Techno-economic challenges of alternative fuels in port operations

A literature review connected to storage, transport & distribution and bunkering in the maritime sector

Master's thesis in Maritime Management

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Abstract

The maritime sector is in need of decarbonization to lower GHG emissions and to fulfill goals set by IMO. This thesis analyzes hydrogen, methanol, and ammonia as alternative fuels to traditional fuels. The purpose of this thesis is to analyze the selected energy carriers' techno-economic challenges in terms of transportation, distribution, storage, and bunkering. Based on scientific articles published up until 2023, the primary emphasis according to the reviewed research in this thesis is on hydrogen, followed by ammonia, and finally methanol. Methodically, this thesis investigates literature published on the scholarly database Scopus and reviews case studies in order to comparatively assess the challenges and viabilities of the selected alternative fuels. Common challenges found in the scientific literature reviewed, includes lower density than conventional fuels, safety hazards, and redevelopment costs. Of the three alternative fuels investigated, hydrogen requires the largest storage facilities, the most significant investments for development, and is the most expensive to transport. Whereas ammonia benefits from pre-existing infrastructure as it is used within other sectors. However, both ammonia and hydrogen require special storage units, and suffer from boil-off, leakage, and need investments in bunkering facilities. Methanol does not have any special individual challenges and notably, the mean transportation costs via vessel for methanol is 0,77 USD/GJ/10 000 km which is a fraction in costs compared to hydrogen at 41,89 USD/GJ/10 000 km and ammonia at 5,71USD/GJ/10 000 km. In conclusion, hydrogen faces the most prominent challenges, despite the fact that more research is being published than ammonia and methanol. Methanol has the least techno-economic challenges but is on the other hand notcarbon free. Therefore, methanol is not a viable option to obtain zero carbon emissions from ships.

Keywords: hydrogen, methanol, ammonia, port infrastructure, fuel storage, fuel transport, fuel distribution, fuel bunkering,

Table of Contents

Preface

The master thesis challenged us in many ways. Since our prior experience was not connected to this area of the maritime sector we had the chance to immerse ourselves in the highly relevant subject of alternative fuels. Which broadened our views and showed the challenges for the future to adapt alternative fuels from a techno-economic view.

Special thanks to our supervisor Fayas Malik Kanchiralla for his invaluable guidance and support during the work on the thesis and to our examiner Selma Brynolf for providing excellent and constructive feedback.

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Sten Olsson & Richard Yang

Abbreviations

AF	Alternative Fuel
AFI	The Alternative Fuel Infrastructure
BOG	Boil-Off Gas
Capex	Capital Expenses
CH_3OH	Methanol
CO_2	Carbon Dioxide
EGR	Exhaust Gas Recirculation
EU	European Union
GHG	Greenhouse Gas
H_2	Hydrogen
H_2O	Water
HFO	Heavy Fuel Oil
HRS	Hydrogen Refueling Station
ICE	Internal Combustion Engine
IGC	International Code For The Construction And Equipment Of Ships Carrying Liquefied Gasses In Bulk
IGF	International Code Of Safety For Ships Using Gases Or Other Low-Flash Point Fuels
IMO	International Maritime Organization
LHV	Lower Heating Value
LNG	Liquified Natural Gas
LOHC	Liquid Organic Hydrogen Carriers
MGO	Marine Gas Oil
N_2	Nitrogen Gas
NH_3	Ammonia

$NH4^+$	Ammonium Ions
NO_x	Nitrogen Oxides
Opex	Operational Expenses
PM	Particular Matter
RoRo	Roll On Roll Off
SCC	Stress Corrosion Cracking
SCR	Selective Catalytic Reduction
SECA	Sulphur Emission Control Areas
SMR	Steam Methane Reforming
SO_x	Sulfur Oxides
TWC	Three-Way Catalysts

1 Introduction

The earth is covered by approximately 70% ocean by surface area (Andersson et al., 2016). In addition, the maritime sector serves as a central pillar of international trade with modern shipping accounting for over 80% of global trade traveling through ports (Damman & Steen, 2021; Millefiori et al., 2020). It will be necessary to substitute fossil fuels with sustainable alternative fuels (AFs) on a wide scale to meet the International Maritime Organization (IMO) decarbonization and desulfurization goals and standards (IRENA, 2022; Serra & Fancello, 2020). There are several potential alternatives to traditional marine fuels making the choice difficult for the shipping industry (Serra & Fancello, 2020). Among the frequently mentioned alternative fuels that seem to have the greatest potential are hydrogen, ammonia, and methanol (ben Brahim et al., 2019; IRENA, 2022; Serra & Fancello, 2020).

Presently, most marine vessels run on fossil fuels such as heavy fuel oil (HFO) and marine gas oil (MGO), which negatively impact the climate, natural environment, and human health. Approximately 2,2% of total global carbon dioxide (CO_2) emissions can be traced to the maritime sector (Sadiq et al., 2021). Additionally, 15% of nitrogen oxides (NO_x) and 6% of sulfur oxides (SO_x) are emitted by the maritime sector. The most polluted cities in the world are all located near the coast, which is made worse by the fact that approximately 70% of ship emissions take place within 400 km of coastal regions (Alzahrani et al., 2021). In 2018, the IMO adopted a strategy to reduce greenhouse gas (GHG) emissions from ships (IMO, 2021). The main goals of the strategy are the following: to reduce GHG emissions by at least 40% by 2030 and by at least 70% in 2050, compared to 2008 levels. Primary measures to reach this goal are developing and using more efficient ships and implementing the usage of alternative fuels. Another key milestone was the Paris Agreement which was signed by 184 countries to show commitment to taking action to decrease the average global temperature by decreasing emissions and relying more on renewable energy (Alzahrani et al., 2021). The global CO_2 would need to decrease by 30% by 2030 to restrict the temperature increase to 2℃ as per the Paris Agreement's goals (AbouSeada & Hatem, 2022).

In the context of selecting an alternative fuel within the maritime sector, liquified natural gas (LNG) has been introduced to the shipping industry as a sustainable alternative to MGO and HFO. The introduction of strict Sulphur Emission Control Areas (SECA) favored the increased use of LNG (Aronietis et al., 2016). When LNG is used in an internal combustion engine (ICE) onboard a vessel the CO_2 emissions are less than HFO and MGO emissions. However, research shows that LNGs' reduction in CO_2 emissions is not enough to replace conventional fuels (ben Brahim et al., 2019; Pavlenko et al., 2020). In addition, methane slips while using LNG resulting in increased GHG emissions as methane is a stronger GHG than CO_2. This has promoted the interest in using other alternative energy carriers such as hydrogen (H_2), methanol (CH_3OH), and ammonia (NH_3) within the shipping industry. Reducing GHG emissions to meet the IMO goals is the primary reason for researching these energy carriers as they are considered sustainable alternatives to be adopted shortly to reduce the climate impact from a life cycle perspective (Song et al., 2022).

1.1 Background

One alternative to traditional energy carriers is hydrogen within shipping. According to IRENA (2022), hydrogen is a milestone needed to achieve decarbonization. Hydrogen is one of the most abundant elements in the universe sitting at the top of the periodic table. It is usually bound up with other elements for example water (H_2O) and needs to be separated through electrolysis (Ocko & Hamburg, 2022). Currently, approximately 95% of hydrogen is produced from nonrenewable resources (Amirante et al., 2017). The majority of the world's supply of hydrogen is produced through a method called steam methane reforming (SMR) (Amirante et al., 2017; Capurso et al., 2022; Mazloomi & Gomes, 2012). As the name suggests, it revolves around reacting natural gas consisting of methane with high-pressure steam to produce hydrogen gas. However, for one ton of hydrogen produced with natural gas, there are 2,5 tons of CO_2 released, while using coal releases 5 tons of CO_2 (Amirante et al., 2017). Producing hydrogen with fossil fuels with carbon capture and storage is referred to as blue hydrogen (Amirante et al., 2017). By increasing the efficiency of industrial SMR plants by managing the excessive heat from the plants combined with currently existing carbon capture technology would decrease CO_2 emissions during hydrogen production. As per Katebah et al. (2022), the CO_2 emissions from an industrial SMR combustion plant are escaped as flue gas and can be captured at three different locations of the plant with the maximum estimated carbon captured being around 70% of the CO_2 emissions. The hydrogen production cost is estimated to only increase by 7% excluding the CO_2 transport, utilization, and storage costs (Katebah et al., 2022).

Other than hydrogen gas, CO_2 is also created as a byproduct in the process. Currently, the SMR method relies on fossil natural gas to produce hydrogen (Capurso et al., 2022; El-Shafie et al., 2019). Hydrogen produced from fossil fuels is also known as gray hydrogen. Moreover, it would not meet future demands. The increase needed is approximately five times the present production, i.e., 614 megatonnes per year, which is only 12% of the energy demand in 2050 (IRENA, 2022). The usage of fossil fuels such as natural gas in production results in the same emission as the combined CO_2 emissions of the United Kingdom and Indonesia combined, i.e., 830 metric tons of carbon dioxide per year. Substituting fossil fuels with only hydrogen is highly unlikely, as hydrogen has a low density which results in several challenges associated with transportation and storage. Therefore, other alternative fuels such as ammonia and methanol are likely to assist with decarbonizing the maritime industry (IRENA, 2022). Hydrogen is also needed to produce energy carriers such as ammonia and methanol. The current hydrogen production methods need further development to increase the feasibility of hydrogen, ammonia, and methanol as sustainable alternatives (IRENA, 2022).

A more sustainable method for hydrogen production is where water electrolysis is powered by renewable energy sources such as biomass, wind, solar, or a mix of these (Amirante et al., 2017; IEA, 2019). Using water creates oxygen and hydrogen and therefore no CO_2 emissions. Hydrogen produced from this method is known as green hydrogen. Currently, green hydrogen is more expensive than gray hydrogen. Gray hydrogen and methanol are mainly produced by natural gas, but also by coal. The production of these alternative fuels is more expensive than using natural gas, as water electrolysis requires energy and expensive materials (Amirante et al., 2017; DNV GL, 2018). Hence, with current technology, the higher production costs of gray hydrogen compared to natural gas are existing economic barriers. The economic barriers to green hydrogen including ammonia and methanol produced from green hydrogen are even bigger. However, the development of green hydrogen is not likely to happen if blue hydrogen is not explored before (Tvedten & Bauer, 2022). Due to the cost and scalability advantages of fossil fuel. To develop the hydrogen supply chain IRENA (2022) mentions that 4 trillion USD is needed to be invested to trade 36% of the global volume into green hydrogen. The cost of hydrogen is expected to decline in the future due to the increased production of green hydrogen (Latapí et al., 2023). The EU has a goal of increasing green hydrogen production by up to 1 million tons in 2024 and up to 10 million tons by 2030.

Another alternative energy carrier is ammonia consisting of hydrogen and nitrogen and is most commonly used for fertilization (McKinlay, 2021). Ammonia does not contain carbon and therefore it will not result in carbon emissions when combusted and is not flammable in the air. However, there are other disadvantages to the energy carrier. Such as forming NO_x when used in an internal combustion engine, high toxicity for humans, and corrosiveness. Similar to blue hydrogen, ammonia produced from natural gas with carbon capture is referred to as blue ammonia (Laursen et al., 2022). Furthermore, ammonia can be produced sustainably by using hydrogen from water electrolysis and nitrogen from air separation (Wang et al., 2022). The process can also be powered by a renewable source, e.g., wind power, this is then called green ammonia when only using renewable sources to produce the compound. Since ammonia is commonly used as a commodity there are already established storage and distribution infrastructures. However, presently most of the ammonia is produced from fossil fuels (Pawar et al., 2021).

Methanol is a type of alcohol with high energy density, negligible SO_x emissions, and 60% lower NO_x emissions than HFO and notably lower than ammonia (McKinlay, 2021). Using methanol directly as an energy carrier would emit CO_2 in a comparative amount to LNG combustion (McKinlay, 2021). It can be used as fuel in either a combustion dual-fuel engine or in a fuel cell. A more sustainable alternative would be to use methanol produced from green hydrogen (green methanol) or using bio-methanol or liquefied biogas will be required to cut total GHG emissions (IRENA, 2022; Christodoulou & Cullinane, 2021). However, using methanol as a fuel might be easier as it can be much more conveniently stored and distributed due to it being a liquid at ambient temperatures (DNV GL, 2018). Overall, methanol is an alternative fuel that resembles traditional fossil fuels. Meaning, that the existing bunkering infrastructure can be used for methanol with minor modifications (Evergren et al., 2017).

1.2 Purpose

Using energy carriers such as hydrogen, ammonia, and methanol has the potential to reduce GHG emissions from shipping, however, more knowledge is required on the supply chain of these energy carriers from fuel production to the fuel to be used for propelling the ship. This master thesis focuses on the storage, transportation & distribution, and bunkering of three alternative energy carriers: hydrogen, methanol, and ammonia. The purpose is to analyze and assess the technical and economic challenges associated with the usage of these energy carriers connected to port infrastructure using a literature study. The study will include a comprehensive report that should provide challenges of implementing infrastructure for the analyzed energy carriers.

The main objective is to identify how the supply chains and facilities of these alternative fuels can be established for distribution, storage, and bunkering, with a focus on port infrastructure and the bunkering of vessels. Moreover, a cost analysis of the infrastructure for the above-mentioned alternative energy carriers will also be conducted. This should provide a better understanding of the economic feasibility of adopting newer energy sources and their impacts on the port and the maritime industry.

1.3 Research question

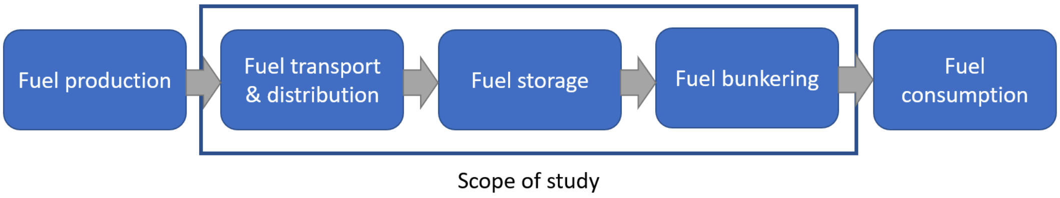
The following research question is being answered in the report:

What are the techno-economic challenges associated with the storage, transportation, distribution, and bunkering phases of hydrogen, methanol, and ammonia for use in shipping within their respective supply chains?

1.4 Scope

Figure 1 shows a simplified supply chain of energy carriers from production to actual usage in ships. The scope of the thesis is to review the current state and future of hydrogen, methanol, and ammonia in port infrastructure connected to transportation and distribution, storage, and bunkering.

Figure 1.
Scope of the thesis



1.5 Limitations

Due to the broad subject, there is a need to limit the subject. Limitations were chosen to clarify what will be included and excluded from the research. The scope and boundaries of the study are made more feasible and the objectives more achievable. The following limitations were chosen:

1. Technical limitations: The type of energy carriers included in this study are hydrogen, methanol, and ammonia.
2. System boundary: This study will also focus on the techno-economic impact of the implementation of alternative fuels in port and to its stakeholders, within the specified areas.

3. Geographical scope: the study will not focus on a specific geographic region, but on a broader global scale as the research on this subject is not bound by geographic location.
4. Type of ships: The study will not focus on a specific vessel type as the research revolves around the port facilities and their compatibility with the above-mentioned alternative fuels. Container-, RoRo-, ferries, bulk- and tanker- vessels are, however, the most commonly researched and cited ships relevant to this study.

2 Theory

2.1 Hydrogen

Hydrogen is the simplest and most abundant element in the universe. On Earth, it is primarily found bound together with other elements such as carbon in hydrocarbons and oxygen in water (Mazloomi & Gomes, 2012). Table 1 summarizes a few of the properties of hydrogen.

Table 1.
Properties of hydrogen

Properties	**Value**
Name, Molecular formula	Hydrogen, H_2
Phase	Gas (Room temperature)
Melting point	−259.14℃
Boiling point	−252.9℃
Flash point	−252.9℃ (Gas form)
Auto-ignition	585℃
Chemical safety	Explosion and fire hazards
Compressed hydrogen density	39 kg/m^3
Liquid hydrogen density	70,8 kg/m^3
Compressed hydrogen volumetric energy density	4,5 MJ/l
Liquid hydrogen volumetric energy density	8,49 MJ/l
Compressed hydrogen gravimetric energy density	120 MJ/kg
Liquid hydrogen gravimetric energy density	120 MJ/kg

Note. Density, volumetric energy density, and gravimetric energy density are for both compressed and liquid hydrogen as they differ (Aziz & Nandiyanto, 2020).

The concept of a CO_2 free hydrogen chain as mentioned by Kawasaki (2022) contains three steps: 1. Produce, 2. Transport/storage and 3. Use. The first step is to produce hydrogen from renewable energy or use fossil fuels in combination with carbon capture and storage. The second step is transportation and storage. Transportation of hydrogen may be performed by liquified hydrogen carriers or liquefied hydrogen trailers or pipelines (Kawasaki, 2022; IEA, 2019). Moreover, the storage occurs in liquid or gaseous hydrogen storage tanks. Geographical locations can also be used for long-term storage. The final point to consider is that hydrogen could be used through either ICEs or as fuel cells. However, usage in ICEs leads to a 20% to 25% effectiveness considering the supply chain (Ravi & Aziz, 2022). That is lower than the effectiveness of oil or diesel which corresponds to 30% to 35% in combination with an ICE.

