternative fuels in a more holistic and systematic way. We also suggest exploring more factors that might affect the performance and feasibility of the alternative fuels, such as the stakeholder perceptions, preferences, and behaviors, and the social and institutional barriers and drivers.

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## 8 Appendix

Table A.1. Comparison table of weights for criteria.

<b>Criterion</b>	<b>Method 1</b>	<b>Method 2</b>	<b>Method 3</b>	<b>Weight (avg.)</b>
Economy	0.055	0.055	0.055	0.055
Environment	0.329	0.329	0.330	0.329
Technology	0.200	0.198	0.199	0.199
Safety	0.417	0.418	0.417	0.417
CR = 0.010 < 0.1, consistent				

Table A.2 Comparison table of weights for economic sub-criteria.

<b>Economy criterion</b>	<b>Method 1</b>	<b>Method 2</b>	<b>Method 3</b>	<b>Weight (avg.)</b>
Investment	0.464	0.467	0.467	0.466
Fuel price	0.306	0.305	0.305	0.305
Operation cost	0.230	0.228	0.228	0.229
CR = 0.047 < 0.1, consistent				

Table A.3 Comparison table of weights for environmental sub-criteria.

<b>Environment criterion</b>	<b>Method 1</b>	<b>Method 2</b>	<b>Method 3</b>	<b>Weight (avg.)</b>
Marine pollution	0.754	0.754	0.754	0.754
GHG	0.246	0.246	0.246	0.246
CR= 0 < 0.1, consistent				

Table A.4 Comparison table of weights for technology sub-criteria.

<b>Technology criterion</b>	<b>Method 1</b>	<b>Method 2</b>	<b>Method 3</b>	<b>Weight (avg.)</b>
Engine type	0.597	0.597	0.597	0.597
Infrastructure	0.403	0.403	0.403	0.403
CR= 0 < 0.1, consistent				

Table A.5 Comparison table of weights for safety sub-criteria.

Safety Criterion	Method 1	Method 2	Method 3	Weight (avg.)
Health impact	0.554	0.554	0.554	0.554
Onbroad hazard	0.446	0.446	0.446	0.446
CR= 0 < 0.1, consistent				

Table A.6 The scores of economic sub-criteria.

Fuel	Fuel Price	Weight (FP)	Investment	Weight (inv)	Operation cost	Weight (OC)	Economy weight	Score
Hydrogen	4	0.305	2	0.466	4	0.229	0.055	0.169
Ammonia	2	0.305	2	0.466	3	0.229	0.055	0.123
Methanol	3	0.305	1	0.466	2	0.229	0.055	0.101
LNG	1	0.305	1	0.466	1	0.229	0.055	<b>0.055</b>

Table A.7 The scores of environmental sub-criteria.

Fuel	GHG	Weight (GHG)	Marine Pollution	Weight (MP)	Env. weight	Score
Hydrogen	1	0.246	1	0.754	0.329	<b>0.329</b>
Ammonia	3	0.246	3	0.754	0.329	0.987
Methanol	3	0.246	2	0.754	0.329	0.739
LNG	2	0.246	1	0.754	0.329	0.410

Table A.8 The scores of technology sub-criteria.

Fuel	Engine type	weight (ET)	Infrastructure	Weight (Inf)	Tec. weight	Score
Hydrogen	2	0.597	4	0.403	0.199	0.558
Ammonia	2	0.597	3	0.403	0.199	0.478
Methanol	1	0.597	2	0.403	0.199	0.279
LNG	1	0.597	1	0.403	0.199	<b>0.199</b>

Table A.9 The scores of safety sub-criteria.

<b>Fuel</b>	<b>Health impacts</b>	<b>weight (HI)</b>	<b>Onboard hazards</b>	<b>weight (OH)</b>	<b>Safety weight</b>	<b>Score</b>
Hydrogen	1	0.554	4	0.446	0.417	0.975
Ammonia	3	0.554	1	0.446	0.417	0.879
Methanol	2	0.554	3	0.446	0.417	1.020
LNG	1	0.554	2	0.446	0.417	<b>0.603</b>



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