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Abstract	Hydrogen and hydrogen-based fuels (such as methanol and ammonia) offer tremendous potential for the decarbonisation of the worldwide maritime fleet. This study includes a comprehensive evaluation of the feasibility and potential environmental impacts of using hydrogen as a fuel source for marine transportation, including screening of existing solutions and assessing their applicability for the project in terms of environmental impact and operational requirements. The analysis included four fuels, namely compressed hydrogen, liquid hydrogen, methanol and ammonia, and the screening process involve considering a range of factors, such as availability, safety, costs, and infrastructure requirements. This study concluded that compressed hydrogen with PEMFC is the most cost-effective option for relatively small ships with an operational profile that allows for frequent refuelling. Ammonia with SOFC is the best for deep-sea shipping applications or smaller vessels with high-value cargo (e.g. chemical tankers), and liquefied hydrogen with PEMFC for every ship in between. Selection of the best climate neutral fuel for a particular ship must also take into consideration local fuel availability and infrastructure as well as technical difficulties related to handling the refuelling process. For this project, as it involves relatively small ship with operational profile that allows for frequent refuelling, the best option would be compressed hydrogen. Although, currently there is no infrastructure in Croatia for any of the considered fuels, securing supply of compressed hydrogen would be relatively easy. Hydrogen, if properly handled, does not have significant environmental impact through the entire supply chain – from production, through transport, storage and utilization. Also, again if properly handled, hydrogen does not pose significant safety hazard in spite of its perception. Many studies and its record prove that hydrogen is not more dangerous than other fuels.
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ACRONYMS

AFC	alkaline fuel cell
aLCA	attributional life-cycle assessment
BECCS	bioenergy with carbon capture and storage
CCUS	carbon capture, utilisation, and storage
CHP	Combined Heat and Power
CNG	compressed natural gas
DAC	direct air capture
DME	dimethyl ether
DMFC	direct methanol fuel cell
FC	fuel cell
GH_2	gaseous hydrogen, compressed hydrogen
GHG	greenhouse gas
HFO	heavy fuel oil
ICE	internal combustion engines
IDLH	immediately dangerous to life or health
IMO	International Maritime Organisation
LH_2	liquid hydrogen
LNG	liquefied natural gas
LPG	liquefied petroleum gas
LSHFO	low-sulfur heavy fuel oil
MCFC	molten carbonate fuel cell
MDO	marine diesel oil
MeOH	methanol
MGO	marine gas oil
MTBE/TAME	methyl tert-butyl ether/methyl tert-amyl ether
PEMFC	proton exchange membrane fuel cell
PM	particulate matter
RNG	renewable natural gas
RSE	renewable energy sources
SECA	sulphur emissions control areas
SOFC	solid oxide fuel cell

VLSFO	very low-sulphur fuel oil

1 INTRODUCTION

Throughout history, humanity has continuously pursued innovative approaches to secure the energy. The 19th-century industrial revolution was a pivotal moment characterised by the extensive utilisation of fossil fuels, which were considered essential for advancement [1]. Currently, worldwide energy demands are rapidly increasing due to factors such as population increase, the desire for improved living standards, and the process of industrialization in developing countries [2]. For decades, the dependence on fossil fuels in traditional energy systems, where they have made up 80% of the overall energy demand [3], has resulted in substantial expenses. These factors encompass a significant surge in the release of greenhouse gases (GHGs), specifically carbon dioxide (CO_2), which leads to later climate consequences such as the rise in sea level [4]. In 2023, there was a 1.1% increase in CO_2 emissions caused by energy-related activities. This resulted in a new record of 37.4 billion tonnes (Gt), which is 410 million tonnes (Mt) higher than the previous year (refer to Figure 1). In comparison, there was a 490 Mt (1.3%) increase in emissions in 2022, primarily due to an increase in coal emissions, which accounted for nearly 65% of the overall increase in 2023 [5].

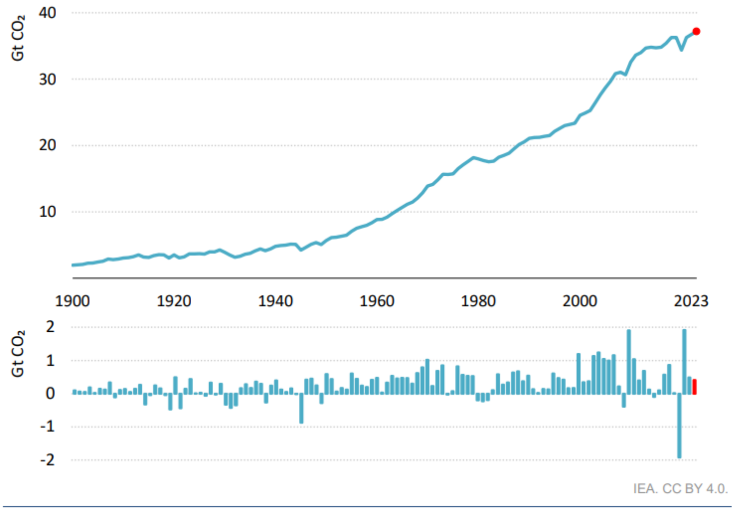

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Figure 1: Global energy-related CO2 emissions and their annual charge.

In 2018, the International Maritime Organisation (IMO) disclosed that worldwide shipping consumed roughly 11 exajoules (EJ) of energy, leading to the release of almost 1 billion tonnes of CO_2 and contributing 3% of yearly GHGs emissions in terms of CO_2-equivalent. Fossil fuels, such as heavy fuel oil (HFO), marine gas oil (MGO), very low-sulphur fuel oil (VLSFO), and, to a lesser extent, liquefied natural gas (LNG), met almost all of the energy demand of the maritime sector, accounting for up to 99%. Additionally, international shipping plays a crucial role in enabling 80-90% of worldwide trade and accounts for approximately 70% of energy emissions in global shipping [6].

In order to support the overarching goal of limiting global temperature increase to 1.5 °C and achieving near-zero CO_2 emissions by 2050, it is crucial to implement focused efforts and strategies to transition towards a maritime shipping sector that is free from carbon emissions. An effective strategy to tackle these difficulties entails the progressive and swift

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substitution of fossil fuels with sustainable alternatives such as cutting-edge biofuels and green fuels like hydrogen, ammonia, and methanol (refer to Figure 2 [7]) [6]. Produced using renewable energy and CO_2, potentially via methods like direct air capture (DAC), these fuels can efficiently complete the carbon cycle and make a substantial contribution towards reaching CO_2 neutrality [8].

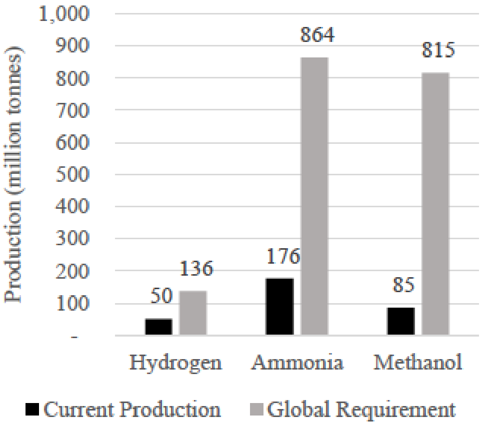
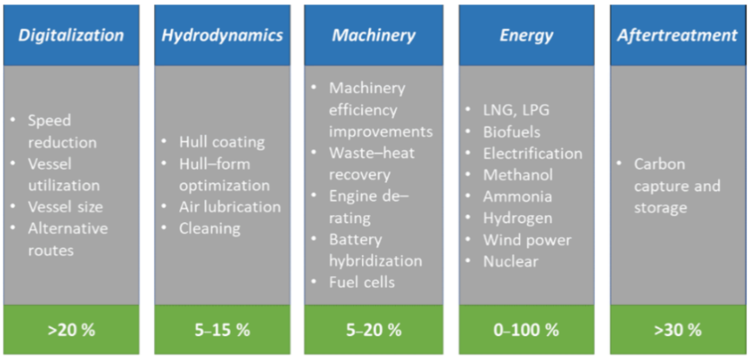


Figure 2: Annual production levels compared to estimated annual demand for 50,000 ships [7], based on data from December 2020.

