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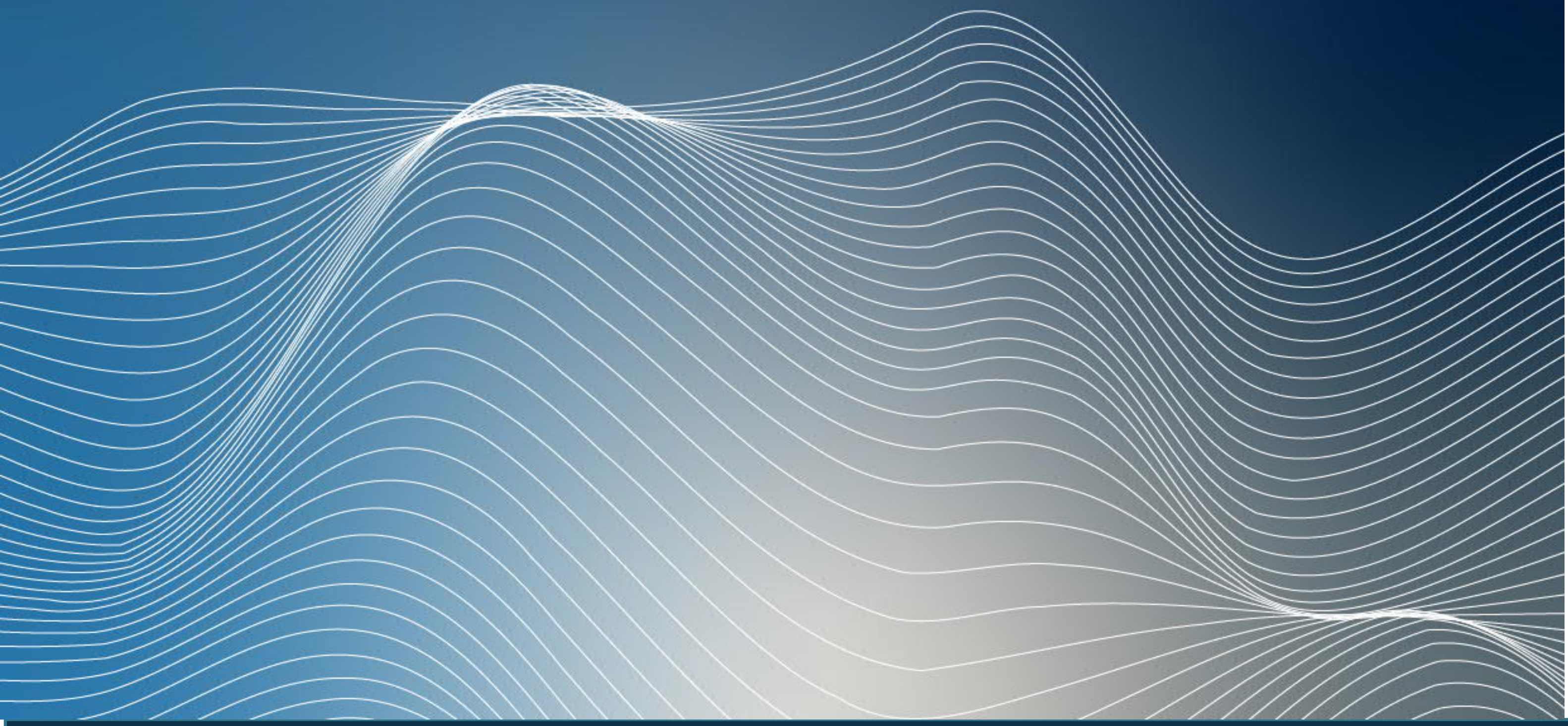
Deliverable D1.2.

Fuel evaluation report

D1.2.



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List of abbreviations

ABBREVIATION	DESCRIPTION
AER	Annual Efficiency Ratio
CCS	Carbon Capture and Storage
CH4	Methane
CH3OH	Methanol
CII	Carbon Intensity Indicator
CO	Carbon monoxid
CO2	Carbon dioxide
GDP	Gross Domestic Product
H2	Hydrogen
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
LOHC	Liquid Organic Hydrogen Carrier
LNG	Liqufied Natural Gas
NG	Natural Gas
NH3	Ammonia
NOx	Nitrogen oxides

SOx	Sulfur oxides
TRL	Technology Readiness Level

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1. Executive Summary

The maritime industry is undergoing a significant transition in fuel usage, moving away from oil-based fuels to adopt alternative options. These include hydrogen-based fuels such as ammonia and methanol, biofuels, and, in limited cases, electrification for short-range vessels. In this fuel evaluation report, different renewable fuels are discussed and evaluated regarding their level of maturity and usability for marine applications. The selected fuels for evaluation are hydrogen and ammonia as carbon-free fuels and methanol and methane as renewable and possibly CO_2-neutral fuels. The focus is always on renewable production based on green electricity and CO_2-neutral carbon sources. Other options like carbon capture and storage (CCS) or nuclear propulsion systems are not included.

The fuel choice depends on various factors, including availability, engine compatibility, environmental impact, and economic feasibility. Among these, the cost of production and the accessibility of renewable fuels are expected to play a decisive role in determining which technologies and fuels are adopted. All fuels besides liquified methane, which can be seen as a drop-in fuel for LNG, are quite different compared to today's marine fuels. Thus, they have other challenges regarding implementation on board and their application in the propulsion system. Furthermore, there are uncertainties regarding costs and regulations, why it isn't possible to identify one favourite fuel to date.

All renewable fuels will be costlier than fossil fuels. Based on the projected production costs, hydrogen and ammonia might be lower than methanol and methane in the future. That is why hydrogen and ammonia are considered promising long-term carbon-free solutions that meet the IMO's decarbonization objectives. However, they require substantial production, storage, and distribution infrastructure investment. Furthermore, they possess additional challenges with respect to safety. Methanol and methane, on the other hand, are more compatible with existing systems, making them practical for earlier adoption but still requiring improvements in renewable energy sourcing and biomass availability for sustainable production.

The energy density of the fuels affects onboard storage requirements. Depending on the size and type of the vessel and the fuel selected, it could impact cargo capacity and revenue. That might balance out the higher fuel costs for methane and methanol, as these fuels could benefit from their higher energy density. Furthermore, their specific challenges constrain the adoption of hydrogen and ammonia as marine fuels. Hydrogen's cryogenic storage and high flammability present challanges risk, while ammonia's toxicity and corrosive nature necessitate stringent handling procedures.

The shift to alternative fuels brings opportunities, as all renewable fuels show significantly lower emissions, but it also presents challenges for engine integration. Hydrogen's high flame velocity and ammonia's low reactivity affect flame stabilization and emissions, particularly the formation of nitrogen oxides (NO_x). While combustion systems for hydrogen are already within reach, the development of ammonia combustion is still in its early stages.

All evaluated fuels show good arguments for their applications, and different fuels will likely be used in the future for different applications. Thus, the fuel flexibility of the engine to be used in different ship types is a relevant aspect. Because of their considerable differences, using different fuels on a ship would likely require two separate bunkering systems and fuel supplies, which seems challenging.

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2. Introduction

Around 90% of international freight transport worldwide is carried by ship. Most ships use heavy fuel oil and are responsible for around 3% of global CO_2 emissions. The decarbonization of shipping plays an important role in achieving a climate-neutral transport industry. Therefore, the International Maritime Organization (IMO) has set itself the goal of "net-zero emissions by or around 2050" and targeting reductions of 20-30% from 2008 levels by 2030 and 70-80% by 2040.

To meet these targets, there is a need for renewable fuels to reduce the environmental and climate impact of shipping in the short and long term. This evaluation report compares alternative fuels for the future of the maritime sector, such as hydrogen, ammonia, methanol, and methane. The report is structured in three main parts. In the first part the general aspects like market, TRL, costs, health, and safety for the evaluated fuels are described. The second part focuses onto the relevant aspects on the ship describing the status of the regulatory framework and the bunkering. The third part focuses on the combustibility of the different fuels and the emission potential. The last section describes the preparation of a techno-economical study focussing on the evaluated fuels, which will be carried out as a follow up of the report.

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3. General Aspects

3.1. Market Analysis

The demand for marine bunkers has experienced rapid growth since the 1980s, driven by the increasing role of maritime shipping in global trade, which facilitates 80-90% of total trade volumes (UNCTAD, 2018). Between 2005 and 2018, bunker demand grew by more than 25%, with an average annual growth rate (AAGR) of 1.77%. As shown in image Figure 1, energy demand in the maritime sector has historically been driven by global GDP growth, the expansion of international trade, and increased activity in the manufacturing sector.

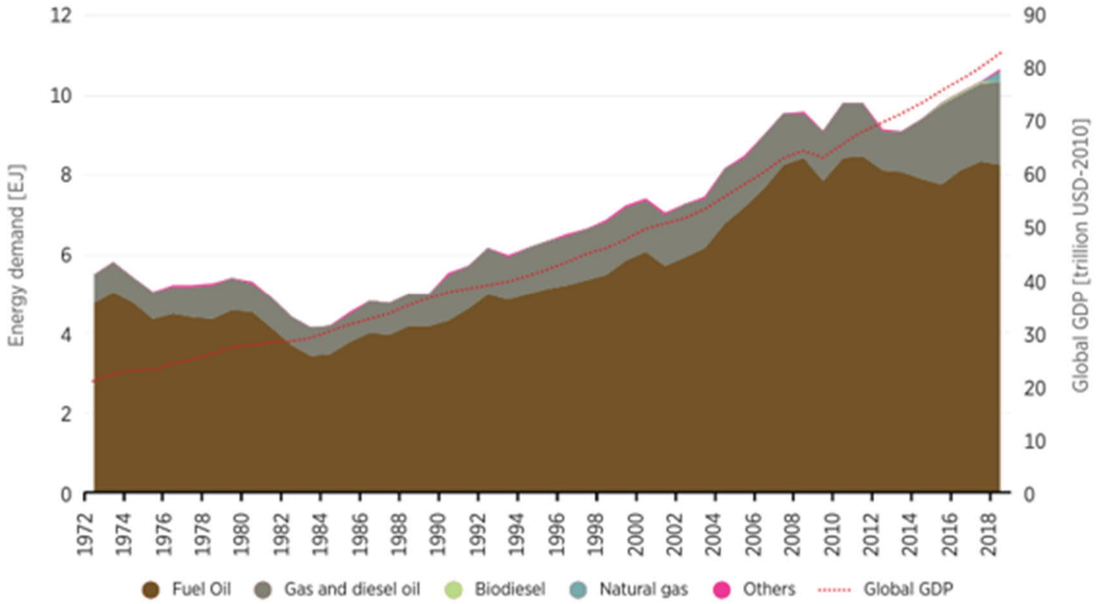

Figure 1: Global shipping energy demand and GDP - Source: IRENA 2021

Organizations such as the International Maritime Organization (IMO) and the European Union (EU) are strongly committed to decarbonizing the maritime sector, driving the search for viable alternatives to fossil fuels. This push for lower-emission solutions is also supported by growing demands from major charterers for sustainable shipping practices.

The transition to alternative fuels is expected to bring substantial cost increases estimated at 70% to 110% of total transport costs (DNV, 2024). These higher costs are likely to encourage greater energy efficiency and may have a modest impact on freight volumes. However, increased transport costs are expected to be passed on to consumers through slight price rises on goods.

The IMO's decarbonization strategy is highly ambitious, aiming for "net-zero emissions by or around 2050" and targeting reductions of 20-30% from 2008 levels by 2030 and 70-80% by 2040. However, the lack of global enforcement mechanisms makes full achievement of these targets uncertain. While stringent EU regulations and charterer pressure are contributing to regional progress, they are

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insufficient to guarantee global implementation. Among these regulations, the EU's "Fit for 55" package plays a critical role. Notably, the Fuel EU Maritime initiative, which will promote, starting in 2025, the use of renewable, low-carbon fuels and clean energy technologies for ships, essential to support decarbonisation in the sector. Additionally, the inclusion of the maritime sector in the EU Emissions Trading System (ETS) introduces financial incentives to cut emissions by setting an overall cap on emissions allowed in Europe, further pushing shipping companies to adopt greener technologies and fuels. Together, these mechanisms leverage both regulatory and market-driven approaches to accelerate decarbonization. Despite these challenges, the industry is advancing rapidly, with projections indicating a 20% reduction in CO_2 emissions by 2040 and a 60% reduction by 2050 compared to 2023 levels. Yet, significant uncertainty remains about which technologies and fuel options will ultimately dominate the sector's decarbonization.

All low-carbon fuel alternatives involve high costs, but one possible option is the continued use of oil combined with onboard CO_2 capture systems. This approach, despite requiring more fuel and offering a moderate capture efficiency of about 75%, is still less expensive than advanced biofuels, methanol, or ammonia (DNV, 2024). However, its success depends on the development of a global infrastructure to manage and store the captured CO_2. DNV estimates that by 2050, onboard carbon capture could account for 15% of maritime fuel use, reducing emissions by capturing 120 $MtCO_2$ annually- around 8% of global carbon capture and storage (CCS) capacity.

Another emerging solution is the potential use of nuclear propulsion through small modular reactors (SMRs) installed onboard ships. These reactors offer the advantage of operating without the need for refuelling over the vessel's lifetime. Unlike onshore nuclear power, which competes with cost-effective renewable energy, onboard nuclear is an alternative to expensive biofuels and e-fuels. However, significant technological, commercial, and regulatory hurdles remain, and nuclear propulsion is expected to comprise only 6% of the maritime fuel mix by 2045.

By 2050, the maritime fuel mix is expected to shift dramatically away from today's oil-based dominance. Hydrogen-based fuels will take the lead, with ammonia accounting for 24%, e-fuels (likely methanol) at 12%, and biofuels at 11%. Electrification will play a minor role (4%), primarily for small ships on short routes. Natural gas is projected to grow until 2040 but decline thereafter due to its carbon intensity, which is incompatible with long-term decarbonization goals.