2.1.1 Emissions

Hydrogen can be used as fuel or energy carrier for ships, cars, trains, and planes. In addition, the only byproduct of hydrogen is water, meaning it has no carbon content and therefore zero CO_2 emissions when used as a fuel. These properties have made hydrogen one of the promising renewable energy carriers as it holds the potential to be fully emission-free when combusted (Hoang et al., 2022; Mazloomi & Gomes, 2012). Furthermore, hydrogen has the highest amount of energy when comparing fossil-free fuels that are combusted with air (Sifakis et al., 2022). When using hydrogen in an ICE there are NO_x emissions (Ravi & Aziz, 2022). Hydrogen can be used in combination with fuel cells (Genovese & Fragiacomo, 2023). The fuel cells can either be used for shore operation in port or on board a vessel (Vicenzutti & Sulligoi, 2021). However, current hydrogen technology, including the whole supply chain, needs to be developed in order to accomplish the goal of zero carbon emissions (IRENA, 2022; Genovese & Fragiacomo, 2023).

2.1.2 Safety

There are several safety concerns regarding hydrogen that need to be addressed before it can be widely accepted as an energy carrier (Mazloomi & Gomes, 2012; Panić et al., 2022; Osman et al., 2021). The main concern is that hydrogen is easily flammable, even a mere concentration of 4% hydrogen gas in the air can be ignited, creating an explosive environment. This can be avoided by properly maintaining the concentration of hydrogen in the air or by converting it to liquid form (Mazloomi & Gomes, 2012). Moreover, the flames are nearly invisible making them difficult to detect. Smoke asphyxiation by fires is considered to be one of the common hazards and has the largest damage share of fire (Panić et al., 2022; Osman et al., 2021). However, unlike conventional fuels with more complex molecule structures, the smoke of hydrogen is completely harmless when inhaled. Furthermore, other several safety concerns are odorless and tasteless (Panić et al., 2022; Osman et al., 2021).

Another related aspect to hydrogen being easily flammable is its low electro-conductivity, which is a safety concern during handling and storing hydrogen, as electrostatic charges can be generated resulting in sparks that ignite the hydrogen (Mazloomi & Gomes, 2012). On the other hand, a safety characteristic of hydrogen is that its auto-ignition temperature is high at 585℃, as seen in Table 1, i.e., hydrogen is easily ignited from external ignition sources but has a high auto-ignition temperature.

For the IGF code (International Code of Safety for Ships Using Gases or Other Low-flash Point Fuels) hydrogen is not directly regulated (DNV, 2021). Low flash point fuels such as hydrogen (-252.9℃) are allowed if the systems can prove to be as safe as new oil vessels. If hydrogen is used with the fuel cell technology it is not decided if the areas where fuel cells are located will be classified as a hazardous zone. A hazardous zone is the result of a research project. However, this has not been conducted for hydrogen fuel ships. Furthermore, liquid hydrogen could lead to cold burns. Wang et al. (2023) mention that the instability and explosive nature of hydrogen requires high technological, transport, and storage investments. However, this can lead the port to develop and use these methods to increase its ability to compete with other ports.

2.1.3 Storage and distribution

Regular hydrogen production, handling, and distribution as a business have been around for decades, mainly used in space applications. There are several ways to store hydrogen, e.g., in tanks. In comparison to storing hydrogen as compressed gas, storing liquid hydrogen in cryogenic tanks has a higher energy content. As liquid hydrogen has a high density at low-pressure levels, which allows for more efficient distribution options due to using less volume than compressed hydrogen (Capurso et al., 2022; Mazloomi & Gomes, 2012). However, the temperature required to liquify hydrogen is below −252,9℃ and adds 30% to power demand. Moreover, using gas liquefiers and maintaining a low temperature further complicates the production system. As a result, the cost of liquid hydrogen is estimated by Mazloomi and Gomes (2012) to be 4-5 times higher compared to compressed hydrogen gas. In addition, hydrogen contains the lowest volumetric density when comparing hydrogen, methanol, and ammonia (Aziz & Nandiyanto, 2020). Furthermore, when storing and transporting liquefied gasses, such as liquified hydrogen at low temperatures, a portion of the liquified gas will constantly warm up and evaporate back into its gaseous state. This effect is called boil-off gas (BOG) (Al-Breiki & Bicer, 2020). As a result, a portion of the loaded liquified gas will inevitably be lost. This can be avoided to a degree by using high-quality insulation materials.

A preferred choice for several vehicle manufacturers is to store hydrogen gas in high-pressure cylinders that can be mounted on vessels for transport (Mazloomi & Gomes, 2012). The advantages of this method are the efficiency, low cost, and being environmentally friendly compared to the other methods. The primary disadvantage of this approach is the storage limitations, due to the low storage density. Which arguably can increase GHG emissions, since less hydrogen is being distributed and requiring additional trips. Hence, many experts predict that high-pressure cylinder storage for hydrogen will not be a popular method in the future (Mazloomi & Gomes, 2012).

Hydrogen can also be stored in metal hydrides through a process called absorption. The hydrogen molecules are absorbed into metal lattices, which form a chemical bond between the hydrogen and certain types of metals. Reduced temperatures absorb the hydrogen gas into the metal hydrides while applying heat to separate the hydrogen gas from the metal (Mazloomi & Gomes, 2012). The hydrogen can essentially be absorbed or released at normal pressure levels. This method has a high storage capacity compared to other storage methods such as compressed gas or liquid hydrogen (Rangel et al., 2022). Storing hydrogen through metal hydrides is also safer and more reliable, as the risk of leaks and explosions due to the absence of high-pressure hydrogen is reduced. However, there are also disadvantages to this storage method. Metallic hydrides have low energy densities per unit mass. The metal adds extra weight that would increase the weight requirements for distribution and transportation with this method (Rangel et al., 2022). In other words, from a technical perspective, storing hydrogen in metal hydrides is a secure and reliable option. But from an economic perspective, the technology is still not yet mature enough.

2.2 Methanol

The simplest alcohol, methanol (CH_3OH) is one alternative fuel used in the shipping industry (DNV GL, 2018). Methanol is a chemical that traditionally is a commodity and is produced on a large scale. Methanol had an annual production capacity of around 110 million tons per year in 2018 (Kajaste-Rudnitskaja et al., 2018). Methanol can be created from natural gas, coal, black liquor (from pulp and paper mills), forests, or agricultural waste (DNV GL, 2018). Another method is capturing CO_2 from power plants. Methanol is created using natural gas by mixing steam reforming and partial oxidation. This leads to an energy efficiency of approximately 70%, measured in energy in the methanol in comparison to the energy in natural gas. On the other hand, using coal is cheaper, but the GHG emissions are double compared to natural gas. Table 2 summarizes some of the properties of methanol.

Table 2.
Properties of methanol

Properties	**Value**
Name, Molecular formula	Methanol, CH_3OH
Phase	Liquid (Room temperature)
Melting point	−97,6℃
Boiling point	64,7℃
Flash point	11 to 12℃
Auto-ignition	358℃
Chemical safety	Acute toxic, flammable, health hazardous
Density	792 kg/m^3
Volumetric energy density	15,8 MJ/L
Gravimetric energy density	20,1 MJ/kg

2.2.1 Emissions

The methanol molecule includes a carbon molecule which makes it inevitable that combustion of methanol would result in carbon emissions (DNV GL, 2018). Although the carbon emissions are significantly less than other traditional fuels it is not a zero-emission fuel. If the energy carrier was produced using biomass, the life cycle emissions would be lower compared to natural gas. There are two different alternatives to traditional engines, two-stroke diesel engines or four-stroke Otto engines. Furthermore, the reduction of CO_2 results in approximately 10% lower than oil-based fuels. SO_x emissions are almost zero and NO_x emissions depend on the engine or technique used. A two-stroke engine results in about 30% lower NO_x

emissions, while a two-stroke Otto engine results in a decrease of approximately 60% lower NO_x compared to oil. However, to comply with Tier III limits there is a need to combine the usage of methanol with either an EGR (exhaust gas recirculation) or SCR (selective catalytic reduction) to further reduce the emissions (DNV GL, 2018).

2.2.2 Safety

Methanol is already a common commodity with large-scale production and a well-established global market. With an annual production capacity of around 110 million tons per year (Kajaste-Rudnitskaja et al., 2018). The safety characteristics and handling of methanol have also been well researched as a result of the extensive experience in transporting and handling methanol as a commodity. There is already existing governance and regulating bodies for the handling of methanol. The main guideline for shipping is the IGF code. The Methanol Safe Handling manual first published in 2013 by the Methanol Institute is another measure to provide an overview of critical methanol safety and handling information of the liquid (Kamaljit, 2016).

Methanol is an easily flammable, clear, and colorless fluid. By IGF standards, it is a fuel that requires special safety measures when handling due to its rather low flash point, i.e., capable of igniting at lower temperatures (Kamaljit, 2016). This can be a safety concern when storing larger quantities of methanol (Svanberg et al., 2018; Paris MoU, 2022). It also has a low boiling point of 64,7°C, allowing it to evaporate quickly when exposed to heat (Kamaljit, 2016). If set ablaze, the flames are difficult to extinguish, and hydrogen fires are difficult to spot in daylight. Methanol flames emit poisonous chemicals, such as formaldehyde. Other safety characteristics of methanol include its being acutely toxic. It can cause serious health issues when in contact with the skin or when inhaled or ingested. Proper equipment and safety measures are therefore important during handling, storage, and transportation to prevent accidents in connection to methanol leaks (Kamaljit, 2016). A positive safety aspect is that methanol is quick to dissolve and biodegrade in water. This means any potential leaks would mean less severe environmental effects (Evergren et al., 2017).

2.2.3 Storage and distribution

In recent years, only a few methanol-based types of ships have emerged. The shipping company, Stena Line modernized one of their ships and introduced the first dual-engine methanol-powered ships in the world: Stena Germanica (Christodoulou & Cullinane, 2021; Kamaljit, 2016). Functioning as a roll-on, roll-off-passenger ship (Ro-pax) and operating between Gothenburg and Kiel. The Port of Gothenburg has a dedicated area for bunkering of methanol that is utilized by Stena Germanica. Methanol is relatively easy to transport, as it is liquid under ambient conditions. Methanol fuel can conveniently be distributed by trucks or bunker vessels to methanol-fueled vessels (DNV GL, 2018). Additionally, methanol shares similar characteristics to oil-based fuels. Meaning, that the existing bunkering infrastructure will require minor modifications (ben Brahim et al., 2019; Evergren et al., 2017).

When used as fuels in an engine, both ammonia and methanol are combusted similarly to the diesel process. However, usage of solely ammonia or methanol is not possible in an ICE, as they have poor ignition capabilities. A dual-fuel engine in combination with an engine igniting pilot fuel is needed to start the combustion

(Hansson et al., 2020). Diesel in small amounts, approximately 5% of the total energy is needed for propelling the ship. In order to reach a 100% decarbonization rate on the fuel combustion part biomass fuel could replace diesel fuel.

2.3 Ammonia

The inorganic compound Ammonia (NH_3) consists of hydrogen and nitrogen. Similar to methanol, ammonia is traditionally a commodity and is produced on a large scale. Ammonia had a global annual production of around 183 million tons in 2020 and is mostly used within the agriculture sector as a fertilizer (McKinlay et al., 2021; Pawar et al., 2021). 85% of the total ammonia output is being utilized as fertilizer. Aside from its current use as a fertilizer, ammonia is viewed as a potential alternative fuel due to its ability to be stored and transferred effectively and affordably, in comparison with pure hydrogen (Pawar et al., 2021). In shipping, ammonia can be used as fuel in either a combustion dual-fuel engine or in fuel cells (Prause et al., 2022). Ammonia has the potential to replace conventional fuels due to it being carbon-free and capability of being handled in existing infrastructure with refurbishment. The energy density is higher than hydrogen's but lower than methanol (Hoang et al., 2022; Reiter & Kong, 2011; Song et al., 2022). A disadvantage of ammonia compared to other fuels is its high auto-ignition temperature as seen in Table 3. Out of all the listed fuels, ammonia has the highest auto-ignition temperature at 651 °C. Unless used in fuel cells, a dual-fuel engine with a pilot fuel is necessary (Hoang et al., 2022; Reiter & Kong, 2011).

Table 3.
Properties of Ammonia

Properties	**Value**
Name, Molecular formula	Ammonia, NH_3
Phase	Gas (Room temperature)
Melting point	−77,73℃
Boiling point	−33,34℃
Flash point	-
Auto-ignition	651℃
Chemical safety	corrosive and toxic
Liquid ammonia density	600 kg/m^3
Liquid ammonia volumetric energy density	12,7 MJ/L
Liquid ammonia gravimetric energy density	18,6 MJ/kg

2.3.1 Emissions

The majority of ammonia is manufactured from fossil fuels such as natural gas, which generates a significant quantity of carbon dioxide. Therefore, it has been preferable to use natural gas directly as a fuel in a vehicle rather than producing ammonia from the natural gas. Similar to producing hydrogen, a renewable production method for ammonia is electrolysis. By remaking a dual-fuel diesel engine's fuel intake system the engine could successfully run on 95% ammonia and the remaining 5% with diesel as a pilot fuel (Reiter & Kong, 2011). The emissions from combustion of ammonia were noted to be carbon-free but emissions of other air pollutants such as NO_x and particulate matter were present (Reiter & Kong, 2011). Various studies show that NO_x emissions are the major pollutant of ammonia. NO_x emissions can however be mitigated by using three-way catalysts (TWC), EGR or SCR technology (Hansson et al., 2020). Furthermore, the possibility to use ammonia with fuel cells exists, as it only emits water and nitrogen gas (N_2) emissions (Nowicki et al., 2022).

2.3.2 Safety

Ammonia is a colorless gas with a strong odor that can be detected at very low concentrations, indicating a leak or spill. There are major safety concerns with ammonia due to its toxicity in human and maritime environments (Prause et al., 2022). Ammonia is corrosive and can severely burn soft tissues, eyes, and respiratory systems. The corrosiveness of the gas also means that the storage material used needs to be considered to prevent degradation, leaks, and spills (McKinlay et al., 2021). Ammonia levels of 2 700 PPM are lethal for humans if exposed for 10 minutes (de Vries, 2019). Ammonia when released into the water is biodegradable and not harmful to humans or plants. The formation of ammonium ions ($NH4^+$) is, however, in the long term harmful for life in the water. There are existing regulations for carrying and handling ammonia as a commodity, such as the IGC Code 2014 abbrived from International Code for the Construction and Equipment of Ships Carrying Liquefied Gasses in Bulk (Ash & Scarbrough, 2019). The IGC code (2014) Chapter 17 provides guidelines for the safe sea transportation of liquefied gasses in bulk. The IGC code does not consider ammonia's flammability and explosivity a significant hazard (IGC code, 2014). The major hazard traits of ammonia are deemed to be its toxicity and corrosiveness. To prevent spills or leakages of the ammonia, the IGC code has minimum requirements for vessels carrying anhydrous ammonia as can be seen in Table 4. However, there is a clear distinction between carrying ammonia as a commodity and using it as the primary fuel for a vessel. Clearer safety regulations that consider the risk of leakage, spills, and other safety concerns during bunkering and operation of the vessel are required to be clarified in the future in case of large-scale implementation (Hansson et al., 2020).

Table 4.
Minimum requirements for anhydrous ammonia (IGC code, 2014).

Minimum requirements	**IGC Code (2014) Chapter**	**Description**
Personal protection	14.4	Individuals on board must have access to appropriate eye protection and respiratory gear in the event of an emergency evacuation.
Materials of construction	17.2.1	Cargo tanks must be designed and built with proper materials of construction and have a corrosion-resistant covering.
Special requirements	17.12.2	Cargo tanks minimum yield strength not exceeding 355 N/mm^2 & actual yield strength not exceeding 440 N/mm^2.
Special requirements for stress corrosion cracking (SCC)	17.12.8	Advised to keep dissolved oxygen levels below 2.5 ppm

2.3.3 Storage and distribution

Ammonia is capable of inflicting severe corrosion, mostly in the form of stress corrosion cracking (SCC) (IGC code, 2014). SCC is especially dangerous since cracks can lead to leakage or spills (Elishav et al., 2021; Trivyza et al., 2021). Considering the toxic nature of ammonia it could have disastrous consequences. Tensile stress combined with a corrosive environment (exposure to high humidity) are usually the culprits for SCC and can result in the protective metal oxide layer of the tank breaking. SCC typically consists of three stages:

1. initiation
2. propagation
3. failure.

In the initiation stage, it starts as a minor defect or cracks at the surface of the metal. The crack quickly spreads throughout the surface in the second stage propagation as a result of further tensile stress and corrosion. Finally in the third step, failure, the cracks are of critical sizes and the material is failing (Rao et al., 2016). SCC can occur in all ammonia storage and distribution systems, such as tanks, pipes, and valves. For instance, SCC might occur in the welds of ammonia pipes due to the significant tension placed on the welds during the welding process. SCC can also happen in the metal's heat-affected zone, where the welding process has changed the metal's mechanical characteristics. Copper and copper alloys have been demonstrated to be especially vulnerable to SCC (Rao et al., 2016). Other metals and metal alloys commonly used such as aluminum and brass risk developing SCC (Ash & Scarbrough, 2019; Elishav et al., 2021). It not only affects metal and its alloys but also other materials such as plastics and ceramics (Elishav et al., 2021).