There are several potential methods and approaches that could be applied to contribute towards decarbonization of the maritime sector, such as digitalization, better hydrodynamics, efficiency, after-treatment, and changing the energy source, Figure 3 [9]. Digitalization resources could be directed towards vessel speed reduction, route optimization, and better vessel utilization, with the overall potential rise of more than 20% carbon footprint reduction. The hydrodynamics approach could tackle a problem through hull coating and cleaning to achieve 5-15% emission reduction, while better efficiency through heat recovery and system efficiency improvement could contribute 5-20%. Carbon capture and storage could be used for the aftertreatment, with a possible emission reduction potential rise of more than 30%. However, the on-board carbon capture technologies are still considered to be in a low stage of development [9]. Therefore, only changing the energy source through the use of an alternative so-called green fuel utilization has 100% carbon reduction potential, depending on the alternative fuel origin and the propulsion system technology [7], [9].



Digitalization	*Hydrodynamics*	*Machinery*	*Energy*	*Aftertreatment*
• Speed reduction • Vessel utilization • Vessel size • Alternative routes	• Hull coating • Hull–form optimization • Air lubrication • Cleaning	• Machinery efficiency improvements • Waste–heat recovery • Engine de–rating • Battery hybridization • Fuel cells	• LNG, LPG • Biofuels • Electrification • Methanol • Ammonia • Hydrogen • Wind power • Nuclear	• Carbon capture and storage
>20 %	5–15 %	5–20 %	0–100 %	>30 %

Figure 3: GHG emission-reduction potential of technologies that can contribute to shipping decarbonization [9].

Hydrogen, methanol, and ammonia as alternative fuels have the most significant potential to contribute to the decarbonization of the maritime sector. However, better logistics and energy efficiency are needed in order to fully realize all the benefits of their use [9]. The first step should be directed towards changes in the main propulsion system technology of the vessel. The majority of vessels currently use internal combustion engines (ICEs) as their main propulsion system, which utilize HFO or marine diesel oil (MDO) as a propellant. Alternative fuels, like the aforementioned hydrogen, ammonia, and methanol, can also power these ICEs. However, although hydrogen and ammonia do not contain carbon in their chemical composition, NO_x emissions are generated due to high pressures and temperatures during ICE operation when using hydrogen [10] or ammonia as a fuel. Furthermore, a similar problem is present when using methanol as a fuel for ICE propulsion, with the addition of CO_2 emissions. By replacing ICE with fuel cell technologies, the problem of all direct harmful emissions is removed, except in the case of methanol, where a certain amount of CO_2 emissions is still present.

The next step should be directed toward the life cycle analysis of the alternative fuel production process. Currently, most of the world's hydrogen production is obtained via methane steam reforming [11]. Therefore, the so-called grey hydrogen is the most accessible as a potential alternative fuel or as a raw material for the production of ammonia and methanol. However, the hydrogen production process by steam reforming leaves the consequences of direct CO_2, CO, NO_x, SO_x emissions, and indirect fugitive CH_4 emissions [11]. Therefore, the use of fossil-origin alternative fuels for the purpose of decarbonization of the maritime sector is justified only in the context of the transition period until the necessary production level of renewable alternative fuels is reached at the global scale. The production of green alternative fuels can be based on the production of green hydrogen by electrolysis of water using electricity directly from renewable energy sources (RES). Furthermore, in order for the ammonia and methanol production process to be completely green in their cases, all the required energy for the purpose of their synthesizer processes should also originate from renewable energy sources.

Biomass is another potential source of raw material for bio-methane production through gasifiers or anaerobic digestion, from which bio-hydrogen would then be produced by steam reforming. Similarly to fossil and renewable cases, bio-methanol and bio-ammonia could be synthesized from bio-hydrogen. Although the bio-methane steam reforming process for hydrogen production generates CO_2, the production process of biofuel production could be considered neutral, as it is considered that the newly growing biomass again absorbs the CO_2 generated during the steam reforming process. However, the carbon neutrality of bio-fuels is still up to debate, as to be truly carbon neutral, stages such as processing and transport would also have to produce no net emissions [7]. Furthermore, the availability of biofuels is bounded by the availability of biomass. Biomass is a limited source of raw material, and the application of shipping fuel is doubtful to be prioritized over food or heating, for instance [12]. Figure 4 shows the simplified supply chain consisting of production, transport, storage, and utilization stages of various alternative fuel types.

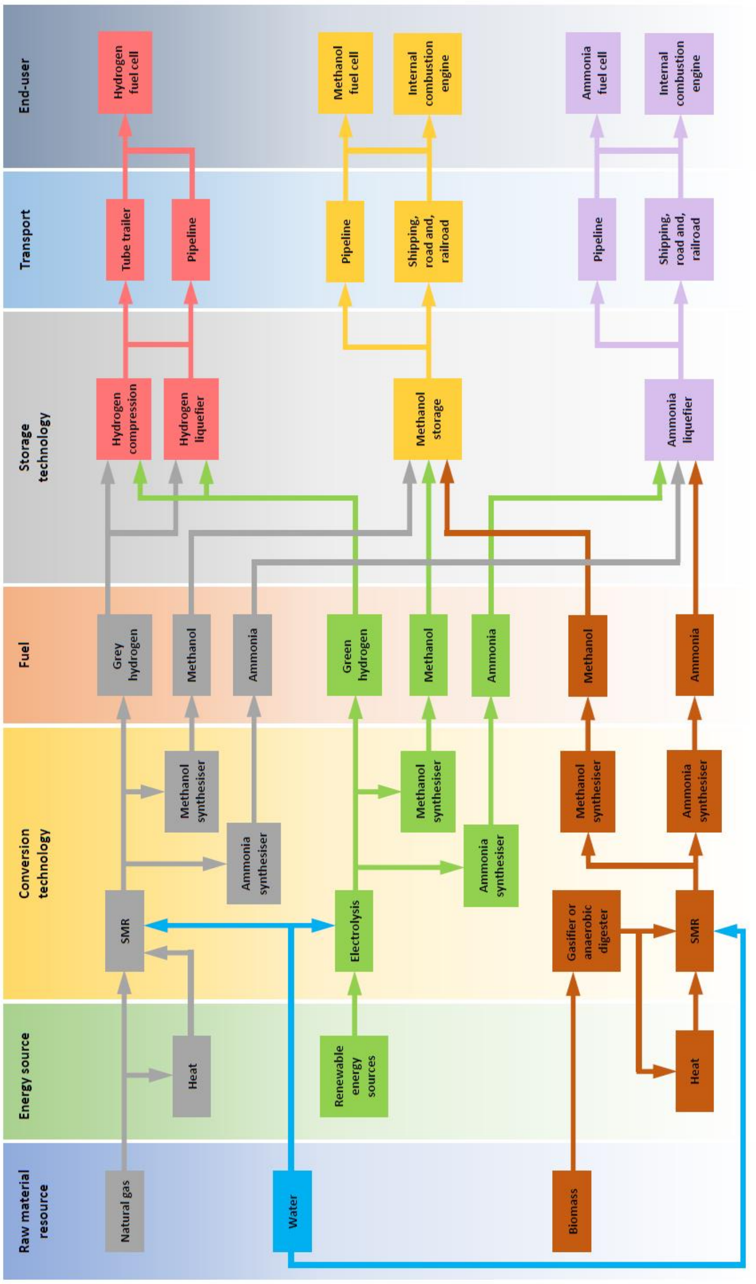


Figure 4: A simplified supply chain consisting of production, transport, storage, and utilization stages of various alternative fuel types.

2 OVERVIEW OF ALTERNATIVE FUELS WITH DECARBONIZATION POTENTIAL OF THE MARITIME SHIPPING SECTOR

2.1 Hydrogen

Currently, the main fuels used in shipping are mostly hydrocarbons, which are molecules made up of carbon and hydrogen atoms. Increased hydrogen-to-carbon ratio in these fuels leads to enhanced energy efficiency and decreased CO_2 emissions. Historically, this dynamic has played a crucial role in shifts from coal to oil and, more recently, from HFO to LNG. Hydrogen, in its pure form, is seen as a viable zero-emission solution for future maritime transportation, as we strive to achieve carbon neutrality [7]. Globally, the primary method for producing hydrogen is through steam methane reforming, which results in significant CO_2 emissions, so-called grey hydrogen. On the other hand, green hydrogen (Table 1), which is produced via water electrolysis using renewable energy sources (RES), stands out as the only feasible alternative fuel for ships. It is the most promising method for creating hydrogen without carbon emissions, which is important for reducing emissions in the maritime sector [6].