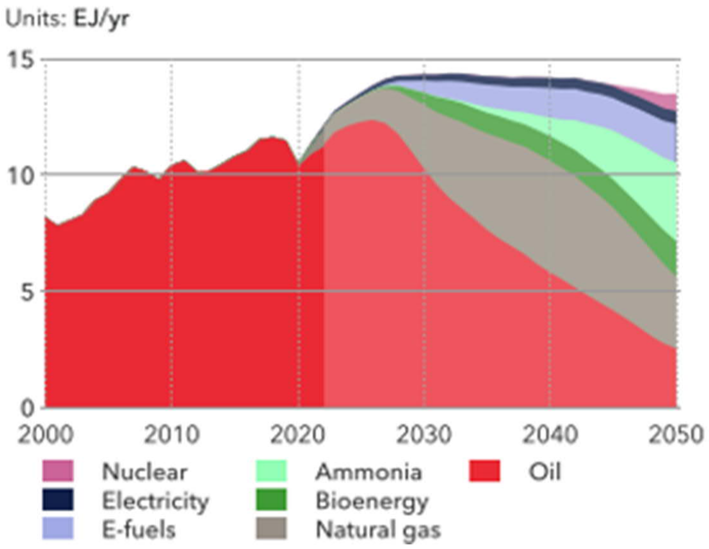

Figure 2: Maritime energy demand by carrier – Source: DNV 2024

This transformation is illustrated in Figure 2, which shows the projected maritime energy demand by carrier. The graph highlights the steady decline of oil and natural gas, replaced by the rising contributions of ammonia, e-fuels, and biofuels, along with modest shares of electrification and nuclear energy. These forecasts represent DNV's best estimates, based on qualitative assessments rather than cost-competition models, emphasizing the uncertainty surrounding the maritime sector's future fuel mix.

3.2. Alternative Fuels Technology Readiness and Costs

Efforts to reduce emissions in the shipping industry are primarily focused on replacing fossil fuels with alternative energy sources. Currently, the sector relies on fuels such as MGO, LNG, and LSFO, which comply with IMO's MARPOL Annex VI amendments due to their low sulfur content (IMO, 2020). Despite this, these fuels, like all fossil fuels, contribute significantly to CO_2 emissions and are a major driver of the industry's carbon footprint. To meet the IMO's target of reducing CO_2 emissions by 50% by 2050, a transition to renewable fuels is necessary (IRENA, 2019). Potential renewable fuel options include biofuel, biogas, methanol, ammonia, and hydrogen. Each of these fuels presents unique opportunities and challenges, which are explored in more detail in the following sections.

The choice of fuel depends on a range of factors, including availability, engine compatibility, environmental impact, and economic feasibility. Among these, the cost of production and the accessibility of renewable fuels are expected to play a decisive role in determining which technologies and fuels are adopted (IRENA, 2019). This chapter examines the readiness of these technologies, along with the associated production costs of the renewable fuels being considered. Other critical aspects include energy density, volumetric density, and storage temperature, as these influence the practicality and economic performance of each option (IRENA, 2019).

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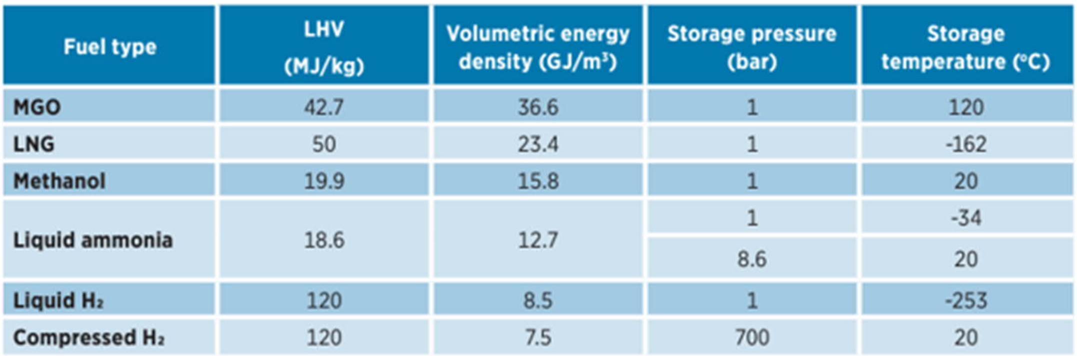
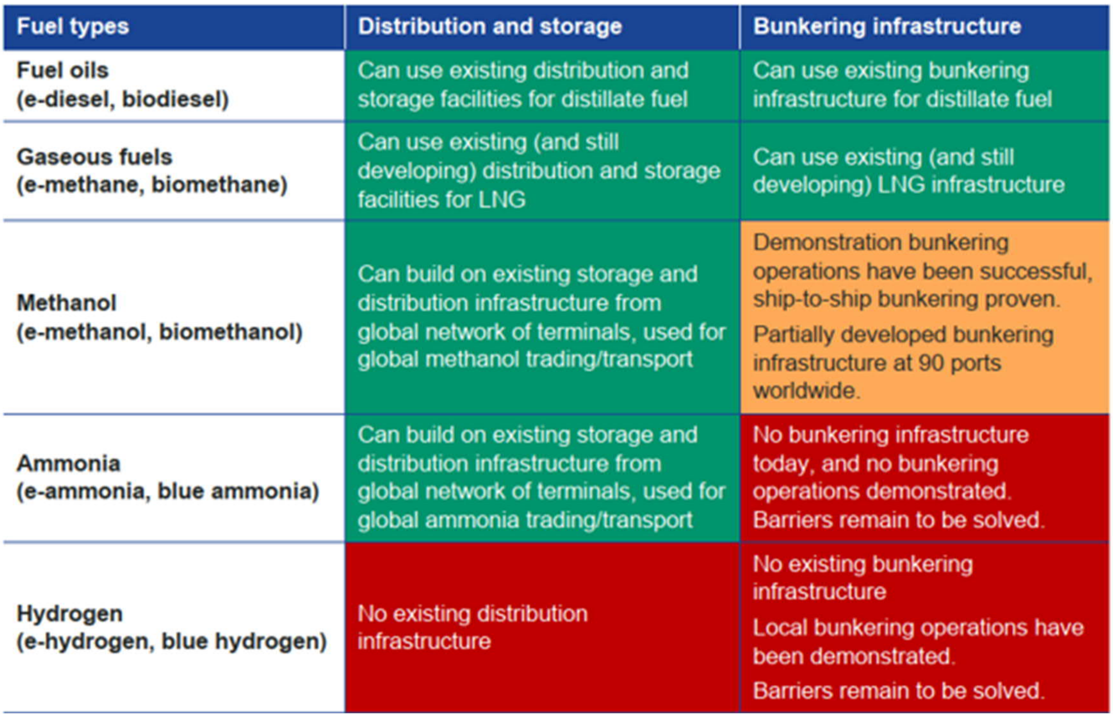
Table 1: Different marine fuels characteristic – Source: IRENA 2021



Fuel type	LHV (MJ/kg)	Volumetric energy density (GJ/m³)	Storage pressure (bar)	Storage temperature (ºC)
MGO	42.7	36.6	1	120
LNG	50	23.4	1	-162
Methanol	19.9	15.8	1	20
Liquid ammonia	18.6	12.7	1	-34
			8.6	20
Liquid H_2	120	8.5	1	-253
Compressed H_2	120	7.5	700	20

For example, energy density affects onboard storage requirements and could potentially impact cargo capacity and revenue, depending on the size and type of the vessel as well as the fuel selected. As shown in Table 1, liquid ammonia has a volumetric energy density that is only one-third that of MGO and two-thirds that of LNG, requiring significantly more storage space for the same energy output (IRENA, 2019). Methanol, in contrast, can be stored as a liquid at ambient temperatures, whereas LNG must be stored at -162°C, presenting additional challenges for infrastructure and transport.

Table 2: Screening of readiness of distribution and storage and bunkering infrastructure for alternative fuels – Source: MEPC80 2023



Fuel types	Distribution and storage	Bunkering infrastructure
Fuel oils (e-diesel, biodiesel)	Can use existing distribution and storage facilities for distillate fuel	Can use existing bunkering infrastructure for distillate fuel
Gaseous fuels (e-methane, biomethane)	Can use existing (and still developing) distribution and storage facilities for LNG	Can use existing (and still developing) LNG infrastructure
Methanol (e-methanol, biomethanol)	Can build on existing storage and distribution infrastructure from global network of terminals, used for global methanol trading/transport	Demonstration bunkering operations have been successful, ship-to-ship bunkering proven. Partially developed bunkering infrastructure at 90 ports worldwide.
Ammonia (e-ammonia, blue ammonia)	Can build on existing storage and distribution infrastructure from global network of terminals, used for global ammonia trading/transport	No bunkering infrastructure today, and no bunkering operations demonstrated. Barriers remain to be solved.
Hydrogen (e-hydrogen, blue hydrogen)	No existing distribution infrastructure	No existing bunkering infrastructure Local bunkering operations have been demonstrated. Barriers remain to be solved.

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The readiness of distribution, storage, and bunkering infrastructure will play a crucial role in enabling the transition to alternative fuels in the maritime sector. As highlighted in Table 2, existing infrastructure for fuel oils such as biodiesel and e-diesel, as well as gaseous fuels like e-methane and biomethane, can largely be utilized with minimal modifications, making these fuels more immediately accessible for adoption. Methanol, which benefits from a global distribution network, also shows significant promise, although adjustments to bunkering systems may be needed due to its low flashpoint. Importantly, these modifications do not involve challenges associated with cryogenic storage or high pressures, simplifying implementation.

On the other hand, ammonia and hydrogen face much greater hurdles, as neither currently has widespread bunkering infrastructure in place. While ammonia can leverage existing global storage and distribution networks used for chemical transport, the construction of entirely new bunkering systems is necessary. Hydrogen, with no established infrastructure for either storage or bunkering, will require extensive investment and development to reach comparable readiness levels. A notable exception is the Norled Hydra, the world's first ship powered by liquid hydrogen (LH2), which successfully demonstrated bunkering operations. This milestone highlights the technical feasibility of LH2 as a maritime fuel, though scaling up such operations remains a significant challenge. Addressing these challenges will demand significant collaboration between ports, fuel producers, and policymakers, especially as new fueling requirements emerge along designated green maritime corridors.

Investments in green corridors, where specific fuels are prioritized for predetermined routes, may accelerate the availability of ammonia and hydrogen by concentrating infrastructure efforts in key locations. Without such initiatives, constraints on the use of these alternative fuels could arise, even assuming their availability. Overall, while biofuels and gaseous fuels may benefit from a head start due to their compatibility with existing infrastructure, ammonia and hydrogen will require transformative efforts in bunkering and distribution systems to achieve widespread adoption in the maritime sector.

3.2.1. Alternative Gaseous Fuels

Key renewable gaseous fuels for shipping include compressed biogas (CBG), liquefied biogas (LBG), and synthetic methane from methanation. LNG has been increasingly used in shipping, but to meet decarbonization goals, integrating LBG and other renewable gases is crucial for reducing CO_2 emissions.

LBG and CBG are generated from biogas produced through the anaerobic digestion of organic materials like food waste. This biogas production method is technologically advanced but faces challenges related to scalability. An alternative approach is methanation, which involves hydrogenating carbon dioxide and carbon monoxide to produce methane. Methane can then be utilized to create various alternative fuels for the shipping industry, with synthetic methane serving as a drop-in fuel. While this method shows potential, it's important to recognize that the technology is still in the early stages of development and experimentation. However, it should be considered that CBG and LBG can be used as drop-in fuels in existing LNG infrastructure, requiring no modifications to fuel or engine systems.

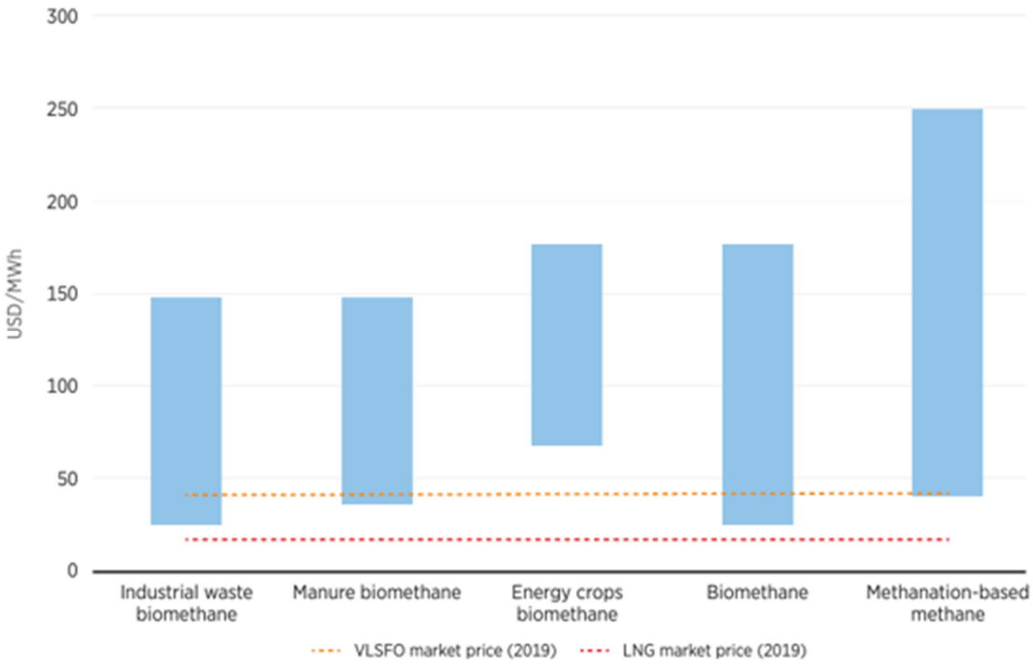

Figure 3: Cost comparison of renewable gaseous fuels – Source IRENA 2021

CBG has been utilized in small vehicles, especially for short-distance transport, and could be suitable for ships operating on shorter routes. However, its large storage volume and frequent refueling requirements make it impractical for deep-sea shipping. Scaling LBG for use in shipping is limited by a lack of refueling infrastructure, which is currently insufficient to support widespread adoption.