There are two primary storage options for ammonia, low-temperature or pressurized storage (Pawar et al., 2021; Reiter & Kong, 2011). Ammonia is a liquid at room temperature at around 9 bar. However, ammonia is frequently pressurized up to 17 bar to keep the chemical in the liquid phase if the temperature were to rise above room temperature. The advantage of pressurized storage is that no energy is required and frequently used to store lower quantities as approximately 1 ton of steel is required to store 2,8 tons of ammonia (Reiter & Kong, 2011). Low-temperature storage, on the other hand, is typically used when storing larger quantities of ammonia. Keeping the ammonia in liquid form and avoiding boiling off is energy intensive but is significantly lighter to store (Pawar et al., 2021; Reiter & Kong, 2011). Furthermore, 1 ton of steel can store approximately 41–45 tons of ammonia. Contrary to liquefied hydrogen, there is no need for cryogenic storage when employing ammonia, meaning less energy is required to store and transport ammonia (Hansson et al., 2020).

Ammonia is commonly transported through pipelines (IEA, 2019). The best way to distribute ammonia to the end users depends on the distance, volume, and usage purpose. Moreover, trucks are another option. Either in pressurized or in refrigerated tanks. Furthermore, LNG is used frequently as a transition fuel; there is a possibility to convert current LNG storage tanks to ammonia storage tanks without any larger adjustments (Prause et al., 2022). Similar to hydrogen, ammonia can also be stored in solid form by binding the ammonia to metal amine complexes (Aziz & Nandiyanto, 2020). This lowers the toxicity to comparable levels to gasoline and methanol and removes the safety issues of transporting liquid ammonia. This technology is however not economically justifiable, similar to how it is for storing hydrogen in metal hydrides.

2.4 Alternative Fuel Infrastructure Directive

The Alternative Fuel Infrastructure (AFI) directive was established by the European Union (EU) to accelerate the installation of infrastructure for alternative fuels. The goal is to aid the goals set by the Paris Agreement in 2015 to combat the global climate crisis (Ertug, 2018). The Paris Agreement stipulated goals of bringing the global temperature below 2℃ and the ideal being 1.5℃. According to the AFI regulation, the transport sector must escalate the reduction of carbon emissions to reach net zero emissions by 2050.

According to the European Parliament's Committee on Transport and Tourism rapporteur, Ertug (2018) switching to AF may help achieve the Paris Agreement’s goals but acknowledges the fact that conventional fuels will be needed for some time. The development of AF has to reach the point where it can fulfill the demand. Shipping accounts for over 3% of GHG emissions and is responsible for air pollution close to coastal areas and ports. The steady adoption of AF would significantly improve the environment (Ertug, 2018). To enable a more seamless transition, the AFI regulations optimize the logistics for sustainable AF such as hydrogen, ammonia, hydrogen, and batteries. Switching to AF is however yet a challenge as several factors have to be taken into consideration. The researchers, Benamara et al. (2019) have identified several restrictions, measures, and solutions to adopting AF in ports, as can be seen in Table 5.

Table 5.
Alternative fuel adoption strategies for ports (Benamara et al, 2019)

Restrictions	**Solutions for the adoption of alternative fuels in ports**
Capital requirements - to identify the key requirements for infrastructure	Government funding and budget allocation
Persistence of using fossil fuels to generate and produce alternative fuels	Utilization of renewable energy sources for alternative fuel production
Environmental issues with AF	1. Conducting life cycle analysis of the alternative fuels' emissions 2. Evaluating the cost-to-benefit ratio
Security issues with AF	1. Training 2. Certification and standards 3. Risk analysis
Promote harmonized standards	Encourages the creation of consistent standards for setting up AF infrastructure. Harmonized standards can help ensure that the infrastructure is interoperable and used by ships across different member states.

2.5 Ports

The definition of a port is a geographical area where vessels discharge and load cargo (Stopford, 2008). The structure of ports can either be public bodies, government organizations, or private companies. The port authority is a service provider within the port environment, e.g., providing vessels berth space. Furthermore, terminals are located in the geographical port area and there can be several terminals in one port. There are different terminal types devoted to various cargo handling categories, such as container-, bulk- and RoRo (roll on roll off)- terminals. Similar to the port governance the terminals can be operated by different actors, such as shipping companies (Damman & Steen, 2021; Stopford, 2008).

The main function of the port is to provide berthing for vessels. There are also other secondary functions, such as investing in facilities and infrastructure (Nisiforou et al., 2022; Stopford, 2009). As well as dredging for vessels with increased draught, and providing different types of cargo handling and storage for export and import cargo. Moreover, integrate roads, inland waterways, and railways to improve connections for the transport of cargo using various modes of transport (Stopford, 2009). Ports are also major stakeholders in the shipping industry. There needs to be coordination between the stakeholders. For instance, if there is no agreement between the shipping industry and ports on what type and quantity of AF will be required. It will prevent investments in new AF technology for both ships and ports (Nisiforou et al., 2022).

There is also the concept of smart and green ports (Nguyen et al., 2022). These port ideas have the same goal, to achieve technical innovation by developing sustainable infrastructure and operations. The purpose of green ports is to use alternative energy sources, and alternative fuels, develop waste management and ecology, and use the

Internet of Things, to consume less energy, less waste, and fewer pollutants. For example, use alternative fuels to power port vehicles and equipment or provide alternative fuels for bunkering of vessels. However, there is still a lack of research on some renewable fuels to be integrated into ports, e.g., hydrogen (Sifakis et al., 2022).

Globally ports struggle with problems such as air quality issues, particular matter (PM), dust, and pollution of NO_x and SO_x (Gibbs et al., 2014). However, ports also have an impact on the climate with emissions of GHG that contribute to global warming. According to Gibbs et al. (2014) data from 2007 and 2008 shows that emission from vessels at berth is ten times greater than emissions from the ports' operation (1,8mt CO_2 versus 174kt CO_2).

3 Method

3.1 Literature review

The main data collection method for the report was a literature review. Data were collected through comprehensive searches of academic databases such as Scopus to identify relevant studies. The search keywords consisted of a combination of keywords relevant to the subject of this literature review. Before searching and reviewing studies for the literature review, delimitations were identified to help narrow down the boundaries of the research process. An inclusion criteria for the studies was concluded to determine the relevancy of the studies. The inclusion criteria for the studies are the following:

1. Published in a peer-reviewed journal or scholarly database such as Scopus.
2. Written in English or Swedish.
3. Studies relevant to the literature review determined from keywords, title, abstract, and potential conclusions.

The snowballing technique was also used, where initial findings lead to the identification of new and relevant sources, which opened up additional sources. In this report, the snowballing technique was relevant to identify additional sources by looking at the reference section of documents already read and documents provided by the supervisor. Broadening the pool of relevant studies and literature on top of the initial findings. The goal of using the snowball technique was to build a profound understanding of the qualitative research topics that this study mainly focused on. While reading articles and reports the reference section contains publications that could be used throughout this thesis.

3.2 Search phrases

Several topics within the scope of this literature review were investigated regarding hydrogen, methanol, and ammonia. To collect data keywords and search phrases were used. Different search phrases were used depending on the information needed. In this study the primary search engine for scientific material was Scopus. A single search term was created in Scopus to gather data. Investigations of storage and distribution processes, refueling processes, risk assessments, safety-related analysis, and technical-economic analysis. The keywords and search phrases are filtered by article title, abstract, and keywords.

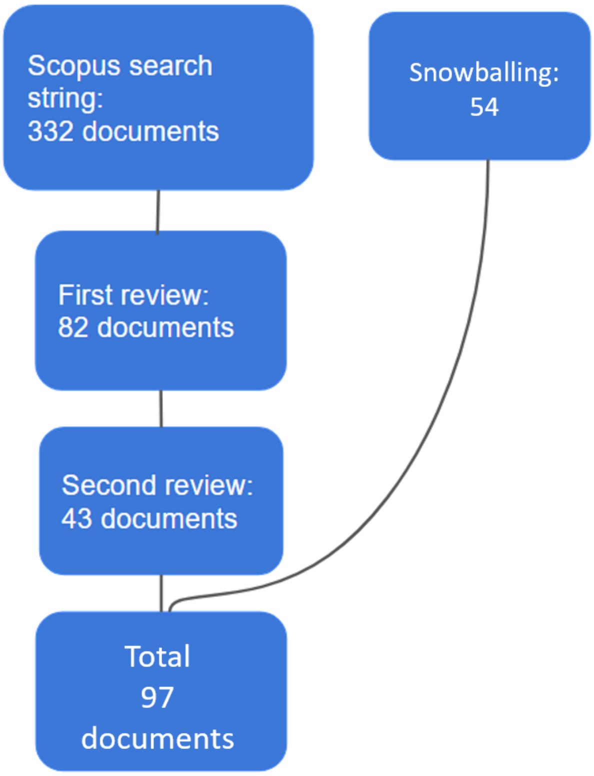
Search terms used in Scopus:
(Hydrogen OR methanol OR ammonia OR electrofuel OR efuel OR electro-fuel OR power-to-fuel) AND infrastructure AND port AND fuel AND (maritime OR shipping OR marine OR ocean AND transport) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE , "re"))
resulted in 332 documents (May, 2023) ranging from 1978-2023

The 332 articles in the list were compiled in a spreadsheet and selected based on title and abstract. Moreover, the selected articles were used as sources throughout the thesis, in either the theory, introduction, or result chapter. In the initial review, the abstract was analyzed for inclusion in the fuel supply chain for assessed fuels. The process of analyzing began with reading the title and thereafter the abstract. If the title was relevant to the selected energy carriers and if the abstract contained information such as fuel transportation & distribution, fuel storage, fuel bunkering, or properties of the energy carriers, it was included in the initial review. In total, 82 articles were found relevant to the thesis scope and included in the first review phase.

In the second review, each study that had passed the first review, i.e., marked as "relevant" was thoroughly analyzed and evaluated if fit for this literature study. All the contents of the documents were taken into consideration. The documents had to include information about transportation & distribution, storage, bunkering, infrastructure, or properties related to the alternative fuels and the thesis. The documents were then divided into category areas based on the information requirement and energy carrier. The categories consisted of hydrogen, methanol, ammonia, storage, transport & distribution, bunkering, and infrastructure. The categories and amount of documents for each are shown in Figure 2. For example, storage could be mentioned in the abstract. However, when the information was analyzed, it was not relevant to the research question or the thesis. Occasionally, information was connected to phases outside the scope, e.g., production of fuels or energy production. Ultimately, the result of chosen documents from the Scopus search string was 43 of 332 documents. In total 97 sources were used as references throughout the report, whereas 54 were acquired through the snowball method. Any literature that were not an article in the scopus search term were classified as part of the snowball referenced literature. Figure 2 includes the articles collected from snowballing with the Scopus combined search string as the primary data collection method.

Figure 2.

Total articles from the combined Scopus search and snowballing data collection method



3.3 Analysis of documents

The analysis was to categorize the energy carriers relevant to the port operation's part of the supply chain. The following categorization areas were investigated: storage, transportation & distribution, and bunkering. This categorization was essential in order to have a deeper understanding of the different roles alternative fuels have in the context of port operations. The information and data gathered relevant to each categorization area from studies were compiled and written down in this report.

By gathering data on the different categorization areas, insights into each alternative fuel could be gained and used for comparison. For example, it was found that the economic and cost aspects were of great importance when choosing an alternative fuel for shipping. Articles connected to cost and economic analysis were thereafter organized according to the categorization. E.g., if a document mentioned transport cost, it was written in the transport section of the corresponding energy carrier. The cost used in the comparison Figures 5, 6, and 7 were based on articles using transport cost that was able to be converted into USD/GJ. If there was no given distance in the data, it was not used in the comparison. There were other documents that mentioned the transport cost of alternative fuels. However, due to the diversity of available cost metrics and data limitations, the decision was to only use data such as USD/GJ, EUR/kgH_2, and USD/kgH_2. These metrics were most consistently used in literature and allowed for convenient direct price comparisons between other alternative fuels. An additional factor that had to be considered and included in the transportation cost formula was transportation distance due to the various available transportation modes that can be utilized for fuel transportation. In the end, out of the extensive literature review conducted, only a limited number of documents met the mentioned criteria for the comparison of transport costs. These documents provided valuable data on the different cost aspects of the alternative fuels as well as the showing the economic implications of transporting these alternative fuels

The metric used for comparing transportation was USD/GJ/10 000 km. Using 10 000 km instead of 1 km eliminates decimals, which improves the readability of Figures. Furthermore, if the original currency was in EUR it was changed to USD. It was done by dividing the original value by the EUR to USD conversion rate (0,92). The rate used was retrieved on 16/05 - 2023 from Google Finance (2023). Moreover, kg H_2 was converted to GJ using the LHV (Lower heating value) for one kg of hydrogen (0,12 GJ), i.e., kg h2 = 0,12 GJ. Thereafter it was divided with USD/kg H_2 resulting in USD/GJ. When the cost was calculated, it was then sorted into transport mode and energy carrier.

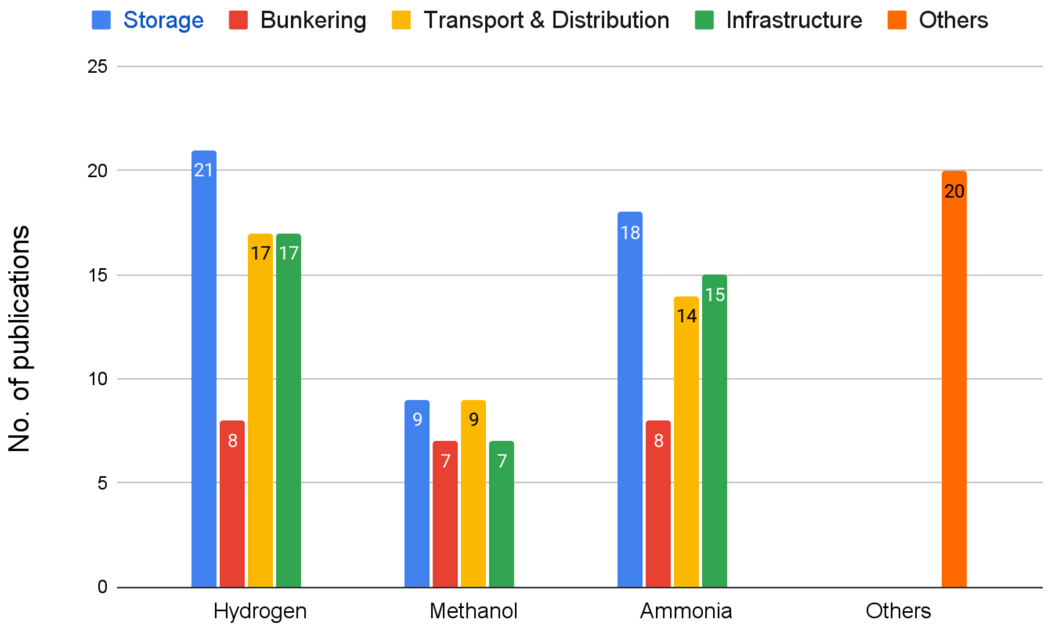
To compile information a summary of the main challenges was created. The challenges are listed in Tables 8, 9, 10, and 11. The information was taken from the reviewed documents and was listed if relevant to challenges.

4 Results and analysis

The thesis was based on a literature review method. Therefore, the data consisted of documents such as reports and articles. To gather documents for the thesis a search string was used in the citation database Scopus. After the reviews of the publications, 43 documents were used in the thesis that originated from the Scopus search string. As seen in Figure 3, the documents were classified according to the type of energy carrier and after that, storage, bunkering, transport & distribution, infrastructure, and others. The" Other" are regarded as topics indirectly relevant to the research question, not concerning the port infrastructure, transport and distribution, and bunkering of hydrogen, methanol, and ammonia. E.g. It could include sources focusing on conventional fuels used as a comparison to alternative fuels in this study. The documents were categorized after relevant energy carriers, which resulted in 48 hydrogen-, 20 methanol-, 35 ammonia-, and 20 other documents.

Figure 3.

The Number of Scopus publications is segregated into Storage, Bunkering, Transport & Distribution, and Infrastructure.