Table 1: Properties of green hydrogen [2,4]

Property	**Green Hydrogen**
Chemical formula	H_2
Appearance	Colourless and odourless gas
Molecular mass	2.0156 g/mol
Melting temperature	-259.2 °C
Boiling point	-252.9 °C

The global production of hydrogen experienced a significant growth in 2022, reaching around 95 million metric tonnes, which represents a 3% rise compared to the previous year (refer to Figure 5). Fossil fuels, excluding carbon capture, utilisation, and storage (CCUS), accounted for the majority of worldwide energy production, with natural gas reforming leading the way with a 62% share. Hydrogen generated from coal came in second place with a tight margin of 21%. In addition, around 16% of worldwide output originated from hydrogen produced as a by-product during naphtha reforming. Nevertheless, the production of low-emission hydrogen remained negligible, constituting less than 1 million tonnes or 0.7% of global production. This hydrogen is mostly derived from fossil fuels with the deployment of CCUS. However, the amount of hydrogen produced via water electrolysis in the year 2022 remained very low, not exceeding 100 kilotonnes [13].

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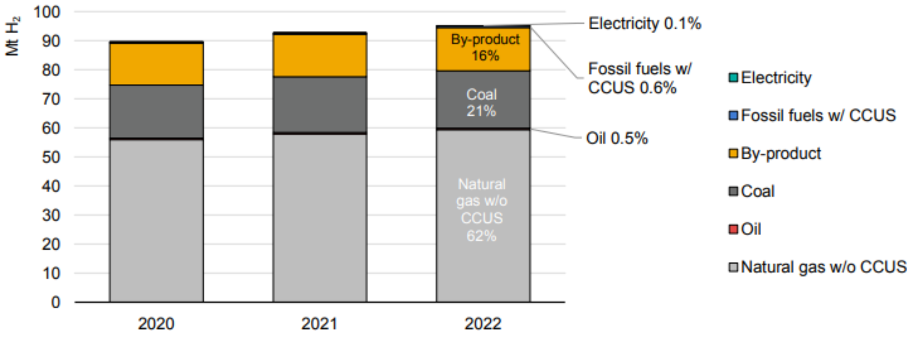

Figure 5: Hydrogen production by technology, 2020-2022 [13].

It is predicted that the production of hydrogen would increase almost five times to reach 614 Mt per year by 2050, as we imagine a world driven by clean energy [14]. This surge is intended to meet 12% of the total energy demand in a scenario that tries to limit global warming to 1.5 °C [15]. Currently, hydrogen is primarily used in the agriculture sector, specifically in the production of ammonia, accounting for around 55% of its overall utilisation. However, recognising the potential of hydrogen as a main fuel for transportation requires a significant rise in production levels. According to certain estimates, there may be a threefold increase in the existing capacity specifically to fulfil the needs of the shipping sector [6]. In addition to its use in agriculture and transportation, hydrogen also plays crucial roles in power generation, synfuel manufacturing, refining operations, and many industrial uses. Figure 6 [13] provides a comprehensive analysis of hydrogen usage in different sectors and areas.

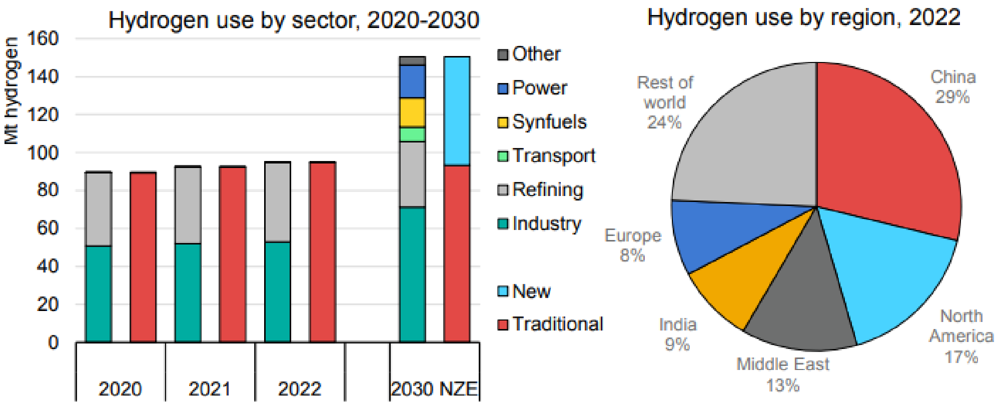

Figure 6: Hydrogen usage by sector from 2020 to 2030 and by region in 2022 [13].

Regarding maritime transportation, the main challenges related to hydrogen pertain to the expenses linked to engine modifications, storage on board, and the provision of ship fuels. Based on the 2021 data, the cost of producing green hydrogen varied from USD 66 to USD 85 per megawatt-hour (MWh). This calculation assumes that energy prices are USD 20/MWh and the cost of electrolysers ranges from USD 650/kW to USD 1000/kW. In comparison, the price of green hydrogen is considerably greater than the current market prices of traditional fossil-based fuels. However, according to IRENA's analyses, there is an expected gradual decrease in the costs of producing green hydrogen in the near future, as shown in Figure 7 [6].

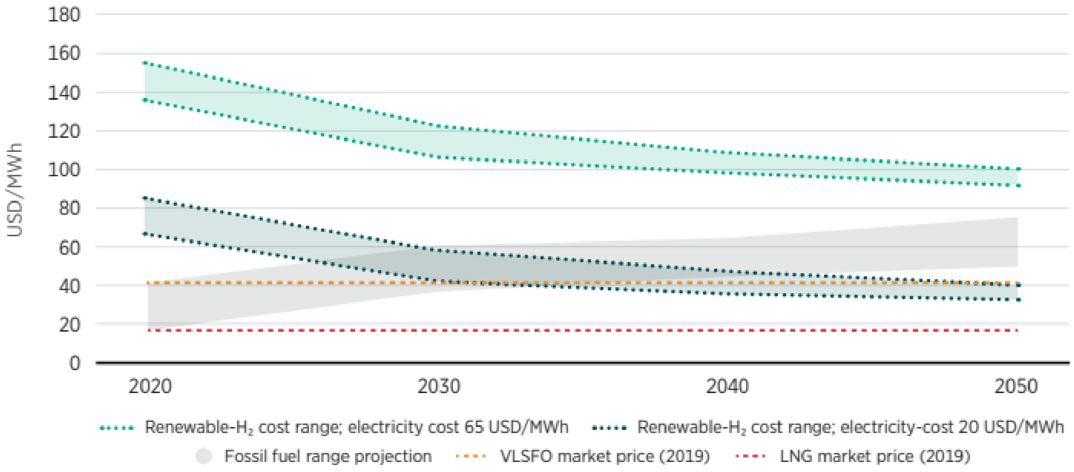

Figure 7: Green hydrogen cost projections [6].

2.1.1 Hydrogen characteristics

Under normal conditions (atmospheric pressure and 0 °C), hydrogen is in a gaseous form [16]. In addition, hydrogen is odourless, non-toxic, and invisible [7]. An important benefit of this is its remarkably high gravimetric energy density, which is 120 MJ/kg, surpassing that of conventional fuels such as petrol, which has an energy density of 44 MJ/kg [4]. The energy released during hydrogen 'combustion' is around 142.26 kJ/g, which is much higher than that of petroleum (35.15-43.10 kJ/g) and wood (17.57 kJ/g) [2]. In addition, hydrogen has a higher ignition energy than petrol and a lower ignition energy than methane. It also has a lower explosive energy [2]. The flammability range of hydrogen extends from 4% to 77% in air [7], which classifies it as an "extremely flammable gas" [17]. Nevertheless, hydrogen's limitation arises from its relatively low volumetric energy density, which is quantified at 0.003 MWh/m^3 [7]. In comparison, batteries have a volumetric energy density that is approximately 220 times greater than hydrogen, while jet fuel exceeds it by almost 3000 times. In order to address this constraint, hydrogen can be compressed to high-pressures or cooled to extremely low temperatures, resulting in an increase in its volumetric energy density [16].

2.1.2 Hydrogen utilization in the maritime sector

In general, hydrogen is used in both internal combustion engines (ICEs) and fuel cells (FCs), with the latter being mostly used in the proton exchange membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs), a comparison of which is given in Table 2. FCs provide numerous benefits, such as low levels of noise, vibration, and pollutant emissions. Additionally, they require less maintenance because they do not have any moving components. Nevertheless, they encounter obstacles such as being very responsive to contaminants, particularly in the process of air intake, specifically for PEMFCs, and being prone to shock. On the other hand, ICEs provide advantages such as improved efficiency for larger sizes, increased power density on average, reduced cost, enhanced ability to handle changes in load, and extended lifespans. However, these systems are known for their tendency to produce noise, vibrations, and have lower efficiencies [16].