From Figure 3 you can see that Biomethane from energy crops is estimated to cost between 68.18$/MWh and 176.36$/MWh, while production from manure ranges from 36.36$/MWh to 148.18$/MWh, and from industrial waste is estimated to cost between 25.45$/MWh and 148.18$/MWh. As demand for renewable gaseous fuels increases, production costs are expected to decline, although these fuels remain subject to localized cost fluctuations driven by infrastructure, land, and feedstock availability. Biomethane from industrial waste and manure is at the lower end of the cost scale and could potentially compete with conventional fuels such as VLSFO. However, scalability remains a challenge for shipping, as the economics of CBG and LBG are hampered by infrastructure and transportation issues. Methane produced via methanation also shows promise, but is still in the research phase, with cost estimates ranging from $40.99/MWh to $249.88/MWh, depending on electricity prices. As research progresses, the costs of these alternatives could decline, although scalability and feedstock limitations remain significant barriers to their widespread use in the maritime sector.

3.2.2.Methanol

Methanol, increasingly considered as a viable alternative fuel for shipping, has attracted attention for its low carbon content and high hydrogen ratio compared to other fuels. It significantly reduces sulfur oxide (SO_x) and nitrogen oxide (NO_x) emissions, by up to 60% compared to heavy fuel oil (HFO), and eliminates particulate matter emissions by almost 95%. While most methanol is currently derived from coal or natural gas, it can also be produced using renewable sources such as agricultural waste, sustainably managed forest biomass, or municipal solid waste via gasification. Biomethane can also serve as a renewable feedstock for methanol. Another method is the synthesis of methanol using CO_2 captured via carbon capture and storage (CCS) combined with renewable energy, although this method still often relies on natural gas, making it less sustainable. It is important to note, however, that the emissions of grey methanol, produced from natural gas, are currently higher than those of marine gas oil (MGO), making it less environmentally beneficial. For methanol to represent a truly viable alternative solution, the industry must prioritize the use of bio-methanol derived from sustainable biomass feedstock sources or e-methanol derived from CO_2 and renewable energy.

The adoption of methanol as a marine fuel is supported by its compatibility with existing storage and transport infrastructure. Furthermore, methanol is already in use on ships equipped with internal combustion engines (ICEs), including both two-stroke and four-stroke engines that have been adapted to run on this fuel. However, scaling up the production and availability of sustainable methanol will be critical to unlocking its full potential as a low-emission alternative in the maritime sector.

Unlike cryogenic fuels such as hydrogen or LNG, methanol can be stored as a liquid at ambient pressure and temperature, allowing it to use standard liquid fuel infrastructure. This reduces the need for extensive new investments. However, the production of e-methanol depends on affordable and sustainable sources of renewable electricity and carbon, which pose challenges. Similarly, bio-methanol production is limited by the availability of biomass feedstocks. Despite these challenges, major shipping companies, are heavily investing in renewable methanol, with pilot projects already underway.

Methanol bunkering requires minimal retrofitting of existing fossil fuel infrastructure, reducing upfront costs. Fossil-derived methanol costs between 18.09$/MWh and 45.23$/MWh, while bio-methanol ranges from 57.89$/MWh to 139.30$/MWh. Green e-methanol, produced using BECCS (Bioenergy with carbon capture and storage), is more expensive, with current costs estimated between 144.72$/MWh and 289.45$/MWh. However, prices are expected to decrease as production technology improves, with estimates for 2050 ranging between 107$/MWh and 145$/MWh.

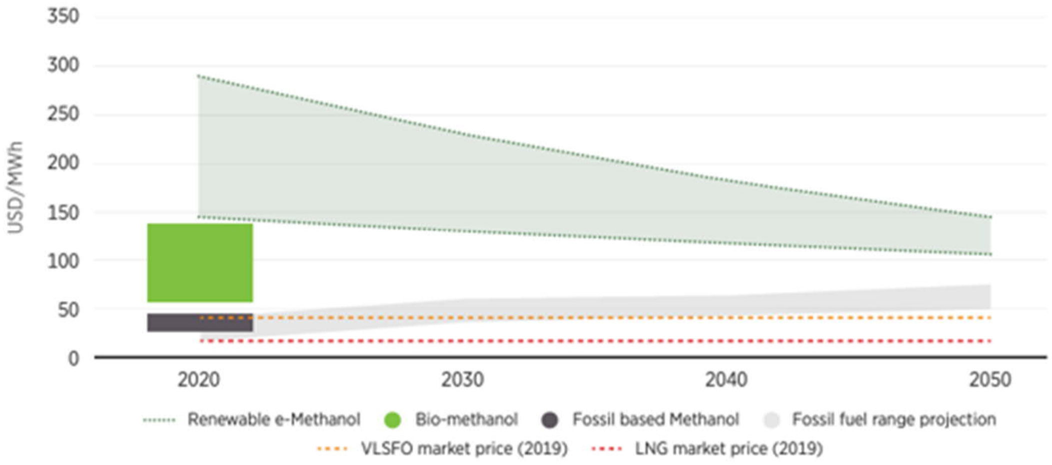

Figure 4: Methanol cost projections – Source: IRENA 2021

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The cost competitiveness of e-methanol depends on advancements in carbon capture technologies and reductions in renewable electricity costs. Bio-methanol benefits from mature gasification technology but may face scalability constraints due to limited biomass resources. Despite these hurdles, renewable methanol remains a promising solution, as evidenced by growing industry investment and the launch of methanol-powered pilot vessels.

3.2.3.Hydrogen

Hydrogen is considered one of the most promising long-term alternatives to conventional fuels for the maritime sector, aligning with the IMO’s emissions reduction objectives. Hydrogen can be utilized in two primary ways: as a fuel in fuel cells (FCs) or in internal combustion engines (ICEs). While hydrogen fuel cells are already widely used in other transportation sectors, such as public transit such as buses. their application in the maritime industry is still in its early stages. However, commercial implementation for merchant vessels remains under development. While gas turbines for stationary power production are standard technology and have already shown the ability to use hydrogen as a fuel, in maritime applications this technology is only a niche product today.

At present, hydrogen-powered fuel cells are most suitable for small vessels, such as ferries or passenger ships, due to their early-stage development. For large-scale merchant vessels, further technological advancements are required before widespread adoption becomes feasible. The technology enabling the use of hydrogen in internal combustion engines is even less developed, presenting additional challenges. Using hydrogen in internal combustion engines requires substantial modifications to engine systems, making it unsuitable as a drop-in replacement fuel

Most of the hydrogen is currently produced using natural gas reforming, which results in significant CO_2 emissions. This process is referred to as steam methane reforming and produces "grey hydrogen". When coupled with carbon capture technologies, it produces "blue hydrogen". However, only "green hydrogen", generated through water electrolysis powered by renewable energy, is considered a viable long-term solution for shipping, as it achieves net-zero emissions throughout its life cycle (DNV GL, 2019).

Currently, global hydrogen production is heavily concentrated in ammonia synthesis for agriculture, which accounts for about 55% of usage. A significant expansion of hydrogen production capacity, estimated at three times the current output, would be required to meet potential shipping demand. While hydrogen has not yet been adopted for commercial shipping, plans are in place to begin using compressed and liquefied hydrogen in vessels. For now, hydrogen is expected to play a more prominent role indirectly, as it is used to produce renewable fuels such as ammonia and methanol. Direct use in fuel cells and engines will likely remain limited to short-range shipping applications.

Infrastructure for hydrogen bunkering is also underdeveloped, as there is currently little demand in the shipping sector. However, with rising interest, various countries, are advancing green hydrogen projects. These initiatives are supported by renewable energy expansion; surplus renewable electricity can be used to produce hydrogen via electrolysis.

The high costs associated with hydrogen fuel adoption, including engine modifications, onboard storage systems, and bunkering infrastructure, are key challenges for the maritime sector. In 2020, green hydrogen production costs ranged from 135$/MWh to 154$/MWh, depending on electricity prices. This

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cost is substantially higher than traditional fossil fuels. Nonetheless, as production technology advances, green hydrogen costs are projected to decline, potentially becoming competitive with LNG and VLSFO by 2030.

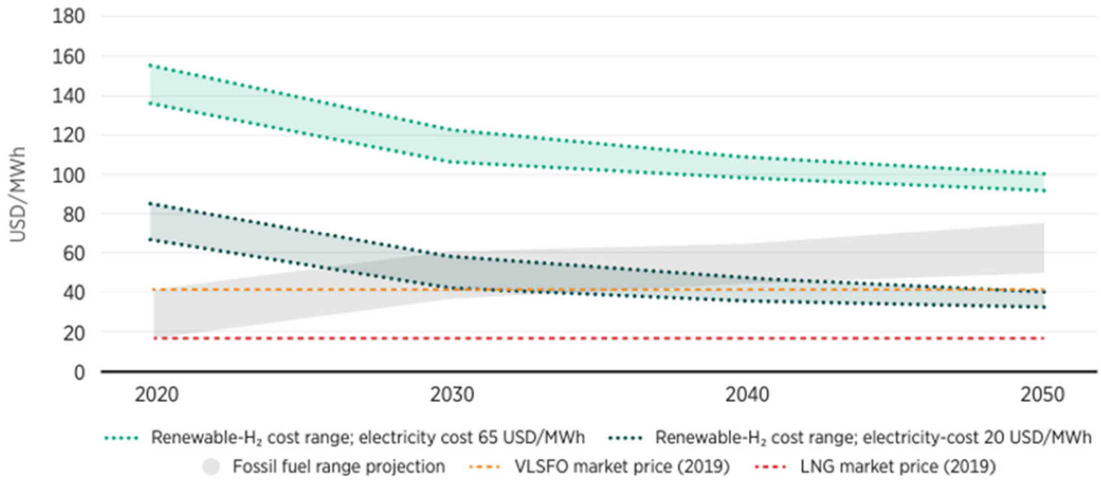

Figure 5: Green Hydrogen cost projections – Source: IRENA 2021

While hydrogen's low energy density compared to other fuels (e.g., ammonia) presents additional drawbacks, its use in shipping could stimulate cost reductions in derivative fuels, such as renewable ammonia and methanol. However, the need for cryogenic storage systems and rigorous safety measures will require significant investment. Despite these obstacles, the falling cost of green hydrogen could make it an economically viable and sustainable solution for the shipping sector in the coming decades.

3.2.4. Ammonia

Green ammonia, a carbon-free fuel, has emerged as one of the most promising solutions to meet the International Maritime Organization's (IMO) greenhouse gas (GHG) emission reduction targets. Research has indicated that ammonia produced through renewable energy-powered electrolysis could play a pivotal role in achieving deep decarbonization of the shipping industry.

Ammonia offers several advantages over other alternative fuels, including an already-established logistical infrastructure and the absence of a need for cryogenic storage. Additionally, it is the carbon-free fuel with the highest energy density, as shown in Table 1; ammonia has a higher energy density than hydrogen. At present, ammonia is primarily produced using natural gas, which results in substantial GHG emissions throughout its lifecycle. Therefore, renewable energy is the only sustainable pathway for producing carbon-free ammonia. Ammonia is synthesized through the Haber-Bosch process, which relies on hydrogen as a feedstock and is primarily used in agriculture, especially for fertilizer production. Plans are underway to scale up ammonia production to meet the needs of the transport sector, but the high demand for ammonia presents challenges for large-scale expansion.

The evolution of ammonia technology can be categorized into three generations (MacFarlane et al., 2020):

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- Generation 1 relies on CCS to produce “blue ammonia,” reducing emissions but still using natural gas as a feedstock.
- Generation 2 utilizes green hydrogen derived from renewable energy to achieve a carbon-free production process. While this represents the ideal solution for the shipping industry, current investment and infrastructure development constraints pose significant challenges.
- Generation 3, still in the research phase, seeks to bypass the Haber-Bosch process entirely by using electrochemical nitrogen reduction. This method has the potential for higher energy efficiency than Generation 2.

Both Generation 2 and Generation 3 technologies are considered green and offer a sustainable pathway for the future ammonia economy.

Compared to hydrogen, ammonia liquefies at a higher, more manageable temperature of -32°C (versus -253°C for hydrogen), making it easier to store and transport. Like hydrogen, ammonia can be utilized in both fuel cells and internal combustion engines (DNV GL, 2019). However, ships using ammonia as fuel would require 1.6 to 2.3 times more storage volume than conventional heavy fuel oil ships.

Fuel cell, internal combustion engine, and gas turbine technologies capable of using ammonia are still in the developmental stage, with limited practical applications in the shipping sector to date and adapting existing engines and fuel systems to operate with ammonia will necessitate significant modifications. However, one notable advantage of ammonia compared to other alternative fuels is the availability of existing infrastructure for its transport and storage, including well-established ammonia terminals.

The high costs associated with producing and deploying ammonia remain a major barrier to its adoption as a maritime fuel. Currently, natural gas-based ammonia costs between 21.29$/MWh and 65.81$/MWh, while renewable ammonia (e-ammonia) costs range from 143$/MWh to 219$/MWh. By 2050, the cost of e-ammonia is expected to drop significantly to between 67$/MWh and 114$/MWh, making it potentially cheaper than very low-sulfur fuel oil (VLSFO).