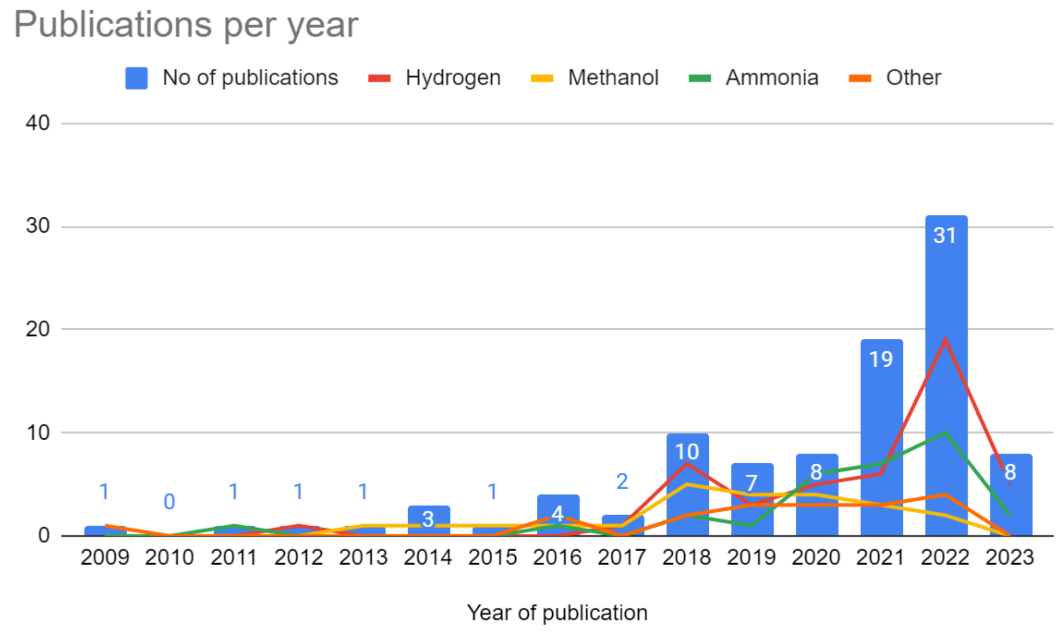


Note. The total of publications for each fuel was: 48 for hydrogen, 20 for methanol, 35 for ammonia, and 20 others.

The literature from the Scopus database search term combined with the literature from snowballing consisted of publications from different years. Figure 4 illustrates the focus of this literature review, as well as the insights into the total literature distribution across the energy carriers: Hydrogen, Methanol, and Ammonia, as well as Other topics. As seen in Figure 4, the majority is hydrogen-related literature, followed by ammonia and lastly methanol. This data imbalance shows that more hydrogen and ammonia publications were gathered from both the Scopus search term as well as snowballing. Another note is that most literature used in this study was published in recent years.

Figure 4.

Literature publications per year



Note. The x-axis shows the years from 2009 to 2023, while the y-axis shows the number of publications.

4.1 Challenges with hydrogen, methanol, and ammonia

4.1.1 Hydrogen

The main technical challenges associated with the fuel supply chain of hydrogen is due to its low density and explosive nature. This makes storage, distribution, and bunkering difficult compared to other fuels. Hydrogen storage is required at the production facility and also at the ports before bunkering. Hydrogen can be stored in tanks, either as liquid or compressed. Furthermore, liquid hydrogen has a density of 70,8 kg/m^3, while compressed hydrogen has a lower density of 39 kg/m (Aziz & Nandiyanto, 2020).

Furthermore, compressing hydrogen leads to energy losses of 10% - 20% (Panić et al., 2022). On the other hand, liquefying hydrogen could result in up to 35% energy losses (Panić et al., 2022; Santos, 2022). Liquid hydrogen is 10 times more expensive than compressed hydrogen when considering storage (Deveci, 2018). Furthermore, according to IRENA (2022) liquid hydrogen value chain needs 2,5 higher investments than the ammonia value chain.

Several studies emphasize the need for larger storage facilities at port for the shift to a hydrogen economy, which includes storage methods other than conventional tanks (Aziz & Nandiyanto, 2020; Amirante et al., 2017; Davis et al., 2018; Nazir et al., 2020; Osman et al., 2021). Studies have explored different options for the storage of hydrogen, such as salt caverns, tanks, oil & gas reservoirs, water aquifers, liquid organic hydrogen carriers (LOHC), depleted hydrocarbon reservoirs, metal hydrides, and natural clay with pores, but these need testing (Deveci, 2018; AbouSeada & Hatem, 2022; Osman et al., 2021; Aakko-Saksa et al., 2023; Santos, 2022; Panić et al., 2022; Rangel et al., 2022; Amirante et al., 2017; IEA, 2019). For long-term storage and large volumes, caverns are economically beneficial compared to tanks.

For distribution, the main challenge is related to the lesser volumetric energy density that hydrogen delivers less energy per liter compared to other fuels (Aziz & Nandiyanto, 2020). Like other fuels, transportation of hydrogen tankers (trucks, trains, and vessels) and pipelines can be used (Genovese & Fragiacomo, 2023; Freer et al., 2021; Buchenberg et al., 2023; Collis & Schomäcker, 2022). Moreover, for long-distance and larger volumes pipelines and shipping are the most efficient options. However, pipelines are capital expenses (Capex) intensive. One option is using existing natural gas pipelines that could be repurposed for hydrogen usage to decrease Capex (IRENA, 2022; Saeedmanesh et al., 2018; Ravi & Aziz, 2022).

There are no bunkering-specific regulations for hydrogen (Halim et al., 2018; Ustolin et al., 2022; Tvedten & Bauer, 2022; Latapí et al., 2023). Currently, there are four main types of bunkering methods for hydrogen (Ustolin et al., 2022). Truck to ship, ship to ship, bunker stations, and swappable containers. Hydrogen can be used in both liquid, compressed, metal hydrates and LOHC for bunkering (Ustolin et al., 2022; Hyde & Ellis, 2019). Furthermore, according to Ustolin et al. (2022) only two liquid hydrogen bunkering facilities exist. The summarized main challenges for hydrogen can be seen in Table 6 and 7 below.

Table 6.
Techno-economic challenges with compressed hydrogen

Challenges with compressed hydrogen		
Area	**Technical**	**Economical**
Storage	● Low density 39 kg/m^3 requires large storage facilities (Aziz & Nandiyanto, 2020; Davis et al., 2018; Nazir et al., 2020; Osman et al., 2021) ● Compression leads to 10% - 20% losses of energy (Panić et al., 2022) ● Compression differences depending on the end users (Panić et al., 2022) ● Increasing demand lead to increased need for material (Aakko-Saksa et al., 2018) ● Leakage of hydrogen (Osman et al., 2021) ● Storage options as oil & gas reservoirs, water aquifers, depleted hydrocarbon reservoirs, metal hydrides and natural clay with pores need testing (Osman et al., 2021; Santos, 2022; Panić et al., 2022; Rangel et al., 2022; Amirante et al., 2017; IEA, 2019)	● Large scale storage options as salt caverns, oil & gas reservoir and water aquifers requires additional costs (Deveci, 2018; AbouSeada & Hatem, 2022; IEA, 2019) ● Geographical locations storage are economically beneficial compared to tanks when large volume is needed to be stored (Deveci, 2018; IEA, 2019) ● Up to 20% energy losses at compression (Panić et al., 2022)
Transport & distribution	● Safety concerns as risk of explosion, risk of fire, tasteless, odorless, colorless and hydrogen embrittlement (Panić et al., 2022; Osman et al., 2021; Wang et al., 2023; Mazloomi & Gomes, 2012; Saeedmanesh et al., 2018; IRENA, 2022)	● Demand needs to increase in collaboration with supply (Latapí et al., 2023) ● Usage of pipeline when transporting large volumes is cost efficient, however more Capex intensive compare to other alternatives (Buchenberg et al., 2023; Collis &

	● Natural gas pipelines could be used for hydrogen but there could be energy losses as the distance of compression stations are not optimized (IRENA, 2022; Saeedmanesh et al., 2018; Ravi & Aziz, 2022) ● Usage of liquid organic hydrogen carriers (IEA, 2019; Aakko-Saksa et al., 2023; Santos, 2022) ● Leakage and compression issues due to light-weight (Capurso et al., 2022; Osman et al., 2021)	Schomäcker, 2022; Genovese & Fragiacomo, 2023) ● Pipelines efficient at 100 km than shipping, however for distances over 2500 km shipping cost less (d'Amore-Domenech et al., 2023) ● Repurposing natural gas pipelines lowers the Capex compared to constructing new infrastructure (IRENA, 2022) ● Using existing natural gas pipelines requires additional compression stations or losses of energy occurs (Saeedmanesh et al., 2018; IRENA, 2022)
Bunkering	● No bunkering regulations and limited bunkering capabilities (Halim et al., 2018; Ustolin et al., 2022; Tvedten & Bauer, 2022; Latapí et al., 2023) ● Demand need to rise or else there is no incentive for hydrogen bunkering facilities (Steen et al., 2022)	● Lack of bunkering facilities increases costs (Ustolin et al., 2022; Latapí et al., 2023)

Table 7.
Techno-economic challenges with liquid hydrogen

Challenges with liquid hydrogen		
Area	**Technical**	**Economical**
Storage	● Low density 70,8 kg/m^3 requires large storage facilities (Aziz & Nandiyanto, 2020; Amirante et al., 2017; Davis et al., 2018; Nazir et al., 2020; Osman et al., 2021) ● Cryogenic tanks for storage and need to withstand ice formation as liquid hydrogen requires -252,9 Celcius to be liquified (Panić et al., 2022; Deveci, 2018; Ustolin et al., 2022; Santos, 2022; Genovese & Fragiacomo, 2023; Mazloomi & Gomes, 2012) ● Energy losses up to 35% at conversion to liquid hydrogen (Panić et al., 2022; Santos, 2022) ● Increasing demand lead to increased need for material (Aakko-Saksa et al., 2018)	● Highest energy loss cost from BOG when stored in liquid state (Al-Breiki & Bicer, 2020) ● Cost up to 10 times more than compressed hydrogen to store (Deveci, 2018) ● Large scale liquefaction units to be beneficial (Buchenberg et al., 2023) ● Up to 35% energy losses at liquefaction (Panić et al., 2022; Santos, 2022) ● Storage capacities for liquid hydrogen needs to expand as the demand rises (Aakko-Saksa et al., 2018)
Transport & distribution	● Usage of liquid organic hydrogen carriers (IEA, 2019; Aakko-Saksa et al., 2023; Santos, 2022) ● Due to the cryogenic nature, transportation storage is limited (Genovese & Fragiacomo, 2023; Mazloomi & Gomes, 2012) ● Suffers from boil-off and evaporation (Aakko-Saksa et al., 2018; Hinkley, 2021)	● Demand needs to increase in collaboration with supply (Latapí et al., 2023) ● Highest transportation cost among compared AF at 3,24 USD/GJ (Al-Breiki & Bicer, 2020).

Bunkering	● No bunkering regulations and limited bunkering capabilities (Halim et al., 2018; Ustolin et al., 2022; Tvedten & Bauer, 2022; Latapí et al., 2023) ● Demand needs to rise or else there is no incentive for hydrogen bunkering facilities (Steen et al., 2022)	● Lack of bunkering facilities increases costs (Ustolin et al., 2022; Latapí et al., 2023)

4.1.1.1 Storage

Hydrogen requires large tanks for storage due to its low density (Davis et al., 2018; Nazir et al., 2020; Osman et al., 2021). Tanks located on land are required to be placed in an area with ventilation and where it is not exposed to temperatures over 500℃ (Panić et al., 2022). The discharge rates are high for tanks and their efficiency is around 99% (IEA, 2019). Storage tanks are commonly used for smaller scales within hydrogen.

For compressed hydrogen, the normal pressure for storage is between 200 bar to 1000 bar, depending on safety requirements and end users (Panić et al., 2022). Furthermore, compressing hydrogen leads to energy losses of about 10% to 20%. According to Panić et al. (2022) within the automotive industry, the pressure of compressed hydrogen is 700 bar due to storage limitations. Whereas, on short-sea, the pressure of hydrogen is lower than in the automotive industry due to safety concerns and hazards (explosions, risk of fire, and storage systems for highly compressed hydrogen). Compared to LNG, liquified hydrogen requires 2,8 times the volume to store. The normal pressure for the storage of liquid hydrogen is 6 bar. Furthermore, it requires a temperature of -252,9℃ and cryogenic tanks (Panić et al., 2022; Genovese & Fragiacomo, 2023; Mazloomi & Gomes, 2012). The cryogenic tanks are double-walled containers composed of steel to withstand the temperature of liquid hydrogen (Deveci, 2018; Ustolin et al., 2022). When the conversion of hydrogen to liquid hydrogen occurs density increases but it results in energy losses (Panić et al., 2022). Up to 35% of the total energy of the liquified hydrogen can disappear (Panić et al., 2022; Santos, 2022). Furthermore, IRENA (2022) estimates the development of a liquid hydrogen value chain needs investments up to 2,5 times higher than the whole ammonia value chain is needed.

Challenges with liquid hydrogen storage are that the storage unit needs to withstand low temperatures and ice formation leading to the rupture of the unit and equipment (Panić et al., 2022; Santos, 2022). Moreover, liquid hydrogen evaporates leading to higher pressure in the tank. Therefore, the need for releasing excessive hydrogen into the air and thus losing energy. Comparing liquid and compressed hydrogen in application in a vehicle, liquid hydrogen performs better due to the higher energy content in the same volume. However, as it requires cryogenic storage tanks the usage would not be feasible depending on transportation devices, e.g., road vehicles (Ravi & Aziz, 2022). Moreover, Deveci (2018) mentions that the cost of liquid hydrogen storage is about ten times the cost of compressed hydrogen storage. A technical challenge that would occur if the hydrogen demand increases is that storage capacities also need to expand (Aakko-Saksa et al., 2018). If the demand was to increase to 410 Mt hydrogen annually the material needed for storage capacity would be equal to 7 500 Mt of material. Most of the materials needed are common in the Earth's crust, but the rarest would be gold, rhodium, and tellurium.

A large-scale and long-term storage option for hydrogen is salt caverns (Deveci, 2018; AbouSeada & Hatem, 2022; IEA, 2019). Currently, natural gas is stored in salt caverns, but they are applicable for the storage of hydrogen. As most caverns are large, they provide economies of scale, low land cost, and low operational expenses (Opex). Therefore, it can be the cheapest long-term storage option for hydrogen. Moreover, the advantages of salt caverns are low risks of contaminating hydrogen, sealing the hydrogen well, and offering high efficiency. Another storage alternative is depleted oil and gas reservoirs. Comparing reservoirs and salt caverns. the reservoir has the possibility of storing larger volumes of hydrogen. However, the reservoirs would need cleaning and removing previous content, before storage of hydrogen. Water aquifers can also be used for the natural storage of hydrogen, but exploration and development costs would most likely occur. Both oil and gas reservoirs and water aquifers store the gas deep underground. Risks are contamination and loss of hydrogen, due to hydrogen reacting with fluids, rocks, and microorganisms. For both last-mentioned storage mediums, the cost and feasibility are unknown. The geographical location also matters due to salt caverns, water aquifers, and oil and gas reservoirs are geographical findings (AbouSeada & Hatem, 2022).

Osman et al. (2021) mention the option of using depleted hydrocarbon reservoirs, which have advantages such as large storage capacity, proven seal, and existing infrastructure (natural gas pipelines). On the other hand, there are also disadvantages, such as the possibility of hydrogen reacting with microorganisms and chemicals, resulting in contamination. Furthermore, as H_2 has a low density, it is also lightweight. Therefore, there is a risk of leakage, due to the buoyancy forces. Transferring hydrogen into ammonia is also a viable option for storage and distribution due to it being easier to handle. However, the conversion leads to a loss of energy and may not be economical for large volumes (AbouSeada & Hatem, 2022; Pawar et al., 2021; Ravi & Aziz, 2022).

The choice of storage method depends on the volume needed to be stored, the required speed of discharge, duration, and geographical location (IEA, 2019). Geographical locations such as caverns, oil and gas reservoirs, and water aquifers are better suited for long-term storage, while tanks are better for short-term storage. Considering if a higher volume is needed to store, geographical locations are more economically beneficial (Deveci, 2018). However, compared to natural gas, hydrogen is expensive to store, due to the volumetric energy density being almost a third of natural gas.

Another option for storing hydrogen is using LOHC (Aakko-Saksa et al., 2023; Santos, 2022; IEA, 2019). The concept is not widely proven (exists in Germany and Japan) but has potential due to it safely storing hydrogen without losses (Aakko-Saksa et al., 2018; Santos, 2022). LOHC are solids or liquids that can be reversibly hydrogenated and de-hydrogenerated with elevated pressure and temperature to release or absorb hydrogen, e.g., methanol. Meaning that standard liquid storage tanks can be used and storage of hydrogen for extended periods without energy losses can be achieved (Santos, 2022; IEA, 2019). However, there are some challenges, such as using ammonia borane as a LOHC to replace 10% of the global energy supply requires more boron than its global reserve (730 Mt needed while the global reserve is at 110 Mt). Another challenge is that the technology is new and there is limited experience. There are also losses of hydrogen ranging between 35% to 40% when converting to a LOHC (IEA, 2019). Furthermore, the carrier's molecules remain when extracting the hydrogen and they are needed to be transported again.

Hydrogen can also be stored in metal hydrides (Panić et al., 2022; Rangel et al., 2022; Amirante et al., 2017). A drawback of using this technique is the cost of material and the hydrogen content per weight (12,5 kg metal stores 1 kg hydrogen). The benefits include lower service costs, compact storage (200% higher density), and making storage of hydrogen safer. Furthermore, natural clay with pores can be used as hydrogen storage. As the nanomaterial is cheap, durable, biocompatible, and most importantly has a high hydrogen storage capability. Pristine nanotubes made from clay can store up to 0,22% of hydrogen weight, but if the nanoparticles are up to 5% the stored hydrogen can be equal to 2,88% of the hydrogen weight.

4.1.1.2 Transportation and distribution

Presently, there are a few logistical challenges connected to hydrogen, such as transportation and distribution. An approach to hydrogen distribution to land-based vessels is a hydrogen refueling station (HRS). The hydrogen stored can either be liquid or gaseous and the supply can be produced on-, off-site, or a combination of both. In 2020 there were 553 HRS for road vehicles in the world (Wang et al., 2022b).