Table 2: Comparison between direct hydrogen use in FC and ICE [16]. Red, yellow, and green colours denote low, moderate, and high favourability (viability), respectively. Specific power is commonly defined as power output (kW) per unit of weight, but the inverse is reported here to give values higher than 1.

	ICE	**PEMFC**	**SOFC**
Conversion efficiency (%)	50%	52%	60%
System efficiency (%)	50%	56%	80%
Cost (USD/kW)	<500	>1500	>4500
Specific power* (kg/kW)	2-11	4	50
Partial load efficiency	High	High	High
Tolerance to load variations	High	Medium	Low
Maturity	High	Medium	Low
Lifetime	High	Low	Low
Noise/vibration	High	Low	Low
NO_x, CO and hydrocarbon emissions	Medium	Low	Low

When evaluating FC, both PEMFC and SOFC have an efficiency over 60%. The addition of supplementary elements, such as the plant's balance, slightly reduces the total efficiency by a small number of percentage points. Furthermore, when the size of a FC increases, its efficiency tends to decrease. SOFC has the capability to operate at high temperatures, specifically between 700 and 1000 °C. This allows the production of steam and additional power through steam turbines, potentially elevating the overall system efficiency to around 80%. Consequently, the overall efficiency of the system can potentially reach over 80%.

Opposite to that, PEMFC has a higher specific power (kg/kW) than SOFC. Additionally, PEMFC has quicker start-up times and greater tolerance to load changes. FCs have been the favoured choice over ICEs in the maritime sector in recent times. Nevertheless, FCs are predominantly employed in smaller maritime voyages, such as ferries or tugboats, with power capacities ranging up to 600 kW. At present, the highest level for FC power is approximately 2 MW. However, existing commercial ships that run on liquid hydrogen need a minimum capacity of 5 MW [16].

2.1.3 Hydrogen infrastructure and storage

2.1.3.1 Compressed hydrogen

Storing hydrogen in high-pressurized storage tanks provides a means to decrease the amount of space needed for hydrogen storage. Currently, these tanks have the capacity to store hydrogen under pressure ranging from 350 to 700 bar [2]. This technique enables hydrogen to achieve a higher volumetric energy density, ranging from 1.4 to 2.1 MWh/m^3 [7]. The use of compressed hydrogen gas systems has various benefits, such as cost efficiency, quick charging and discharging cycles across a wide range of temperatures (including very low temperatures), and easy operation with the help of a control valve [2]. However, in order to keep a hydrogen storage tank at a consistent pressure, it is necessary to have extra infrastructure, which includes complex structural concerns [7]. Moreover, because hydrogen is lightweight and has a small molecular size, it is susceptible to leakage from high-pressure tanks, which can lead to the problem of hydrogen embrittlement [4].

Research findings from GEV Scoping Study (2021) indicate that ships powered by fuel cells, with a cargo capacity of 2000 tonnes of hydrogen pressurised at 250 bar, have the ability to travel distances of up to 8300 km, using the fuel for both propulsion and freight [18]. In contrast, a separate study conducted by d'Amore-Domenech et al., in 2021 [19] suggests that hydrogen compressed at a pressure of 275 bar can be transported over a maximum distance of 2600 km. This assumes that the entire cargo is used up and none is left for delivery. The study also considers a ship size of approximately 2700 m^3 or roughly 50 tonnes of hydrogen.

Opposite of that, a distinct investigation conducted by the ICCT in 2022 [20] raises doubt on the practicality of successfully finishing trips, especially when limited to a distance of 1000 kilometres. The discrepancy in results indicates a substantial variation in the capacity of hydrogen cargo as a fuel for ships. Therefore, the use of hydrogen as fuel for ship propulsion may lead to a quick depletion of hydrogen and a shortage of hydrogen available for delivery to the targeted location. Furthermore, the price per unit of hydrogen transported increases significantly as the ship travels a greater distance. Compressed hydrogen ships are considered less appealing for large-scale and long-distance journeys because most important maritime routes are longer than 5000 km [16].

2.1.3.2 Liquid hydrogen

An alternative method for hydrogen storage entails the conversion of hydrogen into a liquid form. Liquid hydrogen has a greater amount of energy per unit volume compared to compressed hydrogen, with a range of 2.2 to 2.8 MWh/m^3 [7]. Nevertheless, the liquefaction process involves the reduction of hydrogen's temperature to an extremely cold -253 °C, which requires a significant amount of energy to attain and maintain such extreme temperatures [7,16]. Insights from the LNG sector, where natural gas is liquefied at a temperature of -160 °C, could be applied to the process of hydrogen liquefaction. Generating the low temperatures necessary for hydrogen production entails the use of numerous refrigerant cycles, which leads to energy losses. The minimum energy consumption can be determined by calculating the function of the inlet pressure, as shown in Figure 8. At a feed pressure of 20 bar, the minimum energy required is roughly 2.67 kilowatt-hours per kilogramme of hydrogen, which is equivalent to approximately 8% of the energy content of the hydrogen. Nevertheless, actual processes in the reality deviate significantly from the ideal state, resulting in higher minimum effort requirements due to factors such as pressure, heat, and energy losses [14].

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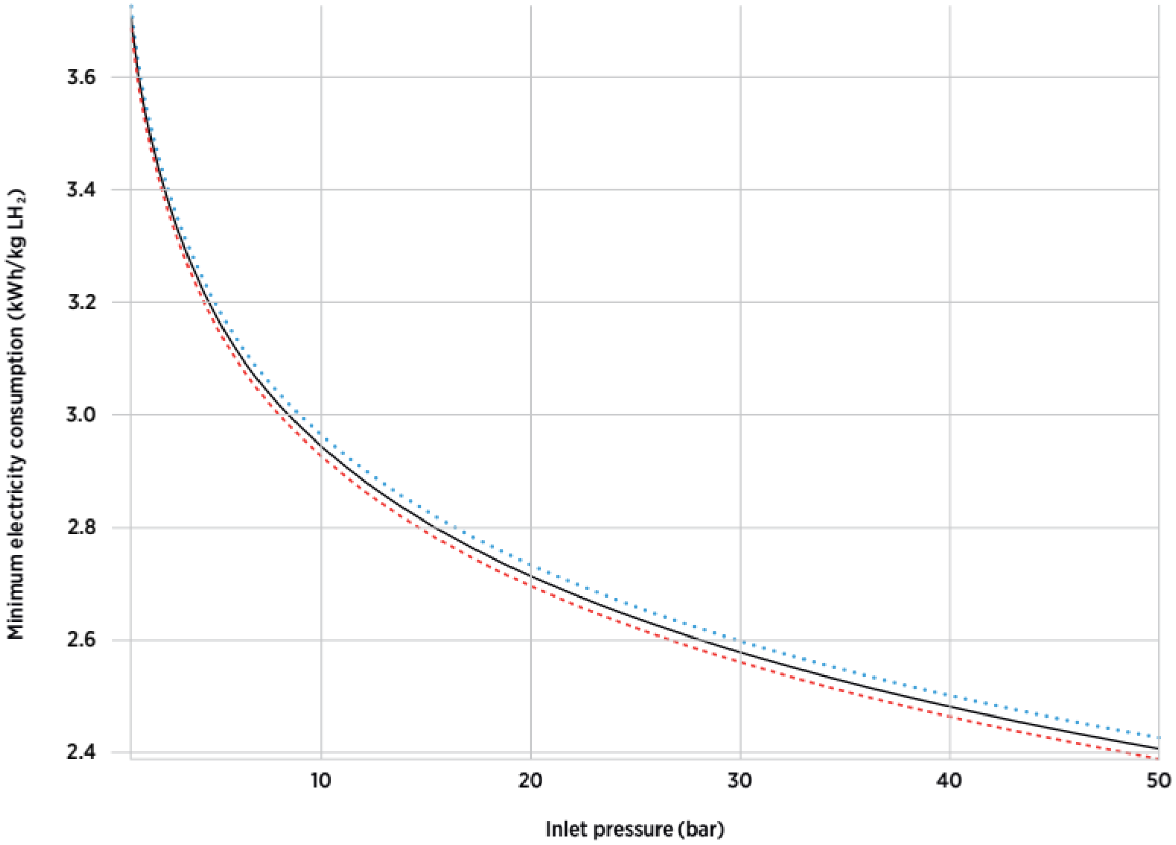

Figure 8: Minimum liquefaction energy consumption as a function of inlet pressure [16]. Lines in the Figure refer to the outlet pressure: 1.3 bar (blue dash-dot line), 1.5 bar (solid line), and 1.7 bar (red dashed line).