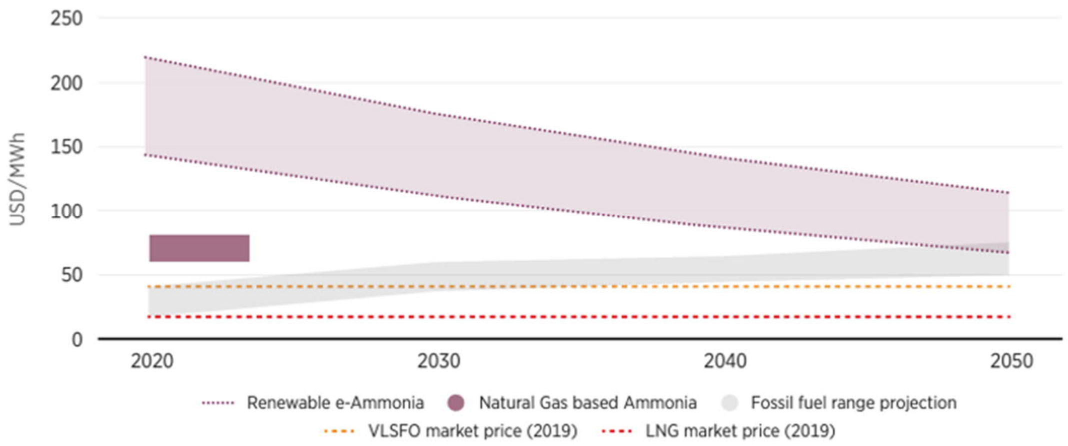

Figure 6: Ammonia cost projections – Source IRENA 2021

Although ammonia production is more expensive than hydrogen, its lower storage and distribution costs may make it a more economic option in the long term. As costs for renewables, electrolysers, and

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hydrogen storage continue to fall, renewable ammonia could become a highly attractive fuel option for decarbonizing international shipping.

3.3. Health, Safety and Environment

The safe application of alternative fuels on ships involves various factors, including their flammability, toxicity, and potential environmental impacts. Each fuel presents unique risks and benefits, necessitating careful consideration and adaptation of safety protocols to ensure their viability for maritime use.

3.3.1.Flammability

Flammability is a critical parameter when considering alternative fuels for shipping. The flammability of a fuel is defined by its Lower Flammable Limit (LFL) and Upper Flammable Limit (UFL)—the range of concentrations within which a fuel mixed with air can ignite. If a fuel concentration is below its LFL, it is too lean to sustain combustion, whereas concentrations above the UFL are too rich to ignite. Understanding the flammability characteristics of alternative fuels is essential for developing safe storage, handling protocols, and onboard systems. Below is a comparison of the flammability ranges of key alternative fuels.

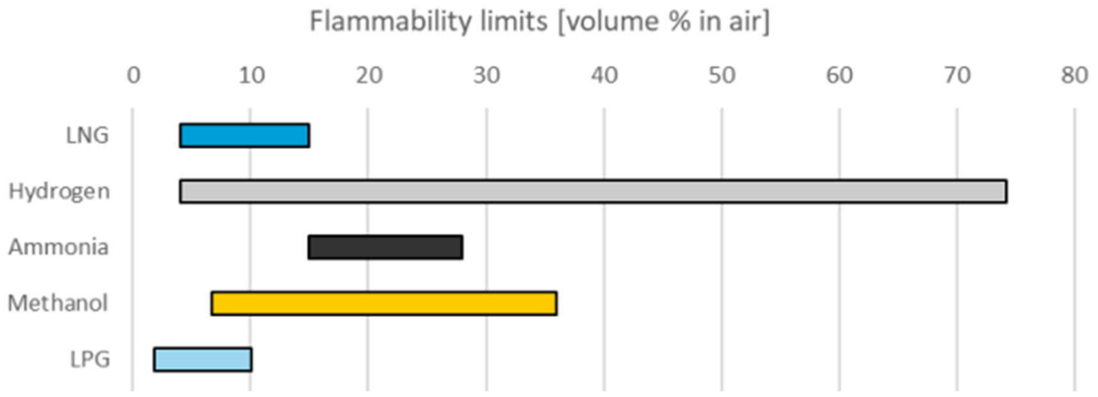

Figure 7: Flammability limits for different fuels – Source: DNV 2019

Hydrogen: Hydrogen has an exceptionally broad flammability range (4%–75%), and a low Minimum Ignition Energy (MIE) of 0.017 mJ, significantly lower than that of other fuels, making it highly susceptible to ignition and the most flammable fuel on the list. Furthermore, hydrogen flames are nearly invisible, posing additional risks of undetected fires.

Methanol: Methanol has a flammability range of 6%–36%, with a flash point around 11°C. Similar to hydrogen, its flames are almost invisible, creating challenges for fire detection during onboard incidents. Methanol spills or fires could escalate quickly if not detected early.

Methane: The upper flammability limit and lower flammability limit are 5% and 15% by volume. In open spaces, methane tends to disperse quickly due to its low molecular weight, reducing the likelihood of

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reaching explosive concentrations. However, if the gas is released in a confined or poorly ventilated area, it can accumulate, and if ignited, cause an explosion.

Ammonia: Ammonia is less flammable than the other alternative fuels, with a range (LFL-UFL) of 15% – 28%. Although the risk of ignition is lower compared to hydrogen or methanol, ammonia can still pose significant safety hazards, particularly if it accumulates in enclosed spaces.

3.3.2. Toxicity

The toxicity of alternative fuels is another critical consideration, as it directly impacts the health and safety of crew members and the surrounding environment.

Ammonia is among the most toxic of the alternative fuels. Inhalation or direct contact can cause severe chemical burns, respiratory damage, and harm to the skin and eyes. The time-weighted average (TWA) concentration for ammonia is set at 25 ppm, which refers to the average exposure level over an 8-hour workday within a 40-hour workweek. Given the low exposure limits, it is essential to implement strict safety measures to protect workers who handle ammonia. Adequate ventilation, personal protective equipment (PPE) and monitoring systems are essential to minimize the risk of exposure and ensure health and safety. Spills in the marine environment can have catastrophic effects on aquatic ecosystems, disrupting marine flora and fauna by altering the water's pH and introducing highly toxic compounds. The LC50 (Lethal Concentration 50) for ammonia is just 0.068 mg/l, making it highly toxic to marine environments and significantly more hazardous than other fuels in terms of acute ecotoxicity. For example, studies have shown that ammonia exposure can severely damage fish gills and other aquatic organisms, leading to long-term ecological imbalances. (Methanol Institute, 2023)

Methanol is also highly toxic. Inhalation, ingestion, or skin contact can cause serious harm, including neurological effects and metabolic acidosis. However, methanol is considered less environmentally hazardous in marine spills than fossil fuels because it dissolves readily in water and biodegrades relatively quickly. This property reduces its persistence in the marine ecosystem, making it a somewhat less harmful alternative from an environmental perspective. Methanol is toxic to aquatic organisms at concentrations above 1,000 mg/l, with an LC50 for fish of 15,400 mg/l, significantly higher than the LC50 for HFO (79 mg/l). (Methanol Institute, 2023)

Methane is toxic to humans, but its primary risk lies in undetected leaks within enclosed spaces. Methane is an asphyxiant that displaces oxygen, posing a risk of suffocation. In the marine environment, methane is less impactful because it volatilizes rapidly into the atmosphere, minimizing its long-term ecological effects. However, methane leaks contribute significantly to atmospheric greenhouse gas concentrations, as methane is more potent than CO_2 as a greenhouse gas.

Hydrogen is non-toxic and does not pose a direct health hazard in terms of chemical toxicity. However, it can cause asphyxiation if released in large amounts in confined spaces by displacing oxygen. In the event of a marine spill, hydrogen has minimal environmental impact because it quickly disperses into the atmosphere and is not harmful to marine organisms.

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4. Fuel on Ships

4.1. Regulations for Fuels

4.1.1.International Maritime Organization - Safety for Low Flash Point Fuels

SOLAS has previously restricted the use of fuel oils having a flashpoint less than 60˚C, except for emergency generators, where the maximum is 43˚C and subject to additional criteria stated in SOLAS II-2 Regulation 4.2.1. The International Maritime Organization (IMO) adopted the IGF Code by IMO Resolution MSC.391(95) in June 2015, as applied from SOLAS II-1, Part G, to establish regulatory safety criteria and a framework for ships employing gases or other low-flashpoint fuels, such as methanol, as fuel. The IGF Code outlines aims and functional criteria for low-flashpoint fuels and gases but only includes comprehensive prescriptive standards for natural gas (methane) in Part A1. Low-flashpoint fuels must follow the Alternative Design standards under 2.3 of the IGF Code and establish equivalence as stated in SOLAS II-1/55, which requires engineering assessments based on MSC.1/Circ.1212 and MSC.1/Circ.1455 principles.

4.1.2.International Maritime Organization - Environment

MARPOL Annex VI, as amended describes the Regulations for the Prevention of Air Pollution from Ships. This definition includes any fuel designed for use aboard a ship. Regulation 14.5 requires suppliers to document the sulphur level of fuel oils delivered to ships in the form of a Bunker Delivery Note (BDN), as per regulation 18. MEPC 81 changes provide updates to needed information for low flashpoint/gas fuels.

The BDN must include information from Appendix V of MARPOL 73/78, Annex VI, as well as the density and temperature of the fuel type. Additionally, the supplier's representative must sign and certify that the fuel oil meets the quality requirements outlined in Regulation 18. The sulphur content of a low flashpoint/gas fuel must be documented in the BDN by the supplier, either through a test method or agreement from the appropriate authority at the port of supply that it is less than 0.001% m/m.

4.2. Bunkering

4.2.1.Fuel Bunkering

The term "bunkering" is typically associated with the maritime industry. It refers to the process of replenishing a vessel's fuel supply for its routine operations. As bunkering is a regulated procedure, there are numerous rules, standards, and regulations that govern this process. The IMO establishes these guidelines to ensure environmental protection and maintain the quality of fuel provided to vessels.

The main aspects of bunkering that are evaluated by the IMO are the environmental regulations which require strict controls on fuel types, transfer procedures, and spill responses to help reduce marine pollution. The IMO's MARPOL Annex VI sets limits on sulphur oxide and nitrogen oxide emissions to prevent air pollution from ships. Also, the IMO sets safety protocols which are placed to prevent

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accidents during the bunkering process. The measures for fire prevention, spill containment, and emergency response. Proper training and certification of personnel involved in bunkering operations are also required.

There are several methods of bunkering a ship with different fuels, being:

- Truck-to-ship (TTS): This approach entails delivering fuel via tanker trucks, which subsequently transfer the fuel directly to the vessel's tanks.
- Ship-to-ship (STS): in this method, fuel is transferred from one ship (the bunker barge) to another (the receiving vessel)
- Port-to-Ship (PTS): fuel is delivered to ships via pipelines from onshore storage facilities.

All these methods have their struggles and gaps which need to be addressed when it comes to the delivery of alternative fuels on a ship.

The positive aspects in the decision of alternative fuels are of course the reduction of emissions, alternative fuels offer a significant reduction in atmospheric pollutants, contributing to improve air quality and combating climate change, also this would help with the regulatory compliance of international environmental regulations, avoiding penalties and operational restrictions.

On the downside the gaps there still to be filled when it comes to bunkering of alternatives fuels. From the technological adaptation, using alternative fuels requires modification of the ship engines and port infrastructure, leading to additional costs and operational complexity. Another important aspect to be address is both the limited availability and high costs of alternative fuels, because the production and distribution of alternative fuels are still limited, making it difficult to ensure a consistent supply for ships, and also due to the limited amount of fuel the costs per liter is of course very high as well as the costs of the bunkering infrastructure, representing a barrier to widespread adoption.

4.2.1.1.Hydrogen

Due to the qualities of hydrogen, particularly the extremely low temperature of liquified hydrogen, expertise learned from bunkering arrangements for liquid natural gas, LNG, cannot be directly used. The bunkering procedure will be more challenging than for LNG since no nitrogen can be present inside the pipe systems when liquified hydrogen is supplied, as it will freeze and clog the systems.

Onboard LH2 bunkering stations will be situated on both sides of the vessel. Bunkering stations would require one bunkering liquid line and perhaps one vapor return line, as well as an inert gas purging facility, accompanying relief/safety valves, safety systems, and a separate control station. The LH2 is routed by pipework from the bunker station to the gas storage tanks.

When designing hydrogen bunkering infrastructure, equipment, and pipes, it will have to be consider factors such as hydrogen permeability, embrittlement, material compatibility, low temperature usage (insulation), and static grounding.

While open bunkering stations are ideal for hydrogen, ventilation may be required for semi-enclosed or enclosed installations. Mechanical ventilation in conjunction with hydrogen presents additional issues, since the ventilation system itself may provide an ignite and explosion danger if flammable quantities

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are vented. Assessing hazards and doing extra testing may be necessary to validate designs. Finally, the Boil Off Gas (BOG), since H_2 is in liquid state must be managed.

4.2.1.2.Methane

LNG has been used on ships for many years now, and it has an ever-growing fleet, so the regulations and technologies are quite mature, and the bunkering handling has a dedicated regulation, the IGF Code, as well as ISO/TS 18683:2021, and LNG Bunkering Guidelines IACS Recommendation.

It is critical that all LNG bunkering activities are carried out with care and attention to prevent leakage of LNG liquid or vapour, and that sources of ignition in the vicinity of the bunkering operation are tightly regulated. Therefore, it is vital that each piece in the LNG bunkering chain be precisely planned and has specific safety, operational, and maintenance processes carried out by skilled staff.

Descriptions of the bunker facility The LNG bunkering system may include the following, if applicable:

- Vapor return and recirculating line system
- Cooling down the LNG fuel tank
- Collapse the receiving tank pressure before and during bunkering
- Pressure relief valve for the LNG fuel tank.
- Ventilation and inlet/outlet placement
- Inerting system and components
- Boil-off gas compressor or re-liquefaction system
- Gas detection system, including detector and alarm locations
- List of gas fuel-related alerts or safety indicators.
- LNG Transfer Line and Connectors
- Emergency Shutdown System Description
- Communication and Control Protocol

4.2.1.3.Methanol

Methanol is liquid at atmospheric temperatures and pressures, making bunkering similar to conventional fuel oils. However, its low flashpoint and hazardous qualities necessitate special equipment and procedures. Hoses and couplings must be approved for methanol use and frequently tested in accordance with the most recent version of MSC.1-Circ. 1621.