An off-site use, e.g., pipelines or tankers (road, rail, or ship) to distribute the hydrogen in either gas or liquid form (Freer et al., 2021). Liquid hydrogen is today not transported through pipelines as it needs to be stored in a cryogenic environment (Genovese & Fragiacomo, 2023; Mazloomi & Gomes, 2012). Furthermore, liquid hydrogen requires large-scale liquefaction units to be economically beneficial (Buchenberg et al., 2023). Trucks often carry hydrogen in pressurized tubes which could lower emissions due to less energy required to keep hydrogen in gas form (Genovese & Fragiacomo, 2023). On the other hand, transporting hydrogen through pipelines is an economically beneficial approach when large quantities are distributed. The initial investment however is more Capex intensive due to establishing new infrastructure with pipelines, compared with the Capex of road transport (Buchenberg et al., 2023; Collis & Schomäcker, 2022; Genovese & Fragiacomo, 2023). Thus, the pipelines offer a lower emission alternative eventually depending on the scale of volume transported. Furthermore, one challenge is that pipelines are only efficient when the demand and supply are coordinated (IRENA, 2022). The cheapest cost for a large pipeline requires almost the same hydrogen demand as the pure hydrogen demand of Northwest Europe.

However, repurposing existing natural gas pipelines into hydrogen pipelines could decrease investment costs and expedite the shift to hydrogen (Ravi & Aziz, 2022; IRENA, 2022). According to IEA (2019), there were approximately 3 million km of natural gas pipelines established in 2019, whereas there were around 5 000 km of hydrogen pipelines. One challenge with repurposing natural gas pipelines is the ideal distance of gas compressors (IRENA, 2022). Resulting in a trade-off between investments in optimizing the distance for compression stations or higher energy losses due to not ideal compression (Saeedmanesh et al., 2018; IRENA, 2022). Another challenge is hydrogen embrittlement occurring in pipelines, which happens at high compression of hydrogen (Panić et al., 2022; Osman et al., 2021; Saeedmanesh et al., 2018; IRENA, 2022). Additionally, if the natural gas pipelines are used the demand for natural gas needs to decrease at the same time as hydrogen demand increases. Furthermore, the same volume of natural gas contains three times the energy of hydrogen, resulting in a need for larger flows of hydrogen (IEA, 2019). Lastly, an individual assessment is required for each pipeline network, as conditions vary from place to place, such as age, operating point, material, and maintenance (IRENA, 2022).

The authors d'Amore-Domenech et al. (2023) calculated the cost of transporting hydrogen (including loading and unloading). For short distances (100 km) the pipeline offers the most economically beneficial mode of transport. For medium distances (2500 km) compressed hydrogen shipping was the best alternative at flow rates of 100 kt/year, while for 1 Mt/year it is equal between liquid- and compressed hydrogen shipping and for 10 Mt/year liquid hydrogen is better (d'Amore-Domenech et al., 2023). When it comes to distances of 5 000 km the best solution is to ship liquid hydrogen for 1 Mt/year and 10 Mt/year, while the cost is similar between shipping liquid and compressed hydrogen at 100 kt/year.

Furthermore, Collis and Schomäcker (2022) estimated that pipelines could be worth the high investment costs when big volumes (1 mt/year) are transported within local or regional distances approximately (pipeline length up to 1120 km). In addition, Monte Carlo simulations show that pipelines (1080 - 1120 km) tend to be more economically viable when big volumes are transported within local or regional distances (Collis & Schomäcker, 2022). There are currently 4500 km of hydrogen pipelines in operation worldwide with operating pressures between 10 - 20 bars and diameters between 25 - 30 cm (Capurso et al., 2022). The average construction cost for these hydrogen pipelines was estimated to be 854 000 USD/km, which is up to 20% more expensive than natural gas pipelines (Capurso et al., 2022). The higher cost is due to the larger diameters required for the pipelines, leaks, and compression-related issues due to the hydrogen's low molecular weight (Capurso et al., 2022). Furthermore, according to Ravi & Aziz (2022), the developing hydrogen market's estimated to cost 210 to 550 billion USD for HSR and pipelines by 2050. This investment is expected to meet 24% of the global energy demand with hydrogen.

Another challenge with liquid and compressed hydrogen is that it suffers from BOG and evaporation during transportation and storage (Aakko-Saksa et al., 2018; Hinkley, 2021). It is estimated that around 1% to 5% is lost daily during truck transport and 0,3% in a tanker that contains about 4 tons of hydrogen. In various cases, the losses can be minimized with the usage of vaporized hydrogen at the same time, but as mentioned by Aakko-Saksa et al. (2018), this requires an ongoing operation. Therefore, LOHC would be a better option to use when transporting hydrogen. As it does not lose hydrogen in transport. LOHC can be transported using conventional oil product tankers for longer distances (IEA, 2019). However, the challenge is that it needs to react before releasing hydrogen (Aakko-Saksa et al., 2018). Furthermore, the cost of transporting LOHC 50 km was calculated to cost 0,414 Euro/kg hydrogen, which includes hydrogenation and hydrogen release (Aakko-Saksa et al., 2018).

Shipping hydrogen is most efficient for large volumes of liquid hydrogen transported over long distances (Collis & Schomäcker, 2022). Al-Breiki and Bicer (2020) compared the transportation costs of LNG, liquid ammonia, methanol, and liquid hydrogen via an ocean tanker from Qatar to Japan (12 000 km). The cost of transporting each energy carrier was estimated by summing the Capex of a tanker, the Opex of the voyage, and the energy loss costs from boil-off. The ocean tanker was assumed to run on HFO and fuel costs were based on 2020 HFO market prices. As shown in Table 8 hydrogen and respectively LNG has the highest Capex due to the need for more expensive insulating materials. Costs from BOG were also significantly higher for hydrogen. Transportation Opex for hydrogen is however the lowest of all the AFs compared, due to less mass of hydrogen able to be loaded. The hydrogen transportation cost from Qatar to Japan is estimated to be the highest at 3,24 USD/GJ. Hydrogen has the ability to be transformed into hydrogen carriers, such as methanol and ammonia (Cui & Aziz, 2023). As hydrogen has a lower density than both methanol and ammonia and therefore it is beneficial to transport hydrogen by using a hydrogen carrier.

Table 8.

Transportation cost (USD/GJ/12000 km) for maritime transportation of LNG, ammonia, methanol, and hydrogen from Qatar to Japan (Adapted and modified from Al-Breiki & Bicer, 2020)

	Unit	**LNG**	**Ammonia**	**Methanol**	**Hydrogen**
Ship capacity	m3	160 000	160 000	160 000	160 000
Capacity	Metric ton	67 696	109 248	128 800	11 376
Voyage distance	km	12000	12000	12000	12000
Vessel capital costs	MM$	192	162	120	216
Operational costs					
Required fuel (HFO)	Metric ton	7327,54	11825,21	13941,55	12737,9
Fuel cost (HFO)	MM$	4,2	6,8	8,0	0,7
Maintenance (4% Capex)	MM$	7,68	6,48	4,8	8,64
Insurance (15% Opex)	MM$	1,782	1,992	1,92	1,401
Misc costs (10% Opex)	MM$	1,188	1,328	1,28	0,934
Total Opex	MM$	14,85	16,6	16,0	11,675
BOG during transportation	Metric ton	25491,0	8570,3	202,1	37838,9
Cost of BOG	MM$	7,3	4,5	0,67	54
Transport cost	$/GJ	0,74	1,09	0,68	3,24

Note. BOG costs are based on energy lost to BOG during transportation and market prices of the energy carriers of various sources. All fuels are in a liquid state.

Furthermore, IEA (2019) compares the cost of transporting hydrogen by using ships, pipelines, and trucks. The comparison contains hydrogen (liquid in vessels and compressed in pipelines), LOHC, and ammonia. The costs include storage, transportation, liquefaction, and conversion when it is applicable for the different hydrogen carriers. At a distance of 1500 km, hydrogen costs less to transport with pipelines and LOHC costs less when using a vessel. However, IEA (2019) mentions that the cost of transporting hydrogen through pipelines is expensive for long distances due to more compression stations needed compared to ammonia. The least expensive alternative was LOHC to transport hydrogen at 1500 km by ocean vessel. The data from IEA (2019) was compiled in Table 9 below.

Table 9.
Transport cost for hydrogen, ammonia and LOHC (IEA, 2019)

1500 km	**Hydrogen**	**Ammonia**	**LOHC**
Pipeline (USD/ kgH_2)	1	1,58	-
Ship (USD/ kgH_2)	2	1,2	0,6

Another report estimates the levelized shipping cost for transportation of hydrogen, LOHC and ammonia in EUR/kg H_2/10 000 km (Wang et al., 2021). The levelized cost of transportation of the hydrogen carriers is approximately 0,78 to 1,31 EUR/kg H_2/10 000 km for liquid hydrogen, 0,83 EUR/kg H_2/10 000 km for ammonia, and 0,76 EUR/kg H_2/10 000 km for LOHC (Wang et al., 2021).

An additional cost is using compressing or liquefaction to store hydrogen, which can cost 0,1 USD to 4 USD/kg hydrogen (Aakko-Saksa et al., 2018). The cost fluctuates depending on the transport mode (tanker or pipeline) and if hydrogen is compressed or liquid. While only considering transport, the cost of transporting hydrogen in tubes on a truck is estimated to be 1,5 USD to 3 USD/kg hydrogen for around 250 - 750kg hydrogen per day in a distance of 100 to 300 miles (Aakko-Saksa et al., 2018).

4.1.1.3 Bunkering

Currently there are no specific regulations or designs and limited bunkering capabilities for hydrogen vessels (Halim et al., 2018; Ustolin et al., 2022; Tvedten & Bauer, 2022; Latapí et al., 2023). Resulting in innovation, as the technology is needed to be tested before usage. Otherwise, regulation can become a barrier that hinders the technological development of new innovations. Furthermore, the process of bunkering with conventional fuels is simple, while hydrogen bunkering is a new process, requiring other safety measurements. Moreover, a demand for hydrogen as a fuel is needed or else there will only be a stored supply of the energy carrier, but no users (Latapí et al., 2023). Since the infrastructure to deliver hydrogen is not currently broadly available in most ports, the costs are high. To lower the price and attract users the prices need to decrease and the availability and volume of hydrogen need to increase.

Ustolin et al. (2022) mention that there are four main types of bunkering for hydrogen:

1. Truck to ship, where a truck with tanks (liquid) or tubes (gaseous) connects to the vessel to bunker the vessel. The advantages are that it is flexible and less initial investments than a bunkering station as there is no need for fixed storage units.
2. Ship to ship, where a ship refuels another ship. Advantages are flexibility, that operation is not bound to happen when it is docked, the operation can occur at sea or at longer distances, and infrastructure needed to fill the vessels are only required. However, the need to invest in a bunker vessel is needed.
3. Bunker station, a fixed structure at a port. This option has a fixed structure and infrastructure and contains large amounts of hydrogen.

4. Swappable containers, a flexible option but not optional when larger volumes of fuel are needed. However, this option should not be used within liquid hydrogen bunkering due to the risk of raising up the containers and their contents.

Furthermore, as of 2022, there were only two existing liquid hydrogen bunkering facilities (Ustolin et al., 2022). In Australia, the Port of Hastings, and in Japan, the Port of Kobe. These are used for the same project. The lack and future uncertainty of hydrogen availability and supply can be attributed to the shipowner's lack of investment in hydrogen-fuelled vessels (Steen et al., 2022). For example, the first hydrogen-powered ferry to be launched in Norway will rely on liquefied hydrogen transported from Germany, as it is simply meaningless to produce hydrogen locally before a market exists. Increasing hydrogen distribution and storage infrastructure may encourage shipping companies to invest in hydrogen-powered ships, which in turn may encourage more investments in bunkering infrastructure (Steen et al., 2022). This is also applicable for terminals within ports, if the supply of hydrogen is lacking and bunkering facilities, there is no need to buy hydrogen-powered equipment (Densberger & Bachkar, 2022).

According to Hyde & Ellis (2019) the bunkering options depend on the storage methods, such as gas, liquid, metal, and LOHC. For hydrogen in gas form, the flow rate is needed to be monitored to avert adiabatic heating. Either pressure balancing or compressing gas onto the ship are two alternatives for gas hydrogen to be bunkered onto the vessel. For the first gas alternative, if the gas stored at the port is at a higher pressure than the vessel a valve should be opened allowing the fuel to flow from port to vessel by its own pressure. This technique requires a large storage capacity at the port, as when the pressure drops under the vessel's pressure area the bunkering method is unable to fill up the rest of the vessel's storage. Therefore, using the cascade method, where several smaller tanks or storages with higher pressure are used for bunkering solves this problem. Furthermore, the benefit of using the pressure balancing approach is that it does not require any compressors.

The second method for hydrogen is compressing the gas into the vessel. In this approach, a throughput compressor is used for moving the fuel from the port to the vessel tank (Hyde & Ellis, 2019). As a compressor is used the hydrogen at port is not required to be pressurized at the same amount as the method before, only to a lower degree. This method allows the hydrogen flow to be controlled and monitored carefully. The downside is that it requires expensive equipment to work.

Since, liquid hydrogen requires regulations of the temperature, cryogenic pumps are used when transferring to a vessel (Ustolin et al., 2022; Hyde & Ellis, 2019). The same technique is used when bunkering LNG, therefore the approach is relatively understood. For metal hydrides, the approach would be to store compressed hydrogen at the port and transfer it to the vessel using one of the mentioned methods for gaseous hydrogen. Thereafter, heat extraction is required from the place of storage. This is to allow the hydrogen to enter the metal matrix. The last method that Hyde & Ellis (2019) mentions is the usage of LOHC. Storage happens in port, happens on the docks, and is transferred through pumps. Furthermore, de-hydrogenated oil from the vessel is stored at the port after removal.

4.1.2 Methanol

Methanol is a well-established alternative fuel, as it has a widespread distribution and storage capability and existing port infrastructure supporting methanol-powered vessels (Kajaste-Rudnitskaja et al., 2018). For example, Stena Line's vessel Stena Germanica, the first commercialized dual-fuel methanol and diesel-powered ferry in operation (Christodoulou & Cullinane, 2021; Kamaljit, 2016). There are no major technical challenges with producing and distributing methanol (Svanberg et al., 2018). Thus, making it a viable AF for the maritime sector. Additionally, there are no substantial issues within the supply chain to supply methanol as fuel for shipping. A major techno-economic benefit is that methanol is liquid at room temperature with a higher density than other analyzed AF. Resulting in easier handling and storage as well as cheaper transportation costs than liquid hydrogen and ammonia and LNG (Brynolf et al., 2014; Al-Breiki & Bicer, 2020).

The current infrastructure used for traditional fuels can easily be modified to be compatible with methanol (IRENA & Methanol Institute, 2021; Svanberg et al., 2018). Most techno-economic challenges are attributed to its chemical properties, such as the low flash point, its toxicity to humans, fire and explosion hazards (IRENA & Methanol Institute, 2021; Svanberg et al., 2018; Paris MoU, 2022). Other challenges can be connected to methanol's lower energy density compared to fossil fuels (diesel, gasoline, and LNG) as well as its lower boiling point (Brynolf et al, 2014; IRENA & Methanol Institute, 2021; Svanberg et al., 2018). This means specialized storage methods are still required for methanol (Svanberg et al., 2018). The identified main challenges with methanol are summarized in the Table below.

Table 10.
Techno-economic challenges with methanol

Challenges with methanol		
Categorisation area	**Technical**	**Economical**
Storage	● Low flash point and toxic (IRENA & Methanol Institute, 2021; Svanberg et al., 2018) ● Tanks require extra “dead” space for thermal expansion as methanol has the ability to absorb moisture from the atmosphere (IRENA & Methanol Institute, 2021) ● Fire & explosion hazards. Explosion-proof, EX-classed equipment required (Paris MoU, 2022)	● Liquid storage preferred due to cost reasons (IRENA & Methanol Institute, 2021)
Transport & distribution	● No major technical challenges with distribution and production (Svanberg et al., 2018)	● Cost of transporting methanol is 0,68USD/GJ, which is cheaper than liquefied- hydrogen, ammonia and LNG (Al-Breiki & Bicer, 2020)
Bunkering	● Lower energy density compared to diesel, gasoline and LNG (IRENA & Methanol Institute, 2021; Svanberg et al., 2018; Brynolf et al., 2014)	● Less revamp needed to be compatible with existing port infrastructure compared to the other two AF (IRENA & Methanol Institute, 2021; Svanberg et al., 2018)

4.1.2.1 Storage

Despite being easier and more economically feasible to store and distribute than hydrogen and ammonia, methanol still has techno-economic challenges regarding storage, such as specialized storage methods (Svanberg et al., 2018; Paris MoU, 2022). Minimum requirements for storing methanol have been identified by Paris MoU (2022) referencing the IGF code. For example, with fire safety in consideration, explosion-proof, EX-classed equipment must be used. Additionally, methanol vapor detection as well as liquid leak detection must be used in case of leaks as it can cause asphyxiation in cramped areas. In addition, methanol is highly toxic, resulting in exposure via inhalation, skin, and eye contact, or ingestion can be fatal and cause blindness (IRENA & Methanol Institute, 2021).