It is crucial to create new facilities that utilise existing LNG technologies in order to incorporate liquid hydrogen into the maritime sector. It is recommended that specific equipment used in LNG operations might be adapted for the first cooling of hydrogen, which can reach temperatures as low as -190 °C. This would result in a decrease in the overall cost of hydrogen liquefaction. Nevertheless, in order to achieve the necessary temperature of -253 °C, the implementation of a novel expansion and cooling mechanism would be essential. Chart Industries, a prominent supplier of LNG technology, claims that adapting current LNG infrastructure for hydrogen applications has the potential to result in cost reductions of 50-60% when compared to building completely new infrastructure. However, it is important to note that not all currently available LNG equipment can be easily adapted to meet the requirements of hydrogen-related applications.

New designs would be required for facilities such as ship fuel and transportation to and from ports [16]. During the process of liquefaction, temperature changes that cannot be avoided cause ortho-hydrogen to convert into para-hydrogen through an exothermic reaction. This reaction generates heat, which in turn partially vaporises the liquid hydrogen. This occurrence is commonly referred to as the boil-off phenomena [4][8][16]. In order to tackle this difficulty, several techniques have been developed, such as redirecting the boil-off gas towards the engine for propulsion or condensing the gas back into a liquid state [7]. To keep the hydrogen fuel in its condensed state, the storage tank requires thermal insulation due to its exceptionally low boiling point. A liquid hydrogen storage tank usually consists of a stainless steel container with two walls, along with additional layers of insulation and bearings that have low heat conduction (see Figure 9). Nevertheless, the inclusion of extra piping and components, such as cryogenic valves, results in an expansion of the storage system's volume and mass, thereby decreasing the amount of mass and volume that can be utilised for transportation [8].

Figure 9: Liquid hydrogen storage tank manufactured by SAG for heavy duty applications [8].

Although liquid hydrogen storage tanks require complex insulating systems, their superior energy density in comparison to compressed gaseous hydrogen storage tanks allows them to maintain their advantage, resulting in a reduced specific cost. Liquid hydrogen has a density that is around 80% higher than compressed hydrogen held at a pressure of 700 bar. When storing liquid hydrogen, around 9 kilogrammes of steel is needed for every kilogramme of hydrogen. On the other hand, compressed hydrogen storage requires around 23-24 kilogrammes of steel per kilogramme of hydrogen [16].

2.1.4 Summary

The following table summarize main features of compressed green hydrogen and liquid green hydrogen to be considered at the time of selecting a clean fuel for the maritime sector.

Table 3: Summary of the main features of green hydrogen: compressed hydrogen vs liquid hydrogen.

Property	**Compressed Green Hydrogen**	**Liquid Green Hydrogen**
volumetric energy density	1.4-2.1 MWh/m^3	2.2-2.8 MWh/m^3
gravimetric energy density	120 MJ/kg	120 MJ/kg
auto-ignition temperature	520 °C	520 °C
storage conditions	350 to 700 bar	-253 °C
current production cost	USD 66-USD 85 per MWh	USD 66-USD 85 per MWh
flammability range in air	4% to 77%	4% to 77%
steel needed for storage	23-24 kg per H_2 kg	9 kg per H_2 kg
toxicity	non-toxic	non-toxic

2.2 Ammonia

Ammonia, with the chemical formula NH_3, is a compound formed by the combination of hydrogen and nitrogen atoms. It is well-known for its use in fertilisation, but it has gained significant interest as a maritime fuel alternative as well. This is mainly because it produces no carbon emissions when used [7]. However, green or renewable ammonia (Table 4) refers to ammonia that is produced by using electrical energy from RES for hydrogen production and nitrogen extraction from the air [2,21], and it retains the same chemical properties as its counterpart. Nevertheless, the process of combustion green ammonia might result in the generation of nitrogen oxides (NO_x), which are gases known for their harmful effects on the environment. These emissions contribute to problems such as the creation of acid rain, smog, loss of the ozone layer, and potential negative impacts on human health [7].

Table 4: Properties of green ammonia [2].

Property	**Green Ammonia**
Chemical formula	NH_3
Appearance	Colourless
Molecular weight	17 g
Vapor pressure (at 25 °C)	7500 mmHg
Critical temperature and critical pressure	132.41 °C and 113.57 bar

Ammonia is becoming increasingly important as a carbon-free fuel and carrier of hydrogen, and it is expected that its demand will greatly increase in the future. By 2050, projections indicate that demand for low-carbon ammonia might increase up to three times compared to the levels seen in 2020. Therefore, under a 1.5 °C scenario by 2050 [21], it is estimated that the worldwide production of ammonia will increase to 688 million metric tonnes (Figure 10), in order to keep up with the estimated worldwide demand (Figure 11).

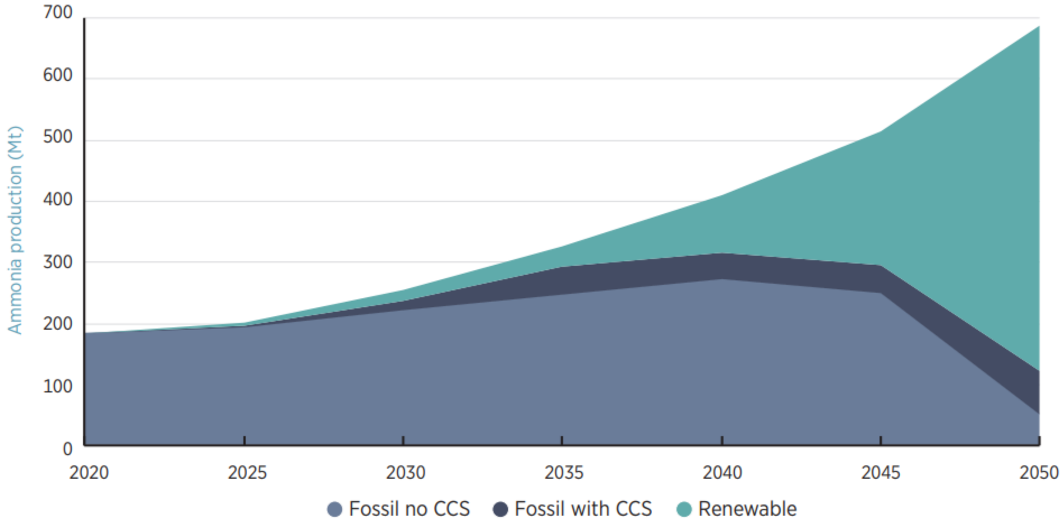

Figure 10: Expected ammonia production capacity up to 2050 for the 1.5 °C scenario [21].

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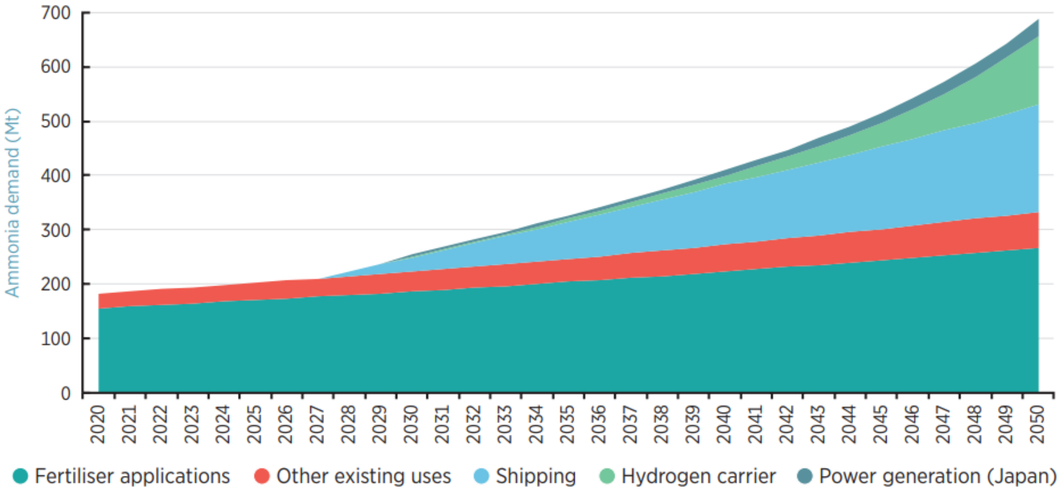

Figure 11: Expected ammonia demand up to 2050 for the 1.5 °C scenario [21].