The bunker station poses clear threats to the ship owing to the probability of methanol liquid and vapor escape. The position of the bunker station is thus an important aspect in determining the amount of risk connected with the ship's bunkering operation. Bunker manifolds are categorized as zone 1 areas within 3 meters of any valves, and section 8 of MSC.1/Circ.1621 specifies the standards for methanol bunkering. Methanol bunker stations should be situated on open decks to allow for enough natural ventilation. Enclosed or semi-enclosed bunker stations should have mechanical ventilation and gas detection systems to ensure equal safety.

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The ship's bunkering pipes and materials must fulfil section 7 of MSC.1/Circ.1621 and prevent leaks that endanger passengers, the environment, or the ship itself.

4.2.1.4.Ammonia

Ammonia's toxic and corrosive properties will impact bunkering procedures, particularly since refilling involves handling anhydrous ammonia as a saturated liquid. It is essential to consider these characteristics due to the associated risks, such as corrosion and potential toxic effects on humans, aquatic life, and the environment. To mitigate these risks, nitrogen gas should be inerted into hoses and pipelines to eliminate moisture and oxygen, thus preventing stress corrosion cracking. Subsequently, the remaining system should be purged with ammonia vapor to remove residual nitrogen. These inerting and purging processes are additional steps not required in Marine Fuel Oil (MFO) bunkering.

Furthermore, unlike conventional liquid marine fuels such as diesel or residual oil, ammonia must be maintained as a saturated liquid through refrigeration or pressure. BOG or flash gas will be produced if the temperature increases or pressure decreases, necessitating effective BOG management on board, which differs from conventional fuels. Additionally, the maximum capacity for utilizing ammonia as fuel is limited to 94% of the total tank capacity, as the maximum filling limit at the supply port is 98% to prevent overpressure, leaving a 4% heel remaining in the tank.

4.2.2.Simultaneous operations (SIMOPS)

One of the novel options being investigated is the use of different fuel kinds aboard a single vessel. This technique brings up new opportunities for minimizing fuel use, lowering environmental impact, and maintaining operational flexibility.

Simultaneous operations with different fuels need the integration of several fuel systems into a single vessel. This can include both traditional marine fuels such as heavy fuel oil (HFO) and marine diesel oil (MDO), as well as alternative fuels such as liquefied natural gas (LNG), biofuels, and hydrogen. The ship's propulsion and auxiliary systems are set up to switch between or blend multiple fuels based on availability, cost, and environmental regulations. This strategy needs complex technology solutions, such as dual-fuel engines, fuel management systems, and storage facilities. Fuel management systems guarantee that numerous fuels are handled and distributed efficiently, while specialized storage tanks and pipes adapt to each fuel's specific qualities.

The benefit of using multiple fuels is of course the environmental impact since using green alternative fuels would result in a reduction on GHG emissions and other pollutants and it could result also in an enhanced operational flexibility especially if the vessel would sail ECA areas, having the possibility to switch from one fuel to the other.

When considering the use of different fuels on the same vessel comes with difficulties and challenges not easy to find a solution to, especially when in the technical complexity, designing and maintaining dual-fuel engines, guaranteeing the interoperability of fuel management and storage systems demands significant effort and skill. Regular maintenance and monitoring are critical to avoiding problems like fuel contamination or system breakdowns. Also, the regulatory compliance, different fuels come with specific regulations and standards, and compliance needs to be ensured, especially from a safety point of view, implementing safety protocols and crew training.

4.3. Storage Technologies on board

4.3.1.Fuel tanks

Gas carriers typically have two types of cargo tanks: atmospheric membrane tanks and self-supporting tanks (pressure tanks). The same classification (IMO Classification) is used for LNG-fueled ships to define the LNG fuel tanks. The following tank types that have been created, are in use:

- Type A
- Type B
- Type C
- Membrane

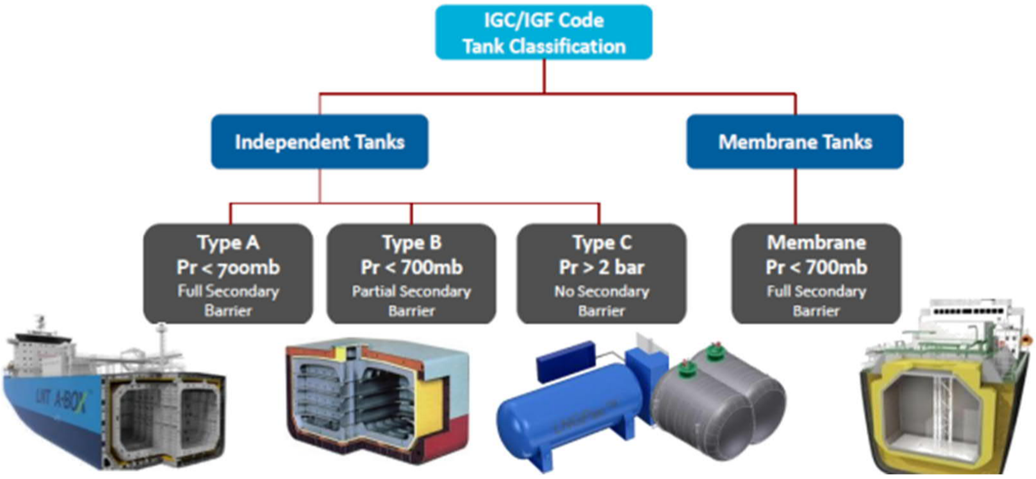

Figure 8 - IMO Classification of Service Tanks

4.3.1.1.IMO Type A Tanks

These prismatic cargo tanks have a design pressure of less than 0.7 bar. The material used to build these tanks has insufficient resistance to fracture propagation, necessitating the deployment of a second shell (tank wall) to confine any leakage. Ship elements, such as the inner hull, can create a second shell if they can withstand the cargo's low temperature.

4.3.1.2.IMO Type B Tanks

These cargo tanks are prismatic or spherical and have a low design pressure (<0.7 barg). Detailed stress evaluations were conducted throughout the design process, including fatigue and fracture propagation. Spherical Moss-Rosenberg tanks are the most common example of this style of tank. The enhanced design of a type B cargo tank requires only a partial second shell on the underside as a drip tray.

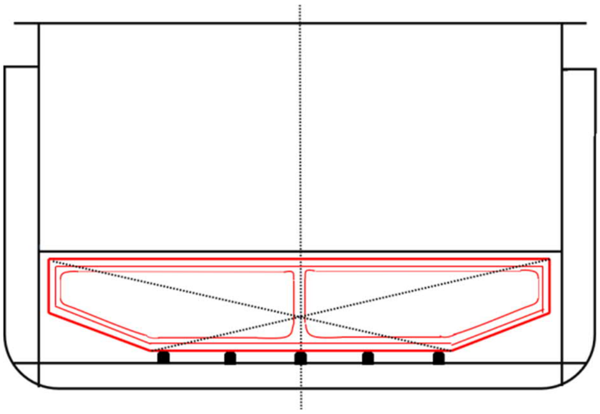

Figure 9 - Type B Tank

4.3.1.3.IMO Type C Tanks

These are spherical, cylindrical, or bilobe pressure tanks having a design pressure of more than 2 barg. The tanks meet typical pressure vessel regulations, allowing for reliable stress evaluations. During the design process, emphasis is placed on minimizing potential stresses in tank materials. Type C cargo tanks do not require a second shell.

Cargo tanks and accompanying equipment on ships that convey cargo in a chilled and partially pressurized state are normally designed for a working pressure of 4 to 6 barg and a vacuum of 0.5 bar. The cargo tanks are usually insulated with polystyrene or polyurethane panels affixed to the tank wall.

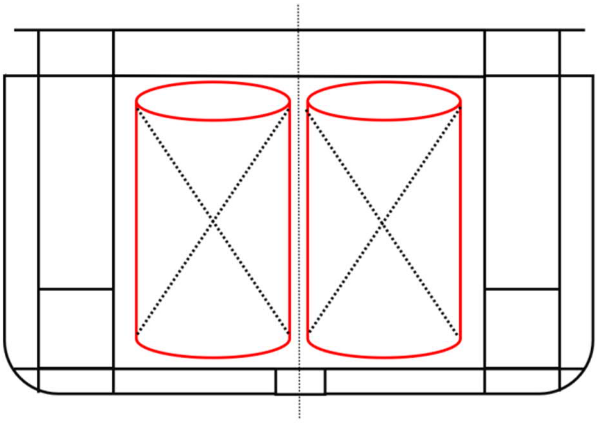

Figure 10 - Type C Tank

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4.3.1.4.IMO Membrane Tanks

The insulation's inner side is exposed to the cargo. Membrane tanks are not self-supporting and rely on insulation from the nearby hull construction. Membrane tanks, such as Type A or B, enhance holding duration through enhanced insulation.

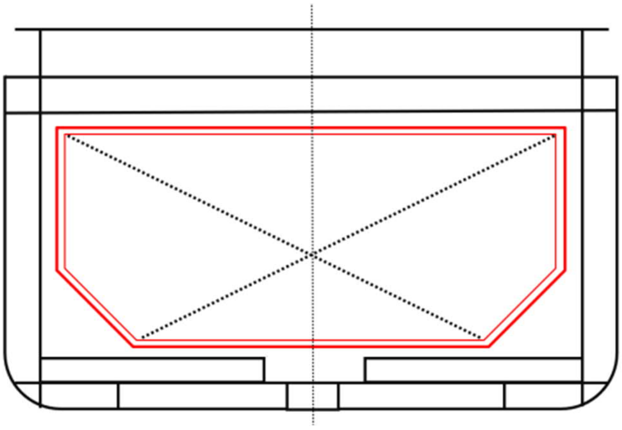

Figure 11 - Membrane Tank

4.3.2.Compatibility of different fuels

Compatibility issues must be addressed promptly since they can cause blackouts, paralyze fuel systems, and make cleanup difficult and time-consuming. The requirements are usually for fuels that have a different chemical element depending on where they are extracted and produced, such as MGO, MDO and LNG, whereas alternative fuels have standard chemical properties. Nonetheless it should be addressed compatibility issues with alternative fuels even though requirements are not available. There are several preventative precautions that can be done:

- Avoid combining bunker fuels from several sources if feasible.
- Store fuels separately until compatibility testing is completed.
- Avoid combining fuels with differing densities.
- When feasible, use fuels with similar viscosity and density.

In practice, it is sometimes impossible to avoid some degree of comingling, and while the general guideline is not to comingle or load on top of more than a 20% mix ratio, the only way to assure there are no problems is to test a sample mix.

It is vital to remember that when a stable fuel is combined with another stable grade, it can become unstable; nevertheless, fuels of the same viscosity grade and density will often be compatible. Also, while ISO 8217 (criteria for Marine Fuels) is the most often used standard for fuel bunkers, it was created before the advent of ECA category fuels, which frequently lie between its grade criteria.

The ASTM D4740 spot test is effective for measuring the compatibility of marine fuels, including residual and distillate fuels, onboard a vessel. The optimal percentage combination is 50/50, which is the worst-

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case situation. It's important to remember that one of the test fuels must be a residual fuel to prevent minor asphaltene precipitation. Comingled distillates have low asphaltene concentration, making spot testing ineffective. Compatibility tests may also yield false positives for distillate blends owing to pigment separation. Spot tests are not suitable for distillate tests with HDME 50.

Finally, to effectively manage on-board fuel, it is imperative to store it at the appropriate temperature. If fuel blending is required, it is essential to understand what it will be mixed with and how to best manage this blending process. Ensuring that the fuel is at the optimal viscosity at the point of engine injection is also crucial.

Even though this are requirements that have been delivered for conventional fuels it can be noted that also crucial when evaluating the possibility of using two alternative fuels together, therefore compatibly with different alternative fuels is quite undoable.

4.4. Volumes on board

The maritime industry is continuously evolving to meet stringent environmental standards and operational efficiencies. One of the critical aspects of vessel design and operation is fuel storage requirements. These requirements can vary significantly depending on whether the vessel is a newbuild or a retrofit. The vessel's trading route is another important aspect in determining fuel storage needs. Vessels traveling lengthy international routes may require more fuel storage capacity to guarantee they can complete their voyages without frequent refuelling stops. In contrast, vessels that travel on regular routes inside an emissions control area (ECA) may not suffer the same issues. For these ships, the ability to bunker fuel more regularly can reduce the requirement for large fuel storage tanks, making fuel storage capacity less of an issue.

Fuel storage needs are a key concern for the marine sector, especially given changing environmental rules and operational demands. While newbuild vessels have greater design freedom, modifying older vessels necessitates innovative methods to incorporate additional fuel storage. So, when it comes to volumes on board a ship, the needs are obvious. The ship has moved from a mere means of transport but is now an important member of the supply chain, where its presence is of vital importance in the distribution of goods.

Given the limited space on a ship, maximizing available cargo space is crucial. Therefore, the ideal fuel should meet energy demands while occupying minimal volume. As we can see from Figure 12 where it is shown the comparison of the same amount of energy per different fuels, the difference in volumes would influence the choice. Heavy Fuel Oil (HFO) is obviously the best choice when it comes to energy stored on board, less space more energy.