Methanol has a lower volumetric energy density in comparison to other traditional liquid fuels (Brynolf et al., 2014). For example, it has about half the volumetric energy density of diesel and gasoline. It also has a lower energy density than LNG. This means more methanol must be stored and delivered to provide the same amount of energy (IRENA & Methanol Institute, 2021; Svanberg et al., 2018). When compared to ammonia and hydrogen, methanol has a moderate amount of energy density as seen in Table 2. This means methanol shares the same energy density disadvantages as the other two AFs. Furthermore, the tanks carrying methanol need to be 2,5 times larger than oil tanks due to density and lower heating value when comparing the same energy value (DNV GL, 2018). This combined with the special requirements in accordance with the IGF code indicates storing and distributing methanol have higher Capex and Opex costs than traditional fuels (Svanberg et al., 2018). Moreover, methanol should be kept in sealed tanks with extra room for thermal expansion as methanol has the ability to absorb moisture from the atmosphere (IRENA & Methanol Institute, 2021).

Considering storage, methanol is less complicated and costly compared to LNG, ammonia, and hydrogen, due to methanol being liquid at room temperature (Panić et al., 2022). According to IRENA & Methanol Institute (2021), liquid storage is preferred over gaseous as this would make the transition from liquid fossil-based fuels easier and less costly. Due to being liquid at atmospheric pressure methanol can be stored in a similar way to traditional bunker fuel, therefore it can be stored in all sizes of storage units (Aakko-Saksa et al., 2018). Furthermore, existing port infrastructure for traditional fuels, such as gasoline tanks, requires only slight modifications to be compatible with methanol (IRENA & Methanol Institute, 2021; Svanberg et al., 2018). A gasoline tank can be converted to be compatible with methanol by adding an internal coating to the existing tank. Tank connections will also need to be updated, and the tank will also need a nitrogen inertization system and new tank ventilation (Ellis & Bomansson, 2018). Transitioning existing infrastructure to be fit for methanol storage and distribution is therefore a significantly lesser economic and technical barrier compared to the other two AFs and LNG. For example, the capital costs of LNG tankers are estimated to be 40% higher than methanol (Al-Breiki & Bicer, 2020).

4.1.2.2 Transportation and distribution

There are currently 12 vessels operating on methanol internationally. The shipping company, Maersk, is also planning to have 8 container ships running on methanol

(Gore et al., 2022). Major ports such as Rotterdam and Antwerp already have well-established infrastructure for the storage and distribution of methanol as a chemical (Svanberg et al., 2018). Furthermore, methanol is easily made compatible with existing distribution and storage infrastructure and can be blended with traditional fuels leading to lower capital costs (IRENA & Methanol Institute, 2021). In total, over 100 ports have methanol available for distribution. Due to its similar characteristics to traditional fuels, methanol is rather uncomplicated to transport and distribute via maritime vessels, trucks, and rails. Just like oil and its byproducts, methanol may also be distributed through pipelines. The methanol transportation cost from Qatar to Japan by ocean vessel was estimated to be the lowest when compared to LNG, ammonia, and liquified hydrogen at 0,68 USD/GJ/12 000 km, as seen in Table 8 (Al-Breiki & Bicer, 2020). The highest value transportation costs of methanol via ocean vessels inquired from the literature were based on estimations of Cui & Aziz (2023). And were approximately 0,94 USD/GJ/10 000 km, significantly cheaper than both ammonia and hydrogen. A complete comparison of the transport costs of the various transport modes can be seen in Figures 5, 6 & 7.

The major technical and economic benefits of methanol can be attributed to its high volumetric density, which means more methanol can be stored in the same size tanker for transportation, compared to the other analyzed fuels (Aziz & Nandiyanto, 2020). Finally, the low BOG costs due to methanol being a liquid at ambient temperatures (Al-Breiki & Bicer, 2020). According to Aakko-Saksa et al. (2018) and Cazzola et al. (2013), the overall transport cost of methanol is comparable with ethanol. Overall, low-energy-density liquid fuels such as methanol are more expensive to transport than oil and diesel which have higher energy densities (Cazzola et al., 2013).

4.1.2.3 Bunkering

Methanol as a fuel is becoming more and more popular in the shipping industry. As an AF, methanol currently accounts for around 31% of the total methanol demand (IRENA & Methanol Institute, 2021). Gothenburg port currently offers one of the only available methanol bunkering facilities to vessels. The bunkering facility is responsible for bunkering the Stena Germanica vessel, which operates between Gothenburg and Kiel (Christodoulou & Cullinane, 2021; Ellis & Tanneberger, 2015; Kamaljit, 2016). The primary reasons Stena chose methanol over LNG other than environmental & sustainability aspects, were due to the availability of methanol supply in Sweden as well as the cost benefits. For example, the cost of revamping the engine for methanol has been noted as cheaper than that of converting to an LNG engine (IRENA & Methanol Institute, 2021; Kamaljit, 2016).

Bunkering of methanol in Gothenburg is done from the quayside using a specially designed pump station that was anticipated to cost 400 000 EUR (Ellis & Tanneberger, 2015; Evergren et al., 2017). In comparison, a LNG terminal would cost 50 million EUR (Evergren et al., 2017). There are also methods such as truck-to-ship bunkering. Whereas, methanol is directly delivered by trucks and pumped on board using quay pumps. The connection to the ship is made using no spill breakaway coupling (Ellis & Tanneberger, 2015). With truck-to-ship bunkering fewer initial investments and no fixed storage units are needed. Another option is using a bunker vessel to refuel the methanol vessels (DNV GL, 2018).

4.1.3 Ammonia

The main techno-economic challenge to the adoption of ammonia as a fuel can be attributed to the risk of SCC destroying the infrastructure, leading to energy loss, economic loss, and potential leakage. Furthermore, ammonia's hazardous and toxic traits require specialized handling and proper safety measures (IGC code, 2014; Salmon et al., 2021). Safely storing and handling ammonia have been well defined by regulations such as the IGC code (IGC code, 2014). But as ammonia production is estimated to quadruple by 2050 careful planning and considerations have to be made (IRENA & AEA, 2022; Saygin et al., 2023). Especially when ammonia is expected to be utilized as an alternative fuel in the shipping industry and new infrastructure solutions are needed to accommodate increased demand. If SCC precautions are not followed, material or mechanical malfunction due to corrosion can lead to leakage during bunkering. The leakage could in turn cause major hazards (Trivyza et al., 2021). These required special measures imply higher costs (Elishav et al., 2021; IGC code, 2014). Despite being a rather well-established commodity, major replacements or modifications of existing port infrastructure have to be made to accommodate for these hazards (Elishav et al., 2021; Salmon et al., 2021; Trivyza et al., 2021).

Other challenges are linked to ammonia being gaseous in ambient temperature complicating the storage and distribution process. The storage capacity for pressurized ammonia is significantly lower than for liquid ammonia. On the other hand, liquid ammonia storage has higher Opex costs and BOG costs (Al-Breiki & Bicer, 2020; Nayak-Luke et al., 2021). Other techno-economic challenges include the relatively low-density liquid ammonia has, 600 kg/m^3, and a higher cost of transportation compared to methanol. For example, marine vessel transportation of liquid ammonia distribution was estimated to be 1,09 USD/GJ/12 000 km as seen in Table 8 (Al-Breiki & Bicer, 2020). Transportation via pipelines is also deemed to be challenging due to the specialized handling and safety requirements in terms of modifying existing infrastructure (IGC code, 2014; Salmon et al., 2021). The main challenges can be seen in the Tables below.

Table 11.
Techno-economic challenges with pressurized ammonia

Challenges with pressurized ammonia		
Categorisation area	**Technical**	**Economical**
Storage	● Less storage capacity for pressurized ammonia. 1 ton of steel can only store 2,8 tons of ammonia, compared to 1 ton of steel storing up to 45 tons of liquefied ammonia (Nayak-Luke et al., 2021)	● Higher Capex than methanol and conventional fuel systems due to larger storage facilities required at port (Gerlitz et al., 2022) ● The Capex for pressurized tanks is 3 USD/kg compared to 0,81 USD/kg for refrigerated ammonia tanks (Nayak-Luke et al., 2021)
Transport & distribution	● Special measures required for corrosion (Elishav et al., 2021; IGC code, 2014) ● Safety concerns due to toxicness (Trivyza et al., 2021)	● High Capex to revamp existing infrastructure (Ejder & Arslanoğlu, 2022) ● Leakage can cause major hazards, fatalities and economical damage (Trivyza et al., 2021)
Bunkering	● No existing ammonia bunkering terminals at ports (Gerliz et al., 2022; IRENA, 2022)	● High Capex cost for bunkering instructure, but cheaper than hydrogen (Gerliz et al., 2022) ● Bunkering cost for ammonia would be insignificant in comparison with production and electric generation, while transportation would equal to 5% of the costs (Wang et al., 2022)

Table 12.
Techno-economic challenges with liquid ammonia

Challenges with liquid ammonia		
Categorisation area	**Technical**	**Economical**
Storage	● Lower density 600 kg/m^3 (but higher than liquid hydrogen) requires larger storage facilities at port (Aziz & Nandiyanto, 2020; Gerlitz et al., 2022) ● Maintaining -33℃ requires insulated tanks (Nayak-Luke et al., 2021)	● Higher Capex due to larger storage storage facilities required at port (Gerlitz et al., 2022) ● Higher cost to maintain -33℃ (Nayak-Luke et al., 2021) ● Higher cost due to special measures required (Elishav et al., 2021; IGC code, 2014) ● Cost of transporting liquid ammonia more expensive than methanol but cheaper than liquid hydrogen (Al-Breiki & Bicer, 2020) ● Energy loss cost from BOG when stored in liquid state, 4,5 million USD (Al-Breiki & Bicer, 2020)
Transport & distribution	● Safety concerns due to toxicness (Trivyza et al., 2021) ● Special measures required for corrosion (Elishav et al., 2021; IGC code, 2014)	● High Capex to revamp existing infrastructure (Ejder & Arslanoğlu, 2022) ● Leakage can cause major hazards, fatalities and economical damage (Trivyza et al., 2021)
Bunkering	● No existing ammonia bunkering terminals at ports (Gerliz et al., 2022; IRENA, 2022).	● Bunkering cost for ammonia would be insignificant in comparison with production and electric generation, while transportation would equal to 5% of the costs (Wang et al., 2022)

4.1.3.1 Storage

Storage of ammonia presents notable challenges mainly due to its corrosiveness, toxicity, low energy density, and BOG energy loss (Al-Breiki & Bicer, 2020; IGC code, 2014; Salmon et al., 2021). Similar to the other AF, liquid ammonia also has a relatively low density, 600 kg/m^3 (Aziz & Nandiyanto, 2020). It is higher than liquid hydrogen but lower than methanol. A lower energy fuel requires larger storage facilities and higher Capex costs in the port (Aziz & Nandiyanto, 2020; Gerlitz et al., 2022). As seen in Table 8, a ship with a 160 000 m^3 capacity can only store 109 248 MT of ammonia while the same ship would be capable of storing, e.g., 128 800 MT of methanol (Al-Breiki & Bicer, 2020).

The special requirements for anhydrous ammonia found in the IGC code, Chapter 17.2.1, in Table 4, states that any type of storage method of ammonia must be built with proper materials and have a corrosion-resistant covering (IGC code, 2014). There are only a few materials that are resistant to SCC. Amongst resistant materials are high-strength alloys with high concentrations of nickel or chromium (Elishav et al., 2021). Applying special metal oxide coatings on the internal surfaces of tanks is an additional precaution required to decrease the risk of SCC (Elishav et al., 2021; IGC code, 2014). In order to mitigate the risks of SCC, a combination of highly resistant metal alloys and reinforcing the welding filler materials and welding process selection should be considered (Elishav et al., 2021; Trivyza et al., 2021). Other special requirements mentioned in Chapter 17.12.2 is that the storage tank should be made of fine-grained steel with specific pressure levels: a minimum yield strength (tensile stress) not exceeding 355 N/mm^2 and with an actual yield strength not exceeding 440 N/mm^2. It is also advised to keep dissolved oxygen levels below 2,5 ppm according to Chapter 17.12.8 (IGC code, 2014).

The preferred storing methods depend on the amount. The Capex for pressurized tanks is estimated to be approximately 3 USD/kg ammonia based on 2019 values (Nayak-Luke et al., 2021). The Opex for the pressurized storage method is low, after the ammonia has been pressurized into a liquid, no other energy costs are applied. For refrigerated liquid ammonia tanks, a significant reduction in steel can be made, only one ton of steel per 41-45 tons of stored ammonia is required versus one ton of steel per 2.8 tons of ammonia (Nayak-Luke et al., 2021). The Capex costs are also considerably lower compared to pressurized tanks, a 25 000 ton refrigerated tank would cost approximately 0.81 USD/kg ammonia stored, or 26.1 million USD based on 2019 values (Nayak-Luke et al., 2021). Although, the annual Opex is significantly higher due to the constant need to maintain low temperatures and is estimated to be approximately 14% of the total Capex (Nayak-Luke et al., 2021).

Compared to hydrogen and LNG less energy is required to liquify ammonia. In addition, smaller tanks are needed for ammonia than for hydrogen due to the higher density (Al-Breiki & Bicer, 2020; Hansson et al., 2020; Hoang et al., 2022; Gerlitz et al., 2022). As a result, the Capex of LNG tankers is estimated to be 15% higher than ammonia tankers (Al-Breiki & Bicer, 2020). Additionally, ammonia has a rather well-developed infrastructure that makes handling and storage of ammonia considerably easier compared to hydrogen (Hoang et al., 2022; Pawar et al., 2021). However, studies from German ports show that the storage facilities, infrastructure, and transportation between ports for ammonia are more than double the cost of LNG. The biggest factor in this is the difference in energy densities. One ton of LNG equals

2,68 tons of ammonia in terms of energy density (Gerlitz et al., 2022; Prause et al., 2022). This requires larger storage facilities at both port and for distribution terminals (Gerlitz et al., 2022; Prause et al., 2022).

4.1.3.2 Transportation and distribution

Transitioning to a future with ammonia as a marine fuel will depend on its availability, the effective implementation of ammonia infrastructure in ports, and existing networks of supply and distribution (Salmon et al., 2021). Prause et al. (2022) evaluated the economical feasibility of distributing ammonia between marine vessels, trucks, and multimodal transportation modes based on the costs, time, and CO_2 emissions. The study looked at an ammonia distribution terminal in Germany, Brunsbüttel, located outside Hamburg. The terminal is responsible for the distribution of ammonia and LNG to other German ports and industrial customers. To properly assess the economic effects of ammonia it was assumed that the demand for LNG was fully replaced by ammonia as a maritime fuel, with the chemical and physical characteristics differences between NH_3 and LNG such as the capacity and storage differences taken into account when calculating the distribution costs (Prause et al, 2022). Comparing only the annual distribution costs (including all transport and operational costs) between the three models reveals that the following order, marine vessels, multimodal, and finally trucks, were respectively the most cost-effective and had the least emissions.

Ammonia production and distribution facilities are likely to be situated in remote areas, such as Brunsbüttel being located outside Hamburg. Marine transportation of ammonia is therefore an important mode of transport. Medium-sized gas carriers (up to 23 000 ton capacity) and large-sized gas carriers (up to 40 200 ton capacity) are currently the most common vessels used to carry ammonia offshore. Very large gas carriers are also capable of transporting ammonia even longer distances but are not used due to the lack of demand for such amounts of ammonia and the lack of port infrastructure (Nayak-Luke et al., 2021). A primary cost driver for distributing ammonia discussed by Prause et al. (2022) is the storage costs during distribution. The storage cost is especially high for vessel distribution due to the slower transport time of tanker vessels. Prause et al. (2022) estimated that the vessel's full round trip to all German ports would take 4 days, including loading and unloading. Hence a 4-day buffer of ammonia must be stored in the port to meet this demand, while trucks would only need 1 day to reach every port. The ammonia transportation cost from Qatar to Japan by marine vessel was estimated to be 1,09 USD/GJ/12 000 km as seen in Table 8. A separate study by Cui & Aziz (2023) estimated the ocean vessel transport cost to be 3,33 USD/GJ/10 000 km. Overall, transport costs are higher than LNG and methanol but still significantly cheaper than liquified hydrogen (Al-Breiki & Bicer., 2020; Cui & Aziz., 2023).

Trucks are the most flexible distribution method for ammonia and are typically employed for distribution to the end customers at the retail level (Elishav et al., 2021). However, distribution costs are more expensive and emissions higher compared to other options (Nayak-Luke et al., 2021; Prause et al., 2022). Trucks equipped with standard ISO T50 pressurized tanks have a maximum capacity of about 36 tons with a maximum range of 770 km, and the estimated Opex for the transportation of ammonia with trucks is 0,21 USD/t/km (Nayak-Luke et al., 2021).

Ammonia distribution in chemical rail tanks is significantly more cost-efficient than trucks and offers excellent fuel efficiency at 0,03 USD/t/km. A chemical train can typically carry between 50 and 150 tanks of which each tank has a maximum capacity of 110 tons. The inflexibility of trains is usually not an issue since most large ports have the necessary infrastructure and are well connected with rails (Nayak-Luke et al., 2021).