Currently, the majority of ammonia production, over 72%, is derived from natural gas, while coal accounts for an additional 22%. As a consequence, there were yearly emissions of 0.5 gigatonnes (Gt) of CO_2, which constituted approximately 1% of world CO_2 emissions and 15-20% of the CO_2 emissions from the chemical sector. The global production of ammonia in 2020 was 183 million metric tonnes [21]. The IRENA research [6] highlights that by 2030, the projected projects for renewable ammonia are expected to reach a total of 17 Mt per year. This would account for about 9% of the world ammonia production in 2020. Nevertheless, the production of renewable ammonia in 2020 was rather minimal, amounting to less than 0.02 Mt, which is only 0.01% of the entire world ammonia output for 2020 [21].

Ammonia is expected to play a key role as a marine fuel, accounting for a significant share of 197 million metric tonnes. Out of these, 183 million metric tonnes would be designated for international transportation, while 15 million metric tonnes would be used for domestic shipping. For context, around 18-20 million metric tonnes (Mt) of ammonia were transported globally in 2020 [21].

The costs related to both the manufacturing and use of ammonia are significantly more when compared to fossil fuel alternatives [6]. The Haber-Bosch method, invented about a century ago, accounts for a substantial proportion, reaching up to 85%, of the worldwide production of ammonia [4]. In the Haber-Bosch synthesis loop, hydrogen and nitrogen are transformed into ammonia by a process called conversion. This conversion takes place at high temperatures, typically ranging from 400 to 650 °C, and under pressures between 200 to 400 bar [16,21]. Renewable ammonia, on the other hand, is generated via processes of water electrolysis to separate hydrogen and oxygen, while nitrogen, on the other hand, is obtained by purifying air [21], as it can be seen in Figure 12.

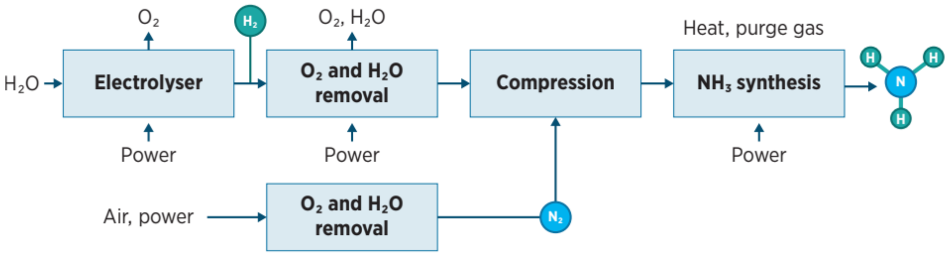

Figure 12: Schematic overview of steps involved in green ammonia synthesis from water and air [21]

The installation of a renewable ammonia plant requires substantial initial investments, mostly determined by either the electrolyser or the ammonia synthesis loop, without considering the expenses of electricity generation. Facilities that produce less than 10 kilotonnes of ammonia per year are mostly affected by the costs of the synthesis loop. On the other hand, larger plants are predominantly influenced by the expenses related to the electrolyser [21]. Moreover, the incompatibility between ammonia with the current ship fuel infrastructure presents a significant financial cost for the installation of such infrastructure [6]. The production costs of natural gas-based ammonia in 2020 varied between USD 21.29/MWh to USD 65.81/MWh. Opposite to that, the expenses of producing renewable ammonia were expected to be between USD 143/MWh and USD 219/MWh in the same year. According to projections [6], there will be a decrease by 2050, with costs estimated to be between USD 67/MWh and USD 114/MWh (see Figure 13). Although the production process for ammonia is more complex and expensive compared to hydrogen, the costs involved with storing and distributing ammonia are cheaper. As a result, the overall cost of delivering ammonia fuel may be significantly lower than that of hydrogen [6].

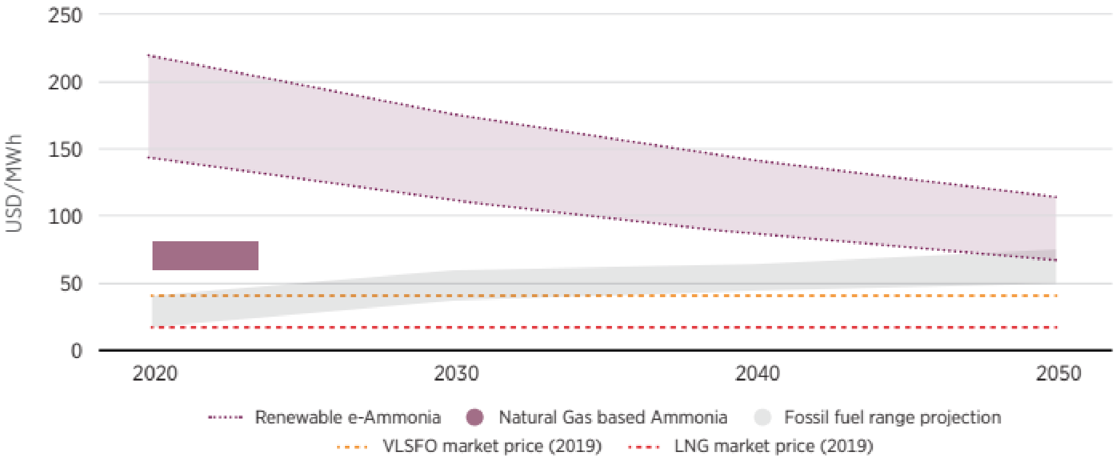

Figure 13: Ammonia production cost projections [6]. The total cost of ownership (e.g. machinery, storage and other) is not captured.

2.2.1 Ammonia characteristics

Ammonia can be stored as a liquid at room temperature at a pressure of 10 bar, or at room pressure with a temperature of -34 °C [7]. Liquid ammonia has a higher volumetric energy density compared to liquid hydrogen (which ranges between 2.2 and 2.8 MWh/m^3) and compressed hydrogen (which ranges between 1.4 and 2.1 MWh/m^3). Its volumetric energy density is roughly 3.53 MWh/m^3 [4]. In addition, ammonia has a considerably greater combustion heat of 11.2 MJ/L, while liquid hydrogen has a combustion heat of 8.58 MJ/L [4]. The gravimetric energy density of ammonia varies from 16 to 20 MJ/kg [2]. Ammonia, while in a gaseous state, has a lower density compared to air. This important characteristic enhances safety by minimising the chances of explosion and fire in case of a leakage. Ammonia has a higher auto-ignition temperature of 650 °C, which makes it less susceptible to ignition compared to hydrogen, which has a temperature of 520 °C. Its flammability range in dry air is 15.15% to 27.35%, while in air with 100% relative humidity it is 15.95% to

26.55%. Ammonia is typically considered as non-flammable during storage and transport [4].

It is important to mention that the perceived toxicity of liquid ammonia is around 1,000 times greater than that of petrol and methanol. Liquid ammonia is considered immediately dangerous to life or health (IDLH) when its concentration reaches around 300 parts per million (ppm). Even a small amount of exposure to liquid ammonia can lead to loss of consciousness. Hence, it is imperative to establish stringent protocols to avoid any direct interaction with humans, and it may be necessary to increase existing safety measures to effectively reduce the hazards posed to both humans and the environment [4,7]. Furthermore, it is crucial to effectively control the combustion of ammonia, as its use at high temperatures can result in the production of NO_x [4].

2.2.2 Ammonia utilization in the maritime sector

Ammonia has attracted interest as a possible fuel for international shipping, with applications in ICEs and FCs [16]. Ammonia, with an octane number of around 120, exceeds that of petrol (86-93), making it a potential candidate for use in ICEs with specific modifications [21]. While early research indicates that ammonia has suboptimal combustion characteristics, such as a slow rate of flame propagation and heat release, these findings do not necessarily rule out its potential as a fuel. Nevertheless, there are still obstacles to overcome, such as increased NO_x emissions during combustion, a significantly higher minimum ignition energy (about 16 times greater than that of fossil fuels) [4], and low radiation intensity [21]. However, ICEs are more economically efficient than SOFCs, with a cost of less than USD 550/kW. They are also more durable, with appropriate power density and load response [16]. Additionally, ICEs typically have an efficiency ranging between 45% and 50% based on lower heating value. Manufacturers of maritime engines are expecting to make ammonia-fuelled two-stroke and four-stroke engines available for commercial use by 2025. The first ships powered by ammonia are also scheduled to start operating around the same period [21].