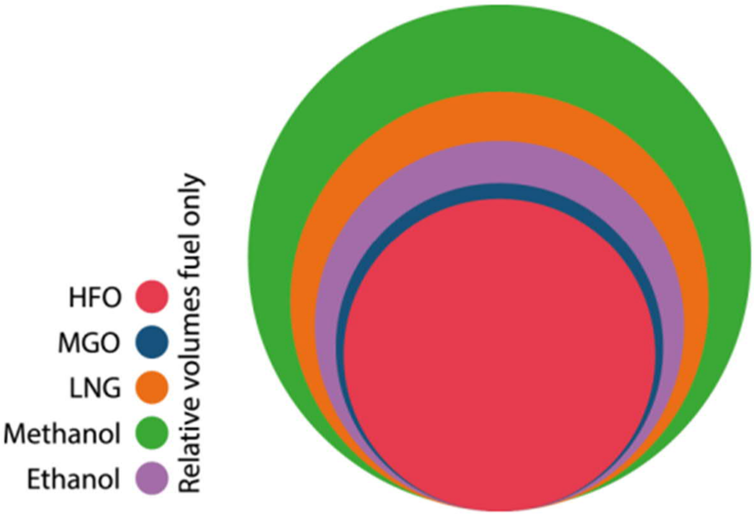


Figure 12 - Volumes of different fuels with the same energy density – Sorce EMSA

When it is discussed about gas fuels, cryogenic it is known to be the best option, in terms of volumes occupied on board, and the safest way to store these fuels, mainly with cylindrical tanks. The IGF Code provides us, as seen in the *Functional Designs* chapter, with the characteristics required of this type of tanks. The tanks present on a conventional ship cannot be used as they do not have the necessary distances from the sides and the bottom of the ship required in the regulations.

The IGF Code requires to have B/5 or 11,5 meters (whichever is less), where with B it is refer to the maximum beam of the ship, from the sides, and B/15 or 2 meters (whichever is less) from the bottom, as it is shown in the Figure 13 below, this will make most of the tanks present on board unusable since are usually positioned in the doble bottom when it comes to pre-existing ships. For new ship the flexibility in design gives you the opportunity to plan beforehand the optimum placement of the tanks. Furthermore, when considering hydrogen or LNG tanks, being cylindrical in shape instead of cubic, they will obviously occupy a different volume, and above all a part of the tank will be lost. Additionally, the hydrogen tanks will not be 100% full but will be 80% filled due to the boil-off, this implies that the tanks capacity is further reduced of 20%.

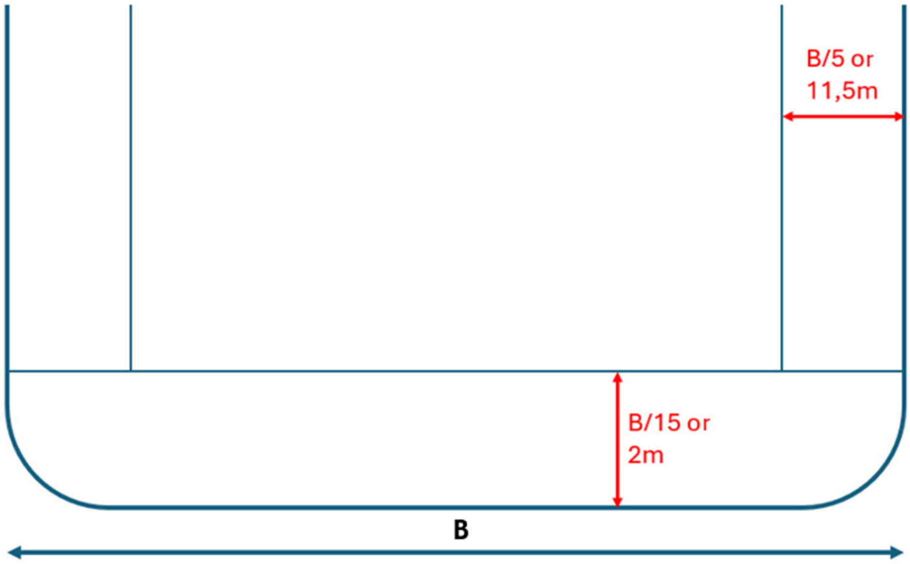


Figure 13 - Design requirements IGF Code

Also, the IGF Code requires that the tanks are at least 900mm from the walls and adjacent rooms if it is not considered a cofferdam, implying an ulterior loss of volume. Figure 14 below shows the configuration of the tank, considering all that was said before.

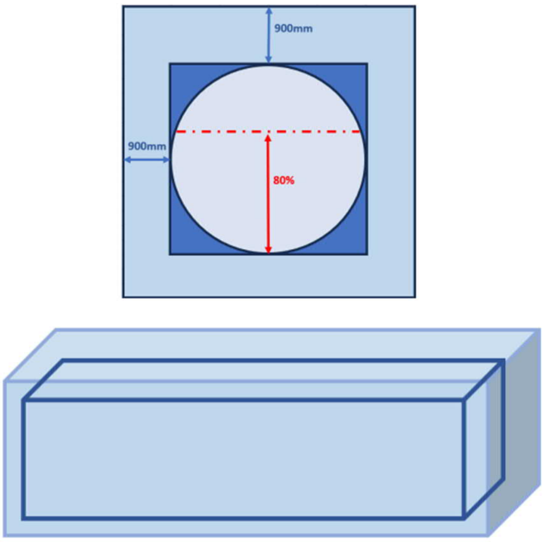


Figure 14 - Volumes necessary for cryogenic tanks

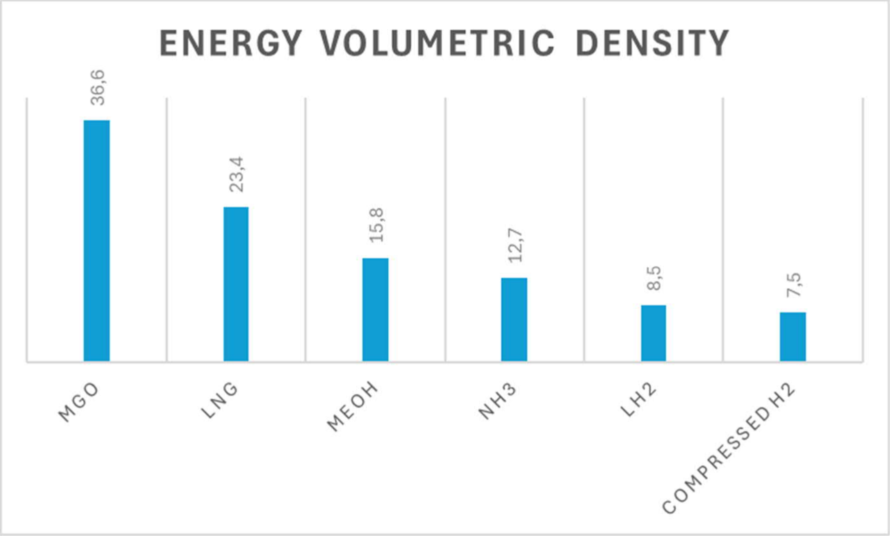
The tank arrangement and capacity plan may require less modifications when retrofitting methanol tanks on ships originally designed to use MGO. The fuel storage temperatures are similar to those of conventional fuels; however, the different specific fuel consumption may require higher tank capacity. Methanol is toxic and more corrosive compared to conventional fuels, and being a low-flashpoint fuels has higher fire and explosion risks. To mitigate these risks protection cofferdams and other provisions have been introduced by MSC.1/Circ.1621 in 2020. More specifically, for fire integrity, the methanol tank boundaries should be separated from the machinery spaces of category A and other rooms with high fire risks by a cofferdam of at least 600 mm, with insulation of not less than A-60 class.

In this context cofferdams are structural spaces surrounding a fuel tank which provide an added layer of gas and liquid tightness protection against external fire, and toxic and flammable vapours between the fuel tank and other areas of the ship. Integral methanol tanks should be surrounded by protective cofferdams, except on those surfaces bound by shell plating below the lowest possible waterline, other fuel tanks containing methyl/ethyl alcohol, or fuel preparation spaces. Tank cofferdams should have suitable access from the open deck, where practicable, for gas freeing, cleaning, maintenance and inspection, and arranged either for purging or filling with water through a non-permanent connection. Alarms such as vapour detection and liquid leakage detection are required, as well as dedicated bilge systems Without direct access to open deck, an entry space to methanol tanks or surrounding cofferdams should be provided, fitted with an independent mechanical extraction ventilation system providing a minimum of six air changes per hour, a low oxygen alarm, a gas detection, and have sufficient open area around the fuel tank hatch for efficient evacuation and rescue operation;

It is therefore evident that these requirements increase the complexity of the ship arrangement, and the overall volume dedicated to fuel tanks and their accessories, compared to conventional fuels.

Using the values of the Volumetric Energy Density reported in Table 1, taken from IRENA study, it can be seen how the difference between conventional and alternative fuel is significant in Table 3.

Table 3 - Energy Density per fuel



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5. Combustibility and emissions

The physical and chemical properties of the fuel are influencing different aspects like fuel storage, fuel handling, fuel control system of the gas turbine and the combustion process. While aspects of fuel storage and handling are described in the sections above this section focuses on the fuel conditioning, the fuel control system and the combustion related aspects.

5.1. Fuel conditioning

Table 4 shows the relevant physical properties of the investigated fuels: hydrogen, methane, methanol, and ammonia. The properties of diesel oil are given for comparison. It is obvious that the fuels are quite different regarding their physical properties and different pressures and temperatures might be optimal for the fuel handling. Typically, on-board of a ship the fuel is prepared in the FPR ("fuel preparation room") to the necessary pressure and temperature conditions of the consumer. For some of the evaluated fuels, it is helpful to separate the transport to the consumer and the fuel control system of the gas turbine. To inject the fuel into the combustion chamber, the pressure of the fuel needs to be equal to or above the pressure of the compressed air at the combustor inlet. The necessary pressure depends on the pressure drop over the combustor and the valves and piping of the fuel control system and is different for liquid and gaseous fuels. While gaseous fuels can be injected directly through fuel injectors into the combustion air with a relatively low excess pressure, liquid fuels must be atomized. Typically, pressure atomizers need a pressure drop of ten or more bars in addition to the surrounding pressure to produce fine droplets of the fuel, which are necessary for fast evaporation and clean combustion.

Table 4: Physical and Chemical Propoerties of Fuels

Properties	Diesel oil	Hydrogen	Methane	Methanol	Ammonia
Density at 0°C, 1.1013 bar, kg/m_N^3	~ 850	0.09	0.72	790	0.77
Lower Heating Value, MJ/kg	43.4	120	50.0	19.9	18.6
Lower Heating Value, MJ/m^3	36 890	10.8	35.9	15 721	17.3
Flammability limits Vol% in air	0.6-6.5	4-75	5-15	7-36	15-34
Boiling point, °C	150-390	-252	-162	65	-33
Vapor pressure at 20°C, bar				0.129	8.573
Self-ignition temperature	255	585	595	455	630
Min. Ignition energy, mJ	0.24	0.011	0.28	0.14	8

The following subsections describes the specific fuel conditioning for the different fuels.

5.1.1.Hydrogen

Hydrogen as a gaseous fuel would need to be provided to the fuel control system with a pressure of some bars above the pressure in the gas turbine. Hydrogen can be stored in different physical states on a ship, like pressurized or liquified cryogenic storage. Hydrogen carriers like LOHC, metal hydrides, or zeolites are not considered as they would need a more complex hydrogen separation process and are still under development.

If hydrogen is stored in pressurized tanks at 350 to 800 bars, the only necessary step is to reduce the pressure to a reasonable pressure before entering the fuel control system. As the pressure is inversely proportional to the volume, keeping the pressure high in the fuel supply line through the ship and reducing the pressure close to the gas turbine is advantageous. It is vital for hydrogen because of its low volumetric energy density.

At room temperature, hydrogen has a negative Joule-Thomson coefficient and tends to warm up slightly when expended from high pressure. Thus, no additional energy is necessary to keep the gas at room temperature. Using an expansion turbine to reduce pressure can help recover some of the compression energy originally used.

If hydrogen is stored as a cryogenic liquid at low pressure and temperatures below -252°C, it must be pressurized, heated, and evaporated before injecting it into the combustor. Pressurizing hydrogen in its liquid form is favourable because a cryogenic pump is much more efficient than a gas compressor.

While, in principle, it would be possible to inject hydrogen in its liquid or supercritical state at low temperatures, this would reduce the efficiency of the gas turbine process. Additional energy from the combustion would be necessary to heat the hydrogen from its low temperature. Thus, from an efficiency point of view, it is beneficial to use environmental or waste heat to heat up the hydrogen before the gas turbine. There is the option to use this cold onboard to reduce energy consumption for other cooling purposes or use it in the gas turbine to reduce the inlet temperature of the air to increase the efficiency. However, such an integration might increase the complexity of the propulsion system.

5.1.2.Methane

Like hydrogen, methane can be stored in compressed (200-250 bar) or cryogenic liquefied (below -163°C, atmospheric pressure) form. Cryogenic conditions are less demanding than for hydrogen, and cryogenic storage for ship transport of methane is a state-of-the-art technology.

Pressurized methane cools down during expansion. Depending on the pressure reduction steps, additional heating might be necessary to prevent the icing of the valves. As the volumetric density of methane is significantly higher compared to hydrogen, the pressure in the fuel supply line can be at a lower level without too much pressure loss or excessively large diameters of the fuel pipe.

LNG can be pressurized by a cryogenic pump prior to evaporation. Compression after evaporation would also be possible, but it increases energy consumption and thus reduces efficiency.

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5.1.3. Methanol

Methanol is a liquid at ambient conditions. Like other liquid fuels, it can be stored in unpressurized tanks on board a ship. Pumps transport it to the gas turbine.

In the combustor, methanol can be used as liquid fuel with a spray atomizer or evaporated as gaseous fuel. If the combustor needs to operate with gaseous and liquid fuels, two different fuel control systems and fuel injectors are generally used. This increases the complexity of the combustor and is challenging in small combustion chambers. Because methanol is a single-component fuel, another option is the evaporation of the fuel and the use of the same fuel injectors as for the gaseous fuel. It reduces the complexity of the combustor but adds the evaporation step for the liquid fuel. The fuel is heated above its vaporization temperature in the evaporator at the given pressure. This can be done by electrical heating. Methanol must be heated to about 160°C to reach a pressure of about 20 bar, which is well below the self-ignition temperature of 585°C.