Distribution via pipelines is another viable option according to Salmon et al. (2021). Pipelines are regarded as a safe and efficient method for distribution. However, there are several challenges associated with distributing ammonia via pipelines. Ammonia has specialized handling and safety requirements (IGC code, 2014; Salmon et al., 2021). These technical challenges lead to economic challenges as it raises the cost of building new ammonia-based pipelines as well as retrofitting existing infrastructure. Furthermore, ammonia is a gas at ambient temperatures, and pipelines are designed to transport liquids. Ammonia needs to be liquefied in order to be carried through pipelines which are time-consuming and add more to the cost. The pressure required to transport ammonia via a pipeline must be carefully maintained to avoid leaking or other safety issues (Nayak-Luke et al., 2021; Salmon et al., 2021).

The cost of using pipelines is found to scale with the increased size of the pipe. Larger flow rates greater than one million tons per year would drop the ammonia pipeline cost to approximately 1% of the total delivered cost of ammonia (Salmon et al., 2021). The majority of the cost is however Capex from materials and construction from establishing the pipeline. Factors such as flow rate, diameter and distance of the pipeline, temperature, and elevation fluctuations affect the Capex. A 25,4 cm diameter pipeline made of carbon steel would in 2019 cost around 1 469 000 USD/km in urban areas and 857 000 USD/km in rural areas. The costs of pump booster stations also have to be considered for longer-distance pipelines (Nayak-Luke et al., 2021). The placement of pump stations depends on elevation levels, flow rate, etc, but placing pump stations every 128 km is generally sufficient to maintain the necessary flow rate. The Capex for a 600 kW boosting station with two pumps costs roughly 1 220 000 USD based on 2019 values. The Opex of such a boosting station would be 408 000 USD/year, assuming the stations are operational for 8 500 hours per year and electricity costs of 0.08 USD/kWh (Nayak-Luke et al., 2021). Table 13 showcases calculations of the estimated Capex of a 3 000 km and a 1 500 km pipeline. The calculation assumes that 75% of the pipeline is built in rural areas and 25% in urban areas.

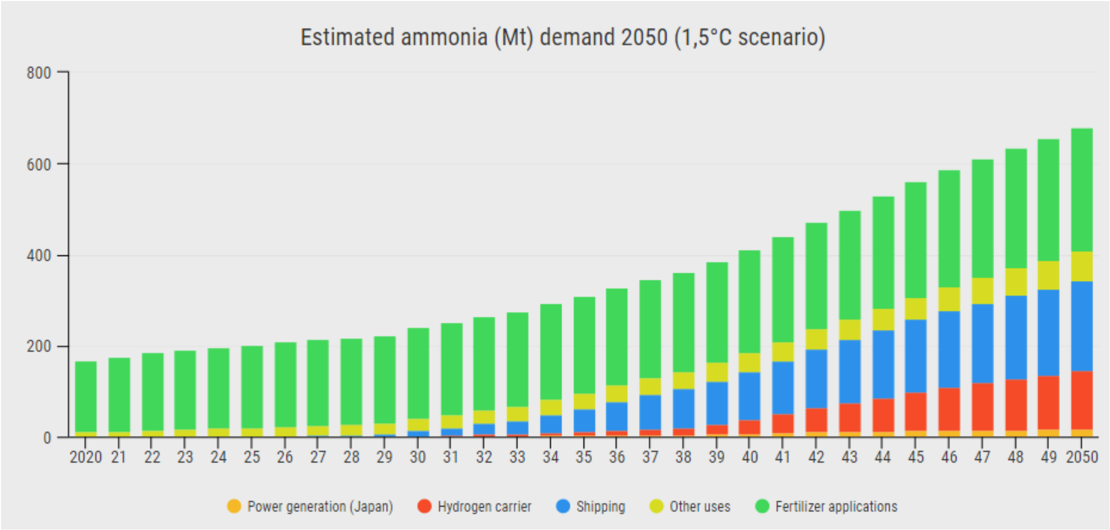
Table 13.
Pipeline Capex costs (Adapted and modified from Nayak-Luke et al., 2021)

Pipeline length (km)	Pipeline Capex (75% Rural, 25% urban)	Boosting stations Capex	Total
3000	$3 030 000 000	$28 593 750	$3 058 593 750
1500	$1 515 000 000	$14 296 875	$1 529 296 875

IRENA & AEA (2022) estimates the projected global demand for ammonia will increase by 20% by 2030 and compared to 2020 levels, 3-4 times to 550 - 665 MT by 2050 as seen in Figure 5. More than half of the ammonia demand in 2050 will come from new uses in the energy sector (IRENA & AEA, 2022; Saygin et al., 2023). Pipelines are suitable for larger volumes of ammonia over longer distances and are advantageous for intercontinental transport. But if there is a lack of demand for larger volumes, transporting via pipelines is deemed to be an economically inferior distribution method (Saygin et al., 2023). The US is the largest ammonia importer in the world with about 4 million tons imported per year (Elishav et al., 2021). Of the ammonia delivered in the US, 43% was transported via rail, 26% by marine vessels, 20% by pipeline, and 11% by trucks and vehicles. Ammonia transported by rail and maritime vessels typically covered far greater distances than trucks and pipelines (Elishav et al., 2021).

Figure 5.

Estimated ammonia demand up to 2050 (Adapted and modified from IRENA & AEA 2022; Saygin et al. 2023).



Note. The figure shows the estimated demand for ammonia up to 2050 categorized in different usage areas, such as power generation, hydrogen carrier, shipping, other uses, and fertilizer applications.

4.1.3.3 Bunkering

The main techno-economic challenges related to the bunkering of ammonia can mostly be attributed to the economic feasibility of adopting an ammonia economy. For example, the Capex and Opex required are significantly higher for ammonia-powered ICE vessels in comparison to conventional fuel engines. Ejder and Arslanoğlu (2022) concluded in a Monte-Carlo simulation the economic viability of a conventional fuel bulk carrier compared to a revamped conventional ICE bulk carrier powered on ammonia. The initial Capex costs (including revamp of the engine and tanks but excluding drydock costs) were estimated to be 71% higher. The average Opex over the estimated lifespan of the ships (23 years) was also significantly higher. According to Laursen et al. (2022) ammonia-fueled vessels' total cost of ownership might be 3 - 3,5 times that of a conventional-fueled vessel between 2030 - 2050. These economic barriers are contributing to the fact that no actual commercial ammonia-powered propulsion vessels are in operation yet. Over 120 to 130 ports already produce, store, and distribute ammonia as a commodity, but none of them are used as bunkering terminals (Gerliz et al., 2022; IRENA, 2022). Implementation of well-established bunkering facilities in ports that supply ammonia as fuel for marine operations will be needed for the transition to ammonia as a future marine alternative fuel option (Hansson et al., 2020). Moreover, due to the existing infrastructure supporting ammonia, the establishment of a bunkering structure will be easier and require less investment than hydrogen (Gerliz et al., 2022).

Another challenge with bunkering ammonia is the risk of spills and leakages (Trivyza et al., 2021). The leakage could in turn cause major hazards, such as damage to local areas and the environment, crew and cargo injuries, and potential fire. There have even been several occasions where accidents have led to fatalities (Trivyza et al., 2021). Therefore it is critical to implement and evaluate safety measures for the personnel on board. Proactive safety measures such as suitable material for NH^3 and other safety measures are mentioned in Table 4. A combination of other proactive precautions such as drip trays during bunkering/handling or placing the bunkering station in a remote and secure area and allowing the crew to monitor the operation remotely. Other safety measures are ammonia detection and alarm systems, airlocks, and outlets for the leaked ammonia to escape. Finally, the crew should be equipped with protective gear to minimize the risk of potential exposure (Trivyza et al., 2021).

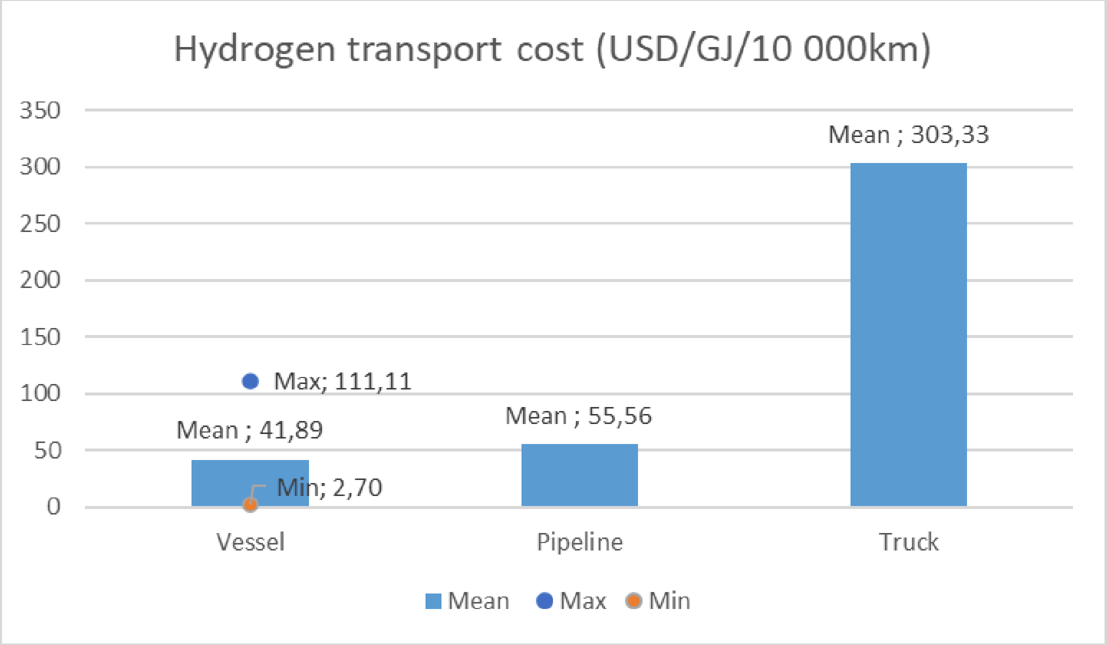
Wang et al. (2022) show a case where 100% of the fuel demand is met with green ammonia and the cost percentages that would occur. In total transportation cost is approximately 5% and infrastructure and bunkering facilities would be insignificant when compared to other categories, such as production and electricity generation which total 95% together. The reason for the insignificant cost of bunkering is that in most ports the infrastructure only needs retrofitting. Furthermore, the cost for 100% of the demand would approximately be 40 billion USD per year. This estimation is based on a specific layout of ports, wind farms, plants, and for 28 major transport routes, which results in 23% of the ocean bound volume.

4.2 Transport cost comparison

Figure 5-7 compiles the cost of transporting alternative fuel using transportation modes as rail, truck, pipeline, and vessel. The data is from several studies included in this literature review. Furthermore, Figures 5-7 include the minimum, maximum, and mean values from the studies, meaning that the bar indicates the average, while dots are the max and min values. The Y-axis indicates the various modes of transportation, while the X-axis represents the transportation cost in USD/GJ/10,000 km for respective AF. Furthermore, 10 000 km is used as a metric solely to make the costs presentable with fewer decimals. As 10 000 km is otherwise an unrealistic distance for some of the transportation modes. By visualizing the transport costs in Figure 5-7, it becomes evident how the costs of AF transportation vary between modalities. The most cost-effective hydrogen transportation mode appears to be the pipeline (no data points for rail available). While the most cost-effective mode of transport for ammonia and methanol is marine vessels followed by pipelines, railways, and trucks.

Figure 5.

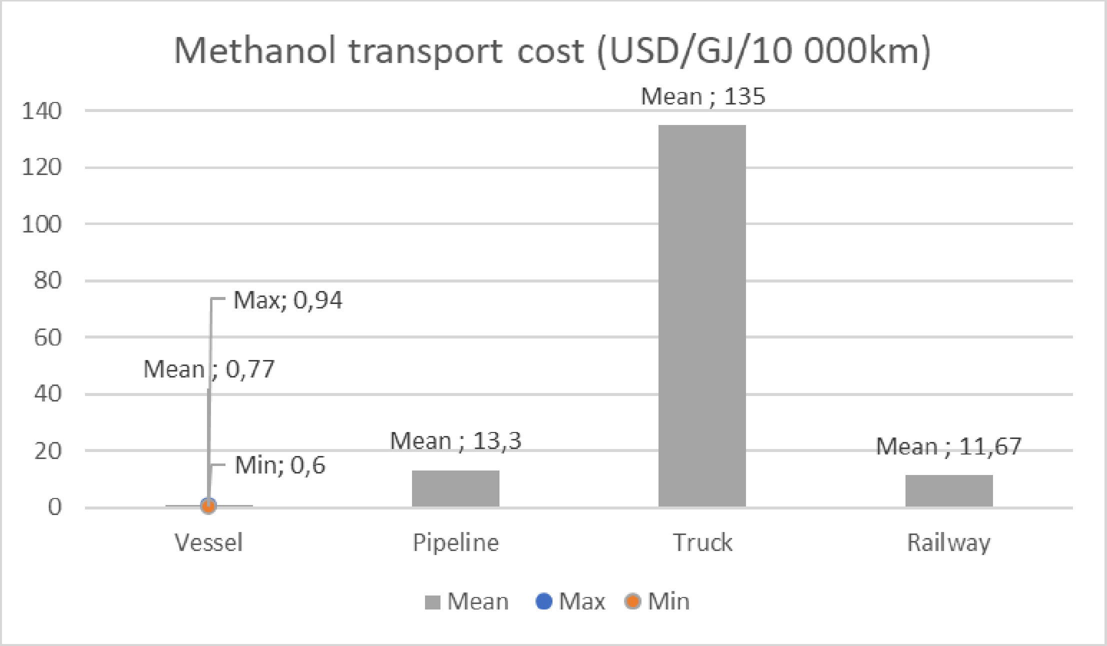
Hydrogen transport cost measured in USD/GJ/10 000 km (Al-Breiki & Bicer, 2020; Wang et al., 2021; IEA, 2019)



Note. There were no available data points for hydrogen rail transportation costs, hence it was excluded. Furthermore, there is only one available data point for the cost of truck and pipeline transports, resulting in no maximum and minimum value being given. The state of hydrogen is liquid at ocean vessel transport and compressed when transported by pipeline and truck.

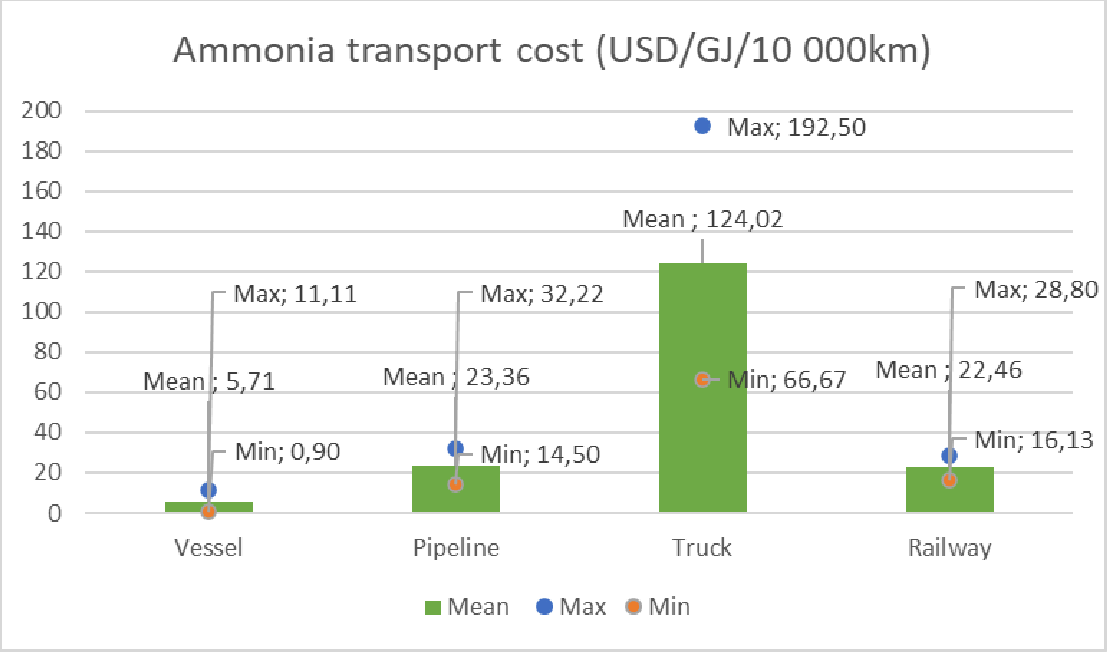
Figure 6.

Methanol transport cost measured in USD/GJ/10 000 km (Cui & Aziz, 2023; Al-Breiki & Bicer, 2020)



Note. There is only one available data point for the cost of rail, truck, and pipeline transport costs. Therefore, does the figure not include the minimum and maximum for rail and truck costs.