On the other hand, ammonia has the potential also to be used directly in FCs, especially in SOFCs [4], which are more appropriate for calm inland waterways as opposed to challenging maritime environments [21]. SOFCs have notable advantages among other types of FCs, including alkaline fuel cells (AFCs) and PEMFCs, such as a high efficiency rate of 55-60% [21], the capacity to use many types of fuel, environmental friendliness, and the capability to operate at high temperatures ranging from 700 to 1000 °C. Nevertheless, there are several disadvantages associated with this technology, such as its low power density and load response, its high costs which exceeds USD 1650 per kilowatt, its vulnerability to pollutants, and its current early stage of development. Using alternative FC types such as PEMFC would need the use of pure hydrogen, which would involve the process of cracking ammonia and ultimately lead to a decrease in overall efficiency [16]. The ShipFC consortium [22] plans to demonstrate the use of ammonia FC utilising a 2 MW SOFC starting in 2024.

FCs and ICEs demonstrate different performance characteristics while operating under partial load settings. FCs generally operate at their highest efficiency when operating within the load range of 15-30% of their maximum capacity, whereas ICEs reach their best efficiency with a load of 65-75%. In addition, FCs face a more significant decrease in efficiency at low loads, with a reduction up to 40% in peak efficiency for loads below 10%. Opposite to that, ICEs maintain efficiency levels that are still above 80% of their peak efficiency (refer to Figure 14) [16].

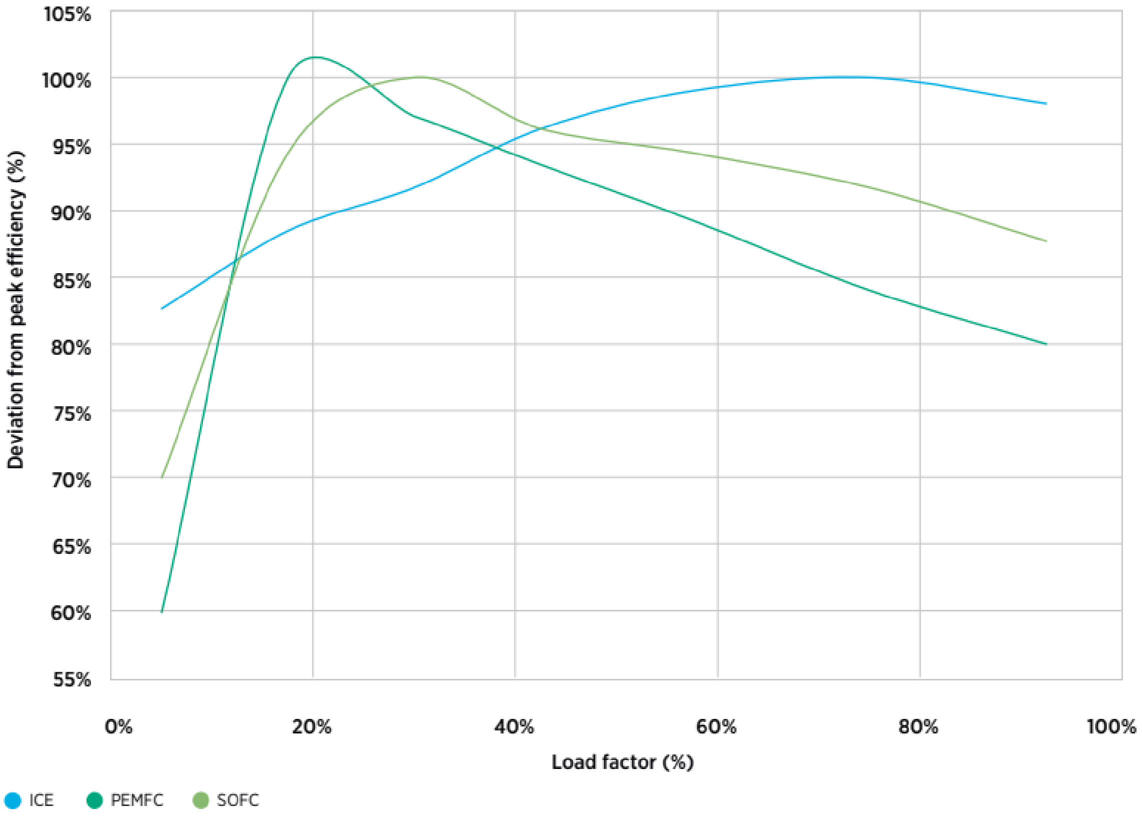

Figure 14: Efficiency of FCs and ICEs as a function of load compared to peak efficiency [16].

2.2.3 Ammonia infrastructure and storage

Ammonia has been identified as a possible solution for the difficulties related to storing and distributing hydrogen, which applies to both the chemical sector and fuel applications [21]. Ammonia cracking, often referred to as dissociation or splitting, is the opposite process of ammonia synthesis, resulting in the production of pure nitrogen and hydrogen. This reaction is dependent on high temperatures and low pressures, as thermal energy is necessary for breaking the bonds inside ammonia molecules. Ammonia cracking can take place at temperatures between 950 and 1050 °C without requiring an optimised catalyst. Alternatively, it can occur at lower temperatures between 500 and 550 °C with the aid of a catalyst, which speeds up the reaction towards equilibrium [16]. Typical catalysts include metallic elements such as cobalt, iron, nickel, and ruthenium. Partial breakdown of ammonia results in a fuel blend composed of different proportions of ammonia and hydrogen. By igniting this combination, the combustion properties of ammonia can be improved by equalising its slow flame velocity with the rapid flame velocity of hydrogen.

When pure hydrogen is required, like as in PEMFCs, it is necessary to decompose it completely and then purify it, which requires additional energy consumption. Under optimal circumstances, the exothermic reaction of ammonia decomposition can utilise around 13% of the available energy to completely convert into hydrogen and nitrogen. Therefore, ammonia decomposition is most useful in situations when using ammonia directly is not possible [21].

Ammonia is considered a preferable choice for storing hydrogen due to its extensive distribution network, well-established handling methods, and regulatory frameworks that govern its transport [4]. The bunkering methods for ammonia are similar to those for other gaseous fuels, but there are specific factors to take into account due to its toxicity and explosiveness [16]. Refrigerating ammonia to approximately -33 °C aboard tanker vessels enables storage in non-pressurized containers, resulting in reduced construction costs compared to pressurized methods [4,16].

Although the transportation of ammonia requires a larger storage volume on-board compared to traditional fossil fuels and LNG, which usually leads to a tolerable decrease in cargo volume, it is crucial to take into account the potential boil-off during transport. Large-scale tanks experience boil-off at a daily rate of 0.04%, which requires extra energy and the use of a re-liquefaction loop [16]. Stainless steel is the preferred material for ammonia storage tanks because it is resistant to corrosion, although this comes at the cost of lower energy density per unit weight. However, ammonia has the advantage of being able to withstand practical fuelling pressures of 1.5 bar and can function in environmental temperatures up to 40 °C without any boil-off occurring. Despite the ongoing issue of boil-off, the use of ammonia, which has a higher boiling point, enables the implementation of insulating technologies and auxiliary components that are more economically efficient, hence reducing tank costs [8], especially if their capacity increases (refer to Figure 15 [16]).