Typical fuel control systems for liquid fuels consist of a fuel pump with a controllable speed. This pump builds up the pressure needed to atomize the fuel.

5.1.4. Ammonia

Ammonia liquifies at ambient temperatures if pressurized to around 9 bars or at atmospheric pressure at temperatures below -33°C. Typically, it is stored in low-pressure tanks at ambient temperature. These properties of ammonia, which simplify storage, represent an increased requirement for use in gas turbines. At pressures of around 20 bars the vaporization temperature is about 50°C. For pumping the liquid ammonia, the fuel control system, and the fuel injectors, it is essential to avoid phase separation of the fuel. For a pump it might be necessary to keep the temperatures low enough to prevent evaporation. However, the injector and the combustor parts might be hot, and the gaseous phase would be preferred. Ammonia must be vaporized at a certain point, and the fuel control system must be heated to avoid unwanted condensation.

5.2. Combustion behaviour of the different fuels

5.2.1. Combustion properties

How a fuel behaves in a combustor in terms of flame stabilization, flashback, and emissions depends on the combustor and the fuel's combustion properties. In this section, different chemical properties are compared that are relevant to the fuel's reaction.

Figure 15 compares the laminar flame velocity of different fuels for different fuel-to-air ratios. Laminar flame velocity is the velocity of the flame front in a perfectly mixed fuel-air mixture in a laminar flow. This is not directly linked to the complex behaviour of a turbulent combustion process, but the trends can be transferred to technical relevant cases for similar conditions. In the diagram, hydrogen shows the highest flame velocity, an order of magnitude higher than methane. This significant factor first explains why hydrogen combustion differs from other fuels. Later in this section the effect of the high flame velocity on emission forming will be discussed in more detail.

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Methanol is like methane, while fuels like diesel oil or kerosene show a higher flame velocity. It needs to be mentioned that these flame velocity values are measured with vaporized fuel. The fuel's atomization and evaporation have an additional effect that is independent of the chemical reaction rate.

Ammonia is at the lower end and is almost as far away from methane as hydrogen but in the other direction. The low flame velocity of ammonia is one reason why flame stabilization in typical combustors is challenging. One way to overcome these difficulties is to partially or completely decompose the ammonia (cracking). This produces a mixture of hydrogen and nitrogen and, depending on the degree of decomposition, a proportion of ammonia. The proportion of hydrogen increases the reactivity of the mixture, which is beneficial for combustion. The inert gas content of nitrogen, on the other hand, ensures that the reactivity does not increase as much as for pure hydrogen, even with a high hydrogen content.

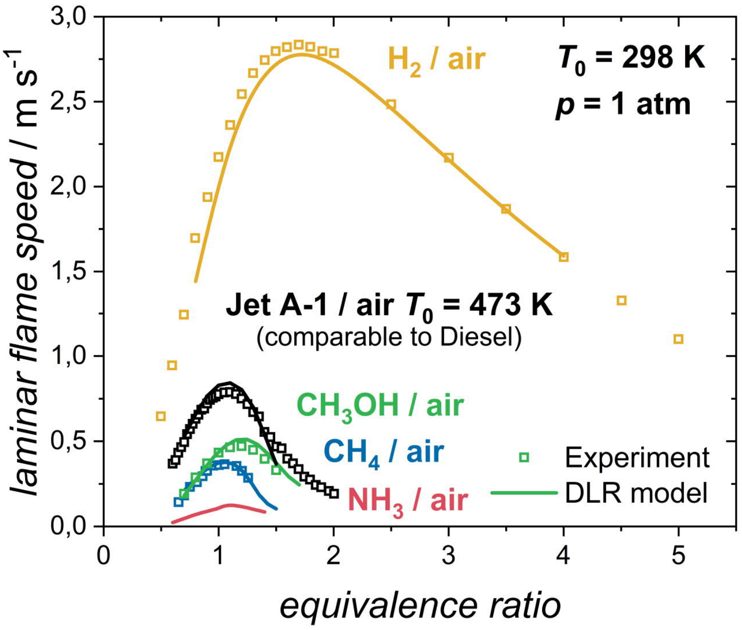

Figure 15: Laminar flame speed for different fuels versus equivalence ratio

Flame stabilization in a combustor is a complex interaction of the flow field and the chemical reactions between fuel and air. Besides the flame velocity, which is responsible for flame stabilization based on flame propagation, the self-ignition of the fuel-air mixture plays an important role. The time that it takes for an air-fuel mixture at a specific temperature to ignite is called the self-ignition time or ignition delay time. Figure 16 shows the self-ignition time for hydrogen (H_2) and methane (CH_4) for different temperatures and pressure levels. The temperature is given as its reciprocal value.

For methane, the ignition delay time is reduced linearly for a given temperature with pressure for all temperatures. This is because the increasing pressure influences the chemical reaction, proportional to the density. The ignition delay time for hydrogen is significantly shorter. However, more important is the more complicated pressure dependence of the ignition delay time of hydrogen. The ignition delay time can increase or decrease with pressure, depending on the temperature. This behavior is relevant in the typical pressure and temperature range in a gas turbine combustion chamber. The reason for this behaviour is competing reactions in hydrogen combustion, which have different pressure dependents.

A combustor can have a great variety of different temperatures, and a gas mixture will have a complex temperature history. However, this pressure dependence can strongly affect flame stabilization and extinction.

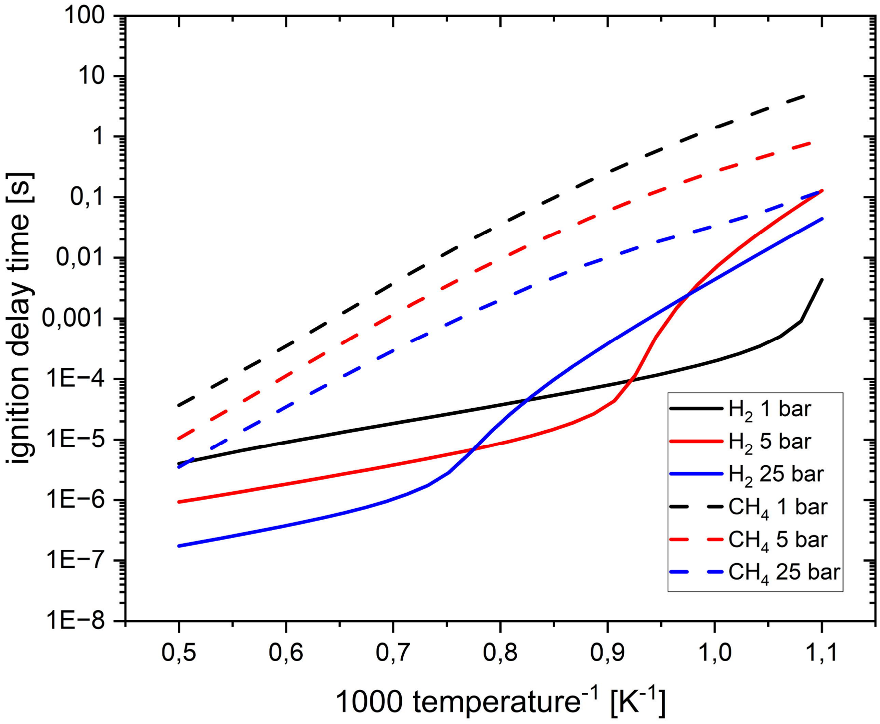

Figure 16: Pressure dependence of ignition delay time for hydrogen and methane

The combustion temperature is another difference that influences combustion behaviour and the formation of pollutants. It has a particular influence on the formation of nitrogen oxides, which are predominantly formed by the thermal NO_x formation path in most fuels. As shown in Figure 17, in addition to the fuel, the combustion temperature also depends on the ratio between air and fuel, represented here by λ, the air-to-fuel ratio. For values of λ below 1, there is more fuel than can be oxidized by the air, so-called fuel-rich conditions. If λ is above 1, the mixture has excess air, and the fuel can be combusted to 100%. In general, gas turbines operate in fuel-lean conditions. To analyse the combustion process, one must differentiate between the global λ, defined by the ratio of air and fuel entering the combustion chamber, and the local λ, at a specific position inside the combustion chamber. The local λ in the gas turbine combustion chamber depends entirely on how the mixing of air and fuel proceeds before the mixture is ignited. As shown in Figure 15, the flame velocity has its maximum around an equivalence ratio of 1, which coincides with a λ of 1. In non-premixed combustion systems, where fuel is directly injected into the combustion chamber, the combustion tends to stabilize in areas with close stoichiometric conditions, even if the overall mixture has excess air (lean conditions). Thus, modern combustion systems try to premix air and fuel to reduce the local combustion temperature. From Figure 17, it is visible that for the same λ, hydrogen has about 200 K higher adiabatic temperature compared to methane. How this can affect NO_x production is shown in Figure 18, where the NO_x concentration is plotted against the residence time for a stoichiometric hydrogen and methane flame, respectively.

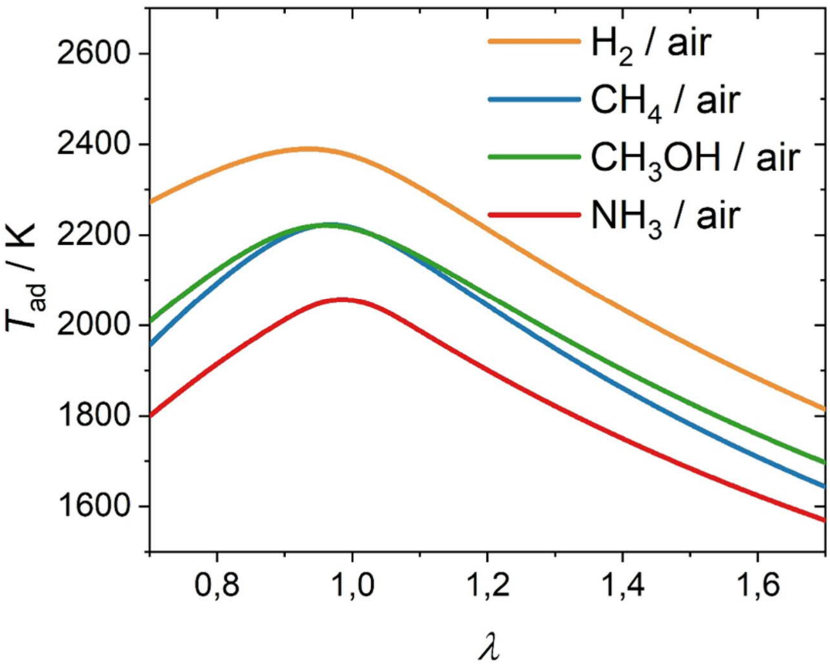

Figure 17: Comparison of adiabatic flame temperatures (T_{ad}) for different fuels and varying air to fuel ratios (λ)

The higher temperature of hydrogen causes a much more substantial increase in NO_x concentration over time compared to methane.

There are two ways to keep the NO_x emissions low for hydrogen flames. One way is to mix more excess air well with fuel. If the hydrogen flame is operated at higher λ values, the adiabatic flame temperature can be reduced to similar levels as for methane. Because of the higher reactivity of hydrogen, operating at leaner conditions is possible without compromising the flame stability. The challenge is to allow for good mixing of fuel and air before combustion without risking the flame's flashback into the combustor's mixing zone. Another way is to limit the residence time in the combustor. This is especially important for

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combustion systems of heavy-duty gas turbines, as they need to operate at high temperatures to reach the necessary efficiency in the turbine.

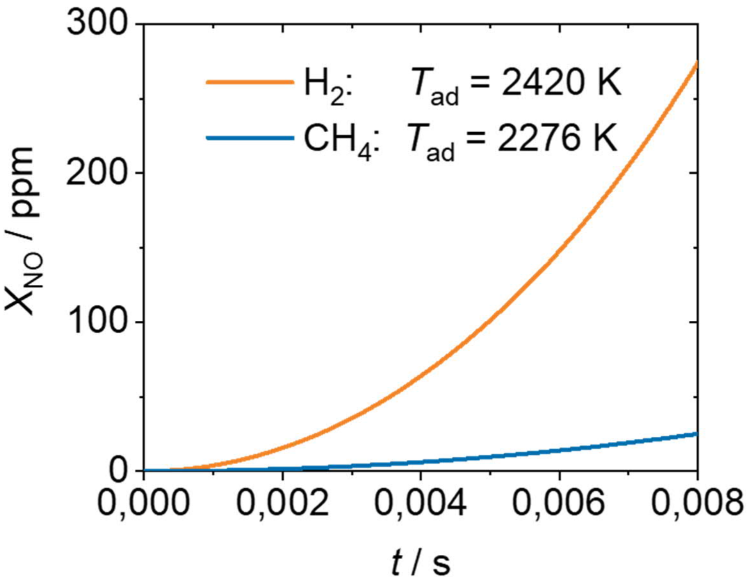

Figure 18: NO_x formation versus residence time for hydrogen and methane at stochiometric conditions and atmospheric pressure

5.2.2.Role of combustion system

Besides the chemical properties of the fuel, the combustor design plays a vital role in flame stabilization and emission formation. Today, most combustion systems in gas turbines are based on swirl-stabilized combustion. Figure 19 shows a schematic of the major elements in a swirl-stabilized combustor. The schematic shows one half of an axial symmetric combustor with the dotted line forming the central axis. In such a combustor, fuel is injected upstream in the swirler, and the fuel-air mixture flows into the combustion chamber as a swirled stream. The radial velocity component forms a low-pressure zone in the centre and sucks in hot exhaust gas from the end of the combustion chamber. The hot exhaust gas is drawn back to the inlet of fresh gas, which leads to ignition and stabilizes the flame. The combustion takes place in a small defined reaction zone. Such combustion systems allow for very compact combustion with low emissions but are sensitive to fuel properties. A significant decrease in reactivity can lead to flame blow-off. An increase in reactivity can cause a flashback of the flame, stabilizing in low-velocity areas in the mixing zone inside the swirler and damaging the combustor. Therefore, most of the actual swirl-stabilized combustion systems designed for natural gas are limited to low hydrogen content in the fuel.