Figure 7.
Ammonia transport cost measured in USD/GJ/10 000 km (Cui & Aziz, 2023; Al-Breiki & Bicer, 2020; Wang et al., 2021; IEA, 2019; Nayak-Luke et al., 2021)



5 Discussion

5.1 Common Challenges

Hydrogen is a promising alternative fuel for the future. However, in terms of cost and infrastructure, it is the most expensive of the three, requiring the most Capex in the development of new infrastructure. Ammonia is also Capex intensive. Despite having a higher energy density than hydrogen, the energy density of ammonia is still low compared to other AFs such as LNG and methanol. As 1 ton of LNG equals 2,68 tons of ammonia in terms of energy density (Gerlitz et al., 2022; Prause et al., 2022). Significantly larger storage facilities will therefore be required to accommodate the lesser energy density and storage capacity of ammonia. The bigger storage facilities required contribute to greater Capex costs in a similar manner as it does for hydrogen (Gerlitz et al., 2022). Ammonia storage facilities at ports and distribution terminals are estimated to be double the cost of LNG (Gerlitz et al., 2022; Prause et al., 2022). Methanol is the least Capex-intensive of the analyzed alternative fuels primarily attributed to its similarity to traditional fuels. It has a low flashpoint, and rather high energy density in comparison to the other AF and maybe most importantly, it is a liquid at ambient temperatures (IRENA & Methanol Institute, 2021; Svanberg et al., 2018; Brynolf et al., 2014). For these reasons, it is highly compatible with existing infrastructure, storage, transport, and bunkering.

Overall, hydrogen and ammonia face many of the same challenges. For example, leakage and BOG (Osman et al., 2021; Al-Breiki & Bicer, 2020). The energy loss cost from BOG is a major factor in the higher costs of transporting and storing liquid hydrogen and ammonia. is. As both hydrogen and ammonia tend to be stored in a liquid state when transported in larger volumes (Al-Breiki & Bicer., 2020). Methanol also suffers from BOG but it is substantially less than that of the hydrogen and ammonia. Table 8 showcases the costs of BOG of the same hypothetical ship carrying the same volume of Hydrogen, ammonia, methanol, and LNG. Hydrogen has the highest BOG costs at 12 times that of ammonia and over 80 times that of methanol BOG costs.

Moreover, compressed hydrogen has a density of 39 kg/m^3, and liquid hydrogen has a density equal to 70,8 kg/m^3 (Aziz & Nandiyanto, 2020; Davis et al., 2018; Nazir et al., 2020; Osman et al., 2021). Liquid ammonia has a density of 600 kg/m^3 (Aziz & Nandiyanto, 2020). Compared to LNG, liquid hydrogen needs a 2,8 times larger storage unit to store the same amount of energy (Panić et al., 2022). Liquid hydrogen also requires special equipment as cryogenic tanks to maintain the right conditions for storage (Panić et al., 2022; Deveci, 2018; Ustolin et al., 2022; Santos, 2022; Genovese & Fragiacomo, 2023; Mazloomi & Gomes, 2012). In terms of gravimetric energy density, hydrogen is richer, at 120 MJ/kg, compared to liquid ammonia at 18,6 MJ/kg and 20,1 MJ/kg for methanol (Aziz & Nandiyanto, 2020). This is related to the weight of the analyzed fuels, as hydrogen is one of the lightest elements, and the energy amount per kg is the highest of the three energy carriers. Methanol has a density of 792 kg/m, higher than both ammonia and hydrogen. Which leads to less expensive transportation and storage costs (Brynolf et al., 2014; Al-Breiki & Bicer, 2020). This is also seen in Figures 5, 6, and 7.

In terms of transportation and distribution of hydrogen and ammonia, the most feasible method depends on the volume transported and distance. In general, larger quantities of ammonia and hydrogen transported over longer distances favor liquidized ammonia and hydrogen. While methanol as a liquid in ambient temperature does not require compression or cooling and is in general significantly cheaper to transport. Figure 5-7 shows that it is significantly cheaper to transport ammonia than hydrogen via ocean-bound vessels, pipelines, and trucks. Ammonia is generally more expensive to transport than methanol with the exception of trucks. Transporting methanol via trucks is according to the single available data point 135 USD/GJ/10 000 km (Cui & Aziz, 2023). Which is slightly more costly than the mean ammonia transport cost of 124 USD/GJ/10 000 km (Cui & Aziz, 2023; Wang et al., 2021; IEA, 2019). However, the mean truck transportation costs of ammonia consists of three data points while methanol's truck transportation cost is only a single data point. One difference when comparing ammonia and hydrogen pipelines is the phases of the fuels, as compressed hydrogen uses compression stations and liquid ammonia uses pumping stations. Hydrogen pipelines would require compression stations to avoid energy losses (Saeedmanesh et al., 2018; IRENA, 2022). While ammonia pipelines require pumping stations**.** The Capex costs for ammonia pipelines were presented in Table 13, as 1 469 000 USD/km in urban areas and 857 000 USD/km in rural areas, with the additional pumping stations every 128 km costing 1 220 000 USD/station. However, no Capex costs for methanol or hydrogen pipelines were found to compare this data with.

5.2 Energy carrier-specific challenges

The emissions of hydrogen, methanol, and ammonia all differ. However, all of them are considered alternatives to conventional fuels due to their ability to impact the Paris Agreement's goal of limiting the temperature increase to 2℃ or ideally 1,5℃ (AbouSeada & Hatem, 2022). Hydrogen contains no carbon and therefore emits zero CO_2 (Hoang et al., 2022; Mazloomi & Gomes, 2012). Methanol contains carbon and emits CO_2 when combusted (DNV GL, 2018). Therefore, it cannot be considered a carbon-free fuel, but using methanol results in less harmful emissions compared to conventional fuels. Ammonia, just like hydrogen contains no carbon and therefore results in no CO_2 emissions (Reiter & Kong, 2011). From the information given hydrogen and ammonia are the best alternatives when considering the environmental impact of usage as a fuel. Since this thesis focuses on the techno-economic challenges and impact of the energy carriers, environmental effects are not taken into consideration.

5.2.1 Hydrogen

Many specific challenges with hydrogen are connected to storage. Hydrogen has a diverse range of alternatives for storage. From tanks to salt caves, oil & gas reservoirs, hydrocarbon reservoirs, water aquifers, metal hydrates, and clay with pores (Osman et al., 2021; Santos, 2022; Panić et al., 2022; Rangel et al., 2022; Amirante et al., 2017; IEA, 2019). Finding a safe and economically feasible way of storing hydrogen is difficult and most of the mentioned options are not even widely used. Salt caverns are used for natural gas storage, but are compatible with hydrogen as well (IEA, 2019). Tanks and salt caves are proven storage methods. Many of the options also depend on geographical locations, making it unsuitable for many ports without access to these locations. Metal hydrates and clay require additional material, occupy space, and could lead to increased weight. For the newer options, the cost has not been properly explored and therefore not concluded if it is feasible for commercialization.

Another notable challenge with storing hydrogen is that liquid hydrogen requires special equipment such as cryogenic tanks to maintain the right conditions (Panić et al., 2022; Deveci, 2018; Ustolin et al., 2022; Santos, 2022; Genovese & Fragiacomo, 2023; Mazloomi & Gomes, 2012). Liquid hydrogen is ten times more expensive to store than compressed (Deveci, 2018). On top of that, the process of transforming hydrogen to liquid hydrogen can lead to 35% energy losses (Panić et al., 2022; Santos, 2022). However, compressed hydrogen also suffers from 10 to 20% losses of energy at compression (Panić et al., 2022). Both main alternatives contain losses of energy, but liquid hydrogen is overall more expensive. As IRENA (2022) mentions that large investments are needed to make the liquid hydrogen value chain feasible. Furthermore, the cost needs to be weighed against other options such as storing and transporting hydrogen by using hydrogen carriers or using other alternative fuels. Alternatives include LOHC and ammonia.

Even though all of the mentioned AF have hazards and safety concerns, they all differ. Hydrogen's primary hazard is its flammability. Hydrogen fires can cause smoke asphyxiation. Safety issues related to the transportation and storage of hydrogen are such as explosions, fires, characteristics such as odorless and colorless, and the risk of embrittlement at high compression rates (Panić et al., 2022; Osman et al., 2021; Wang et al., 2023; Mazloomi & Gomes, 2012; Saeedmanesh et al., 2018; IRENA, 2022). These risks can be mitigated in some parts by storing hydrogen in hydrogen carriers, LOHC, and metal hydrates. Another related aspect to hydrogen being easily flammable is its low electro-conductivity meaning electrostatic charges can be generated resulting in sparks that ignite the hydrogen (Mazloomi & Gomes, 2012). Hydrogen is also easily ignited from external ignition sources. Another concern with hydrogen is the explosion risk. Hydrogen gas can form explosive mixtures with air, and if ignited, could result in an explosion. This can be avoided by properly maintaining the concentration of hydrogen in the air or by converting it to liquid form.

Another specific challenge with hydrogen is the lack of demand for hydrogen as an AF. Without demand for hydrogen ports and its stakeholders would not invest in establishing infrastructure capable of storing, transporting, and transferring hydrogen. Since there is little to no demand in most ports and terminals today there is no reason for constructing new facilities if they are not used (Steen et al., 2022). Resulting in the absence of bunkering facilities and small to no use of hydrogen, leading to higher costs related to the bunkering of hydrogen (Ustolin et al., 2022; Latapí et al., 2023). Bunkering infrastructure is vital for One area that needs regulations and increased structures is the bunkering of hydrogen (Halim et al., 2018; Ustolin et al., 2022; Tvedten & Bauer, 2022; Latapí et al., 2023). Nevertheless, the demand for hydrogen will most likely increase in the future due to laws, regulations, and initiatives. Since actors in the maritime field are needed to comply with laws and regulations to fulfill carbon neutrality, hydrogen is one option for alternative carbon-neutral fuel.

Additionally, there are different transport modes for hydrogen, such as tankers (truck, rail, vessel) and pipelines (Genovese & Fragiacomo, 2023; Freer et al., 2021; Buchenberg et al., 2023; Collis & Schomäcker, 2022). However, only a few are suited for either liquid or compressed hydrogen. For compressed hydrogen, the pipeline is the most economical option for long distances, however, the Capex is expensive.

Shipping is not an option, as compressed hydrogen is not transported on ocean vessels (Buchenberg et al., 2023; Collis & Schomäcker, 2022; Genovese & Fragiacomo, 2023; d'Amore-Domenech et al., 2023). Studies mention the option of using existing natural gas pipelines for hydrogen transportation, leading to decreased Capex (IRENA, 2022; Saeedmanesh et al., 2018; Ravi & Aziz, 2022). For this to be viable the demand and supply need to be even for hydrogen (Latapí et al., 2023). Moreover, the demand for natural gas needs to be reduced, while hydrogen demand is increased if the same pipelines are going to be used. However, the instances of compression stations needed to increase or else energy losses arise (Saeedmanesh et al., 2018; IRENA, 2022).

5.2.2 Ammonia

A unique techno-economic challenge to ammonia is its corrosiveness. To prevent corrosion, special procedures are necessary (Elishav et al., 2021; IGC code, 2014). Preventing leaks and equipment/infrastructural damage caused by SCC is a priority and is regulated under the IGC code (Ash & Scarbrough, 2019; IGC, 2014). The strict regulation of personal protection, materials of construction, and special requirements for SCC are technical barriers to adopting ammonia as an AF. Not following SCC precautions can lead to spills and leakages which are capable of causing major hazards (Trivyza et al., 2021). Although there are no available records on the additional costs, it is highly likely that the special procedures would also increase Capex and be an economical barrier. Compared to hydrogen, ammonia has a significantly more established infrastructure (Hoang et al., 2022; Pawar et al., 2021). There are however no existing bunkering facilities for ammonia.

5.2.3 Methanol

Methanol appears to be the energy carrier with overall the least techno-economic challenges. It is significantly cheaper and easier to transport than hydrogen and ammonia. Methanol's overall cheaper transportation costs can be attributed to being more compatible with existing infrastructure (IRENA & Methanol Institute, 2021; Svanberg et al., 2018). A barrier that can be mentioned even though out of this study's scope is that it is the only AF of the compared fuels that emit CO_2 . This could make methanol, despite its compatibility with existing infrastructure and its lower Capex, to be a less relevant AF for the long term.

5.4 Methodological discussion

For the method, the Scopus search term was used as the base for the thesis there are some imbalances in the number of sources. In the bullet list below the numbers of publications from the Scopus search divided into the relevant energy carriers are shown:

- Hydrogen: 30
- Methanol: 6
- Ammonia: 15

Based on the Scopus search terms hydrogen had the most documents and methanol the least. Simply put, more data on hydrogen and ammonia were at the time of writing available in comparison to methanol. The comparison analysis of this literature study can be deemed less reliable due to the disparity in the quantity of peer-reviewed references available for the three compared energy carriers. To gather more data on methanol, using different search strings and terms as well as different scholarly databases may have changed the skewed data imbalance of this thesis. Furthermore, a mixed approach, combining literature and interviews or surveys with relevant actors or stakeholders may also have positively contributed to this thesis and additional findings to the research questions. In the end, this literature study with this particular data collection method gives a decent overview on how far the research on the three energy carriers has progressed. Methanol having the least published articles is part of the results and could be an indication showing which energy carriers are more researched in the shipping sector. After all, methanol contains carbon and ammonia contains nitrogen. Whereas, hydrogen only emits water vapor and air and is the most environmentally friendly of the compared alternative fuels.

The chosen method is a literature review and it is based on the Scopus search term documents. The documents that were listed in Scopus were between the years 1978 to 2023. However, the oldest source used from the search term was from 2014. The older research in most cases was irrelevant, due to the constant new research and innovations. Furthermore, methanol was the only alternative fuel selected that has been successfully commercialized in the shipping industry. Even though methanol is the most established marine fuel of the three, it had the least documents. Ammonia and hydrogen differ from traditional fuels in all categories covered (storage, transport & distribution, and bunkering). Therefore, further innovation and research related to ammonia and hydrogen are required to improve the feasibility of the fuels.

This study's distance was set to 10 000 km in order to minimize decimals. As all the different documents use different cost frameworks. For example, a framework may contain only transportation costs, while another contains conversion costs, storage, and loading costs. As a result the sources that Figure 5-7 was based on used different units and metrics to measure transport costs. Therefore, conversion was needed to compare the data with each other. Furthermore, various articles included data relating to the transportation cost of alternative fuels but did not include distance or use of other factors making it not possible to convert. Thus, a comparison was not possible.

Another factor to account for is the distance used in the documents compared. The real cost cannot be calculated by dividing the distance and multiplying another distance. There are variables that change the cost other than distance. As an example, hydrogen pipelines need several compression stations to work efficiently. Another example is the number of vessels increasing with distance to fulfill the demand for the fuels. Furthermore, there are storage costs onboard the transportation device and BOG, and evaporation is also needed to be accounted for.

Other search terms could also be included, such as green ports and/or smart ports in a wider range. Furthermore, other steps in the chain could also be covered by including search terms such as production and extraction of the energy carriers. For methods that could be used instead of a literature review, could be a case study. The usage of a case study could lead to findings that are not included in the thesis, as information is taken from other parties than researchers that compose articles. Such as workers within the shipping industry at different positions and companies.

6 Conclusions

The maritime sector is currently relying on traditional fossil-based fuels, such as MGO and HFO. These fuels contribute to harmful emissions to humans and the environment, e.g., NO_x, SO_x, and CO_2. To combat the environmental impact IMO established goals for decreased emissions and less GHG emissions.

Among the three analyzed alternative fuels, hydrogen presents the greatest technological and economic challenges. Major challenges can be found in all investigated areas. It is challenging to store, transport, and distribute hydrogen due to its low density in both compressed and liquid forms. Although it requires adaptation to account for the special characteristics of hydrogen, using existing natural gas pipelines for hydrogen is a feasible option to lower Capex. Additionally, there are challenges connected to the bunkering of hydrogen, namely the lack of regulations and limited bunkering facilities available. The demand needs to increase before facilities and infrastructure should be constructed.

Methanol was the second alternative fuel investigated. Most techno-economic challenges in the storage of methanol are due to its chemical properties. Specialized storage methods are needed to safely store and transport methanol. However, a major benefit is that existing storage options of conventional fuels categorized under the IGF code can be used for methanol with little modification.

In terms of transportation, methanol can be transported via tankers and pipelines. There are no major challenges when considering transportation and distribution. Methanol is the least expensive option out of the analyzed alternative fuels. Infrastructure supporting methanol is well-established and there are commercialized vessels running on methanol, e.g., Stena Germanica. Therefore, the bunkering process is well-defined and established.

The final analyzed alternative fuel was ammonia. Ammonia shares several similar challenges with hydrogen. It is severely corrosive, hazardous, and toxic, requiring investments in safety and security. Based on the findings, ammonia is overall cheaper to transport than hydrogen in all transportation modes. Smaller tanks can be used for ammonia than for hydrogen. It was also found to be overall cheaper to transport than LNG. The transport costs of ammonia are however still expensive compared to methanol, excluding transportation with trucks. Furthermore, ammonia has advantages in terms of available existing infrastructure which could expedite the development of ammonia as a marine fuel. Despite the fact that several existing ports already produce, store, and transport ammonia as a commodity, none of them has functioning bunkering terminals.

In conclusion, the transport cost of all the energy carriers is compared. The comparison showed that hydrogen is the most expensive to transport overall, followed by ammonia and the least expensive to transport is methanol. Based on the findings of this report, methanol is more convenient and economically beneficial to adopt as alternative fuel compared to ammonia and hydrogen. However, the future focuses on energy carriers such as hydrogen and ammonia.

7 Recommendation for future work

This thesis focused on three categories connected to alternative fuels: storage, transportation & distribution, and bunkering. Additionally, there are other categories to analyze, such as production and consumption. Furthermore, there are also other alternatives to be considered, e.g., batteries and biofuels. In the future, an update can be relevant since a lot of data is based on assumptions.

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