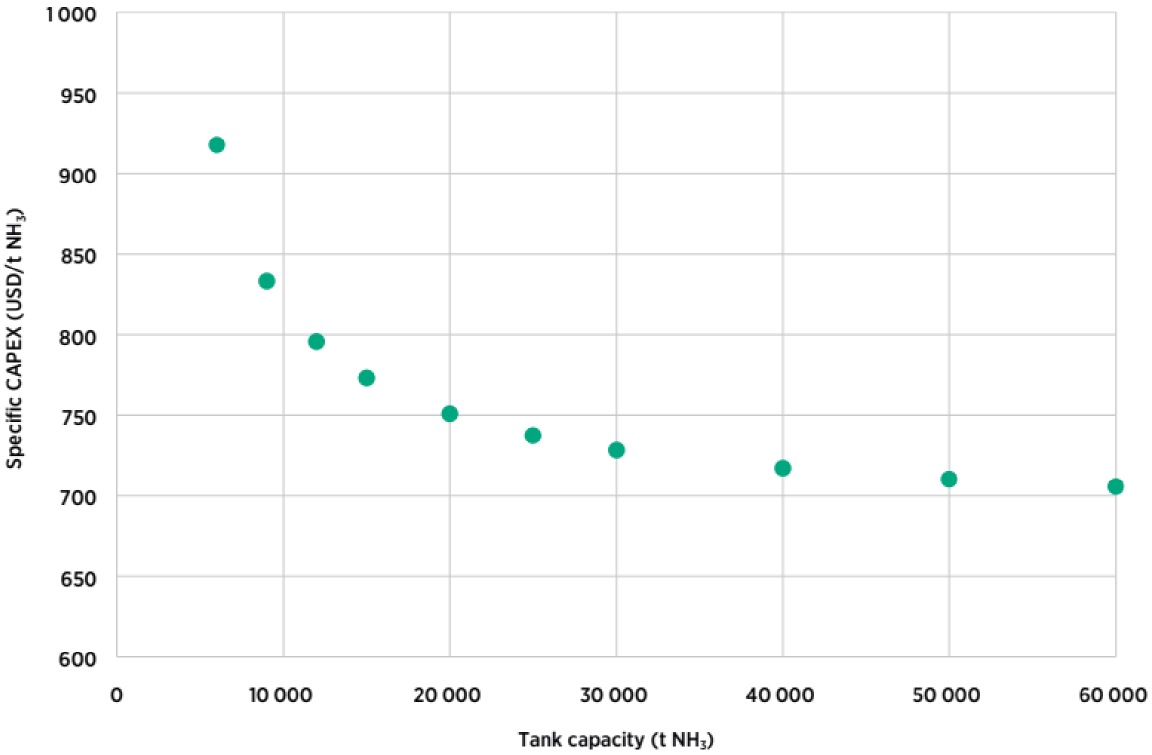

Figure 15: Specific investment cost of an ammonia storage tank [16].

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Nevertheless, preserving ammonia under "mild" cryogenic settings and employing pressure vessels to keep its liquefied form has difficulties that affect both the quantity and weight. Furthermore, the inclusion of double-walled storage tank and necessary components increase expenses in comparison to alternative storage choices. For instance, moderate cryogenic storage of a tank at a maximum pressure of 16 bar has a fuel capacity of around 780 L, which empty weight is around 220 kg, with usable filling mass of around 480 kg [8].

2.2.4 Summary

The following table summarize main features of green ammonia to be considered at the time of selecting a clean fuel for the maritime sector.

Table 5: Summary of the main features of green ammonia.

Property	**Green Ammonia**
volumetric energy density	3.53 MWh/m^3
gravimetric energy density	16-20 MJ/kg
auto-ignition temperature	650 °C
combustion heat	11.2 MJ/L
storage conditions	room temperature at a pressure of 10 bar or at room pressure with a temperature of -34 °C
current production cost	USD 143-219 per MWh
flammability range in air	15.15-27.35% in dry air; 15.95-26.55% with 100% relative humidity
toxicity	IDLH when its concentration reaches around 300 ppm

2.3 Methanol

Methanol is gaining recognition as a highly promising substitute fuel due to its capacity to be produced from a wide range of raw materials and its low-carbon characteristics. In addition to its promise as a renewable fuel, methanol provides environmental benefits for maritime boats by generating minimum amounts of sulphur, NO_x, and particulates. Methanol is a potential solution for meeting the International Maritime Organization's requirements for sulphur emissions control areas (SECA) and sulphur oxides (SO_x) due to its low sulphur emissions [23]. Methanol is predominantly derived from coal and natural gas. Nevertheless, the most encouraging ways for production entail environmentally friendly approaches, such as e-methanol (Table 6) and bio-methanol procedures. The manufacturing of e-methanol requires the process of water electrolysis powered by RES to produce hydrogen. This hydrogen is then combined with sustainably sourced CO_2 obtained from bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC) technologies. However, bio-methanol is produced by the process of biomass gasification and reformation. It uses materials including forestry and agricultural waste, by-products, biogas from landfills, sewage, municipal solid waste, and black liquor from the pulp and paper sector as its sources [6].

Table 6: Properties of green methanol [2].

Property	**Green Methanol**
Chemical formula	CH_3OH
Appearance	Colourless liquid
Molecular weight	32.04 kg/kmol
Melting temperature	-97.8 °C
Vapor pressure (at 20 °C)	12.3 kPa
Critical temperature and critical pressure	240 °C and 73.76 bar

The global consumption of methanol in 2019 amounted to 98.3 million metric tonnes (Figure 16 [24]). However, according to forecasts (refer to Figure 17 [24]), this number is expected to exceed 120 million metric tonnes by 2025 and is projected to reach 500 million metric tonnes by 2050 [24].

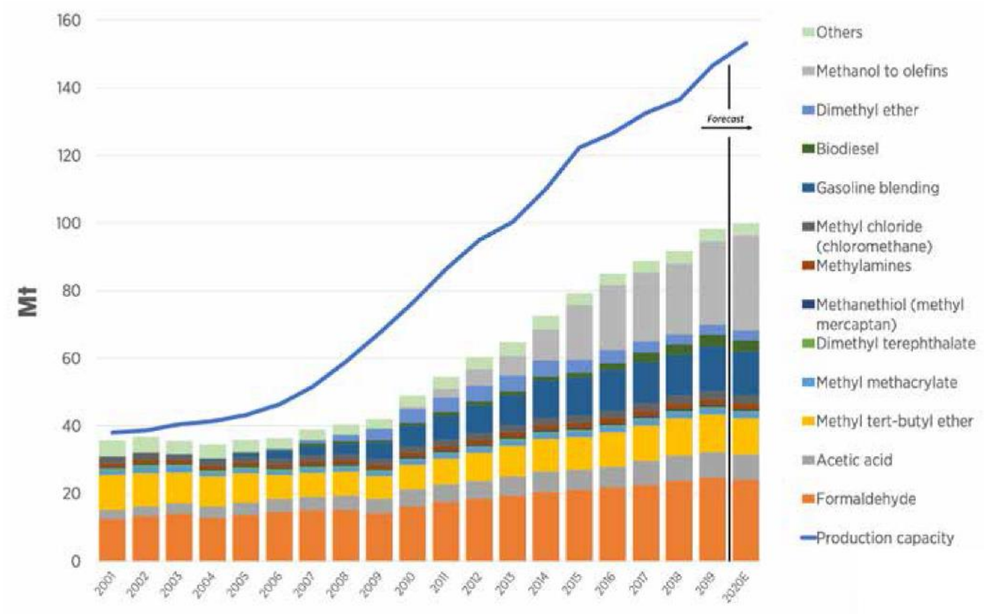

Figure 16: Global methanol demand and production capacity (2001-2019) [24].

Approximately 65% of methanol production is sourced from natural gas reformation, commonly referred to as grey methanol, whereas approximately 35% is obtained by coal gasification, known as brown methanol. Green methanol, sourced from RES contributes a small share, specifically 0.2%, to the overall production of methanol [24].

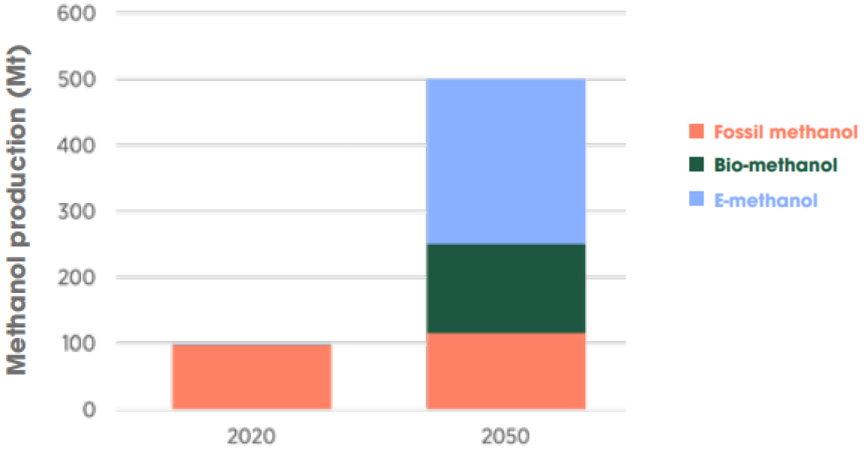

Figure 17: Projection of methanol production by source (2020 and 2050) [24].

Currently, approximately 25% of the worldwide consumption of methanol is allocated to the production of formaldehyde, making it the main purpose for using methanol (refer to Figure 18 [24]). In addition, methanol has several applications, including the synthesis of olefins for