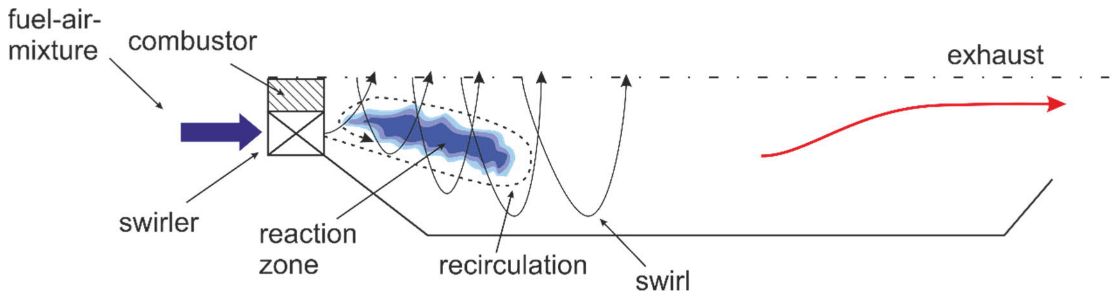

Figure 19: Schematic drawing of the flame stabilization principle of a swirl combustor. Axial symmetric combustor with dotted line as centre axis

Another concept of combustion is jet-stabilized combustion. This concept uses high-velocity jets placed in a circle around the combustion chamber. These jets form a low-pressure zone in the centre, which creates a strong recirculation and transports exhaust gas to the burner face plate. A schematic drawing of such a combustor is shown in Figure 20. Because of the more intense mixing of the incoming fresh gas with the hot exhaust gas, the reaction zone is less localized and more distributed over a larger volume. The high inlet velocity allows for good mixing of fuel and air in the fresh gas prior to combustion. Because of the stable flow field and the more distributed reaction zone, this type of combustion tends to be less sensitive to fuel properties. The absence of low-velocity areas reduces the susceptibility for flashback. Unlike swirl-stabilized combustion, jet-stabilized flames tend to be longer in the axial direction, a hurdle for implementing compact combustion chambers like for aeronautic applications.

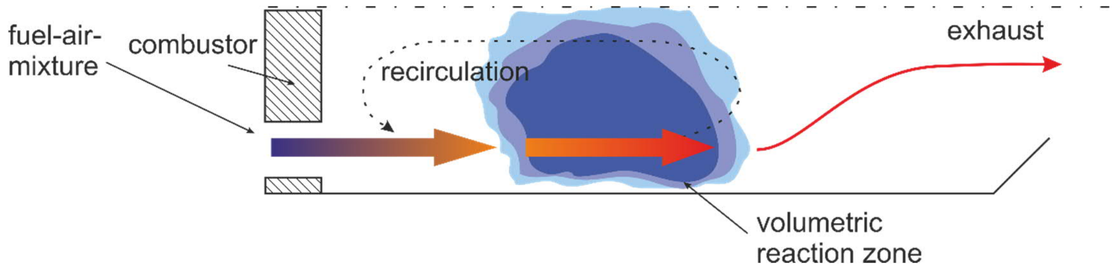

Figure 20: Schematic drawing of the flame stabilization principle of a jet-stabilized combustor. Axial symmetric combustor with dotted line as centre axis

5.2.3. Liquid fuel application

So far, the description of the processes in the combustion chamber has been limited to gaseous fuels. If liquid fuels are to be used, they must first be transferred to the gas phase before combustion to mix with the combustion air. Otherwise, unmixed combustion occurs on the droplets' surface, leading to higher emissions. In the worst case, the droplets are so large that they do not burn in the combustion chamber and leave the combustion chamber as unburned fuel.

Although pre-evaporation can be helpful for an optimum mixture, it also carries the risk of flashbacks. For this reason, the burner systems in widespread use today use atomizer nozzles that first atomize the fuel into a fine spray. An example of such a spray is shown in Figure 21. This spray is usually not fed directly into the combustion chamber but is introduced into the airflow via a so-called pre-filmer. The pre-filmer forms a thin layer of fuel which is picked up and atomized by the airflow. The aim is to achieve tiny droplets that can evaporate fast and a good mixture of air and fuel before combustion.

The challenge of jet-stabilized combustion is that the residence time in the combustion chamber is shorter than in swirl-stabilized combustion. This means that less time is available for the fuel to vaporize in the combustion chamber. If the fuel is only to be introduced shortly before the combustion chamber, special injector concepts are therefore required to allow for stable and low-emission combustion.

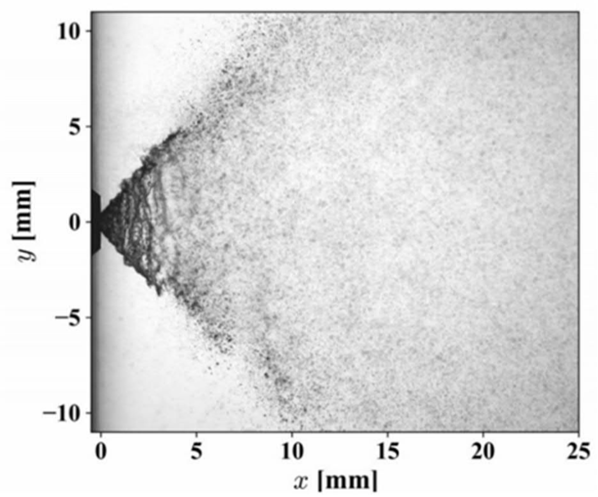

Figure 21: Shadowgraphy image of the fuel spray of a pressure swirl atomizer

Multi-component fuel mixtures like diesel oil include a wide range of components with different boiling points, resulting in a boiling regime starting below 100°C and ending at around 450°C for most of the fuel. Such fuels need a longer time to heat up the droplets and fully evaporate the fuel. In contrast, methanol, considered here, is a single-component fuel with a low boiling point of 65°C. This facilitates vaporization and clean combustion in the combustion chamber.

5.3. Emission potential

The propulsion system emissions relevant to marine applications addressed in this section are sulfur oxides, nitrogen oxides, carbon monoxide, particulates, and ammonia slip. For each pollutant, the source and characteristics of the formation are described and set into the context of the evaluated fuels.

5.3.1. Sulfur oxides

Sulfur is a minor component of fossil fuels. The amount depends heavily on the fuel type and is today limited to 0.5% for heavy fuel oil, which has the highest sulfur content. Sulfur is fully oxidized during combustion, forming SO_x, and there is no way to reduce the amount of sulfur in the combustion process.

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Thus, all sulfur in the fuel forms sulfur oxides in the exhaust gas. This can be reduced by exhaust gas cleaning if necessary.

In addition to the environmental effects, SO_x can react with water in the exhaust gas system and form sulfuric acid. This could cause corrosion to the parts of the exhaust gas system and must be considered when selecting materials.

Neither hydrogen nor ammonia or methanol will contain sulfur, but in principle, this might be possible with biogenic methane. Hydrogen sulfide is formed during fermentation and is initially contained in the biogas. The proportion of hydrogen sulfide ranges from a few 100 ppm to a few thousand ppm and it is removed by gas purification regularly. In this respect, it should not play a role for LBG. It can be assumed that all renewable fuels do not contain any sulfur and that emissions of sulfur oxides are, therefore, not relevant to this analysis.

5.3.2. Nitrogen oxides

As described above, nitrogen oxides are predominantly formed during combustion in high-temperature zones. The primary nitrogen source for this thermal NO_x formation is the air, the major component. Thus, this NO_x production is primarily independent of the fuel used. To reduce this kind of NO_x emissions, it is important to control the combustion process and reduce the local high-temperature zones and residence time.

Another source of NO_x is fuel-bound nitrogen, which is oxidized during fuel combustion. In most fuels, fuel-bound nitrogen plays a subordinated role, as the amount is rather low.

Ammonia occupies a unique position for the fuels examined here. Nitrogen is the main element of the fuel. In the case of ammonia combustion, the ratios are reversed. The oxidation of the nitrogen bound in the fuel is the main formation pathway for NO_x, while thermal NO_x plays no significant role. Various options for reducing NO_x during the combustion of ammonia are currently being investigated in different concepts. One possibility is the combustion of ammonia initially under fuel-rich conditions, whereby hydrogen is formed in addition to NO_x. The hydrogen and the remaining NH_3 can then be used to reduce the NO_x. However, this is still the subject of research. Exhaust gas purification is still required for these concepts. Another way of using ammonia in gas turbine combustion is to break it down into nitrogen and hydrogen before combustion. This costs additional energy but is a good way of using ammonia with low emissions.

5.3.3. Carbon monoxide

Carbon monoxide is formed as an intermediate molecule during the combustion of hydrocarbons. Thus, this can be relevant for methane and methanol as evaluated fuels. CO can be formed when the amount of oxygen during the combustion is not enough for the complete oxidation of the fuel. This can be prevented by sufficient premixing of fuel and air. Another potential formation route is the quenching of the reacting mixture. Suppose the reacting gas stream is mixed with low-temperature gas, and the temperature falls below a specific limit. In that case, the CO oxidation, which needs high activation energy, slows down, and CO remains in the exhaust gas. To prevent this type of CO formation it is necessary to allow enough time for the complete oxidation of CO before mixing cooling air into the exhaust gas.

5.3.4. Particulate matter

Hydrocarbon fuels can form particles that consist of soot. The tendency to form soot particles increases strongly with increasing chain length for aliphatic compounds and the proportion of aromatic compounds in the fuel. This is because the soot molecules themselves consist of large ring-shaped structures. Soot formation would only be possible with methane and methanol for the fuels considered here. However, neither fuel shows a tendency for soot formation in lean gas turbine combustion. Therefore, particle emissions are not expected to be relevant for the fuels considered here.

5.3.5. Fuel slip

Fuel slip describes the escape of unburned fuel from an engine's combustion chamber into the atmosphere. For gas turbines, two cases must be distinguished. The first case concerns the gas turbine's regular operation, and the second case concerns short-term faults, such as an emergency shutdown or the flame going out.

In the first case, it can be assumed that the fuel is completely converted in the combustion chamber, and therefore, no fuel slip occurs during regular operation. This is where gas turbines differ from reciprocating engines. In the gas turbine, continuous combustion takes place after the single ignition to start the gas turbine, ensuring complete fuel conversion. Only during the ignition process is it possible for unburned fuel to leave the combustion chamber. However, ignition occurs only once and at very low fuel quantities, which is why this is irrelevant to the environmental impact. In engine systems, on the other hand, each piston stroke is accompanied by a highly transient ignition process of a large quantity of fuel. There is, therefore, a higher risk of unburned fuel leaving the combustion chamber. The behaviour described above applies to gas turbines for all fuels considered here. There is evidence for methanol, methane, and hydrogen. No gas turbines are running on ammonia today. However, it can be assumed that the combustion system can be designed so that no ammonia slip occurs during regular operation.

During an emergency stop or flame extinguishing, the fuel supply to the gas turbine is stopped immediately. Nevertheless, it is possible for a limited amount of fuel to leave the gas turbine unburned for a short time. Here, the amount of unburned fuel is irrelevant to climate impact. However, aspects of toxicity can play a role here, as even small and short-term exposures can lead to damage, depending on the fuel. This aspect is only assessed as critical for ammonia for the fuels considered. Since even small quantities of ammonia pose a risk, these short-term operating conditions must be given special consideration. Additional exhaust gas after-treatment may be necessary to cover these cases and to reduce the emissions to an acceptable limit.

6. Techno-economic feasibility study

A Delphi study has been designed and will be conducted to assess the feasibility of using sustainable fuels in shipping. Specifically, the Delphi study aims to evaluate the risks and potential of various future maritime fuels, focusing on gathering insights from industry experts to support the Marpower project.

The study is designed to explore the market perspective on the risks and opportunities associated with liquid hydrogen (LH_2), liquid ammonia (LNH_3), methane (LNG), and methanol. The findings of the Delphi

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study will add to the findings of the studies done under Tasks 1.2: Sustainable fuels evaluation and 4.3: Feasibility: Risk assessment, maintenance, LCA & LCC.

The primary objective of the study is to assess the technological, economic, regulatory, and environmental risks related to each fuel type while identifying business opportunities and aligning with CO_2 emission reduction goals. To achieve this, the study will engage maritime logistics operators, fuel technology experts, economists, and risk analysts through a structured, iterative process.

The conceptual framework for the study has been created based on the implementation of the activities in Task 1.2 and the results reported in this deliverable, and to complement with the findings from Tasks 1.2 and 4.3. The study consists of three phases. In the exploratory phase, qualitative insights into risks and opportunities will be gathered using a structured questionnaire, which will focus on high-level analysis of technological, economic, regulatory, and environmental challenges. The refinement phase will involve a follow-up questionnaire to provide more detailed assessments of risk impacts, likelihoods, and market potential for each fuel type. An optional consensus-building phase will include virtual workshops or discussions to align expert opinions and address unresolved issues.

The Delphi study will utilize an online survey platform, such as Webropol, to efficiently collect and analyse responses. Generative AI tools will assist in identifying trends, areas of consensus, and divergent views. The study is expected to produce a comprehensive report detailing business opportunities, technological risks, economic challenges, regulatory barriers, and environmental impacts, offering actionable recommendations for the Marpower project's strategic development.

Scheduled to take place in early 2025, with preparatory work beginning in late 2024, the Delphi study will prioritize recruiting maritime operators, fuel experts, and other key stakeholders to ensure high-quality insights and commitment throughout the process.

The findings of the techno-economic feasibility study will be published in reports on an update-by-update basis using the continuous reporting module of the project.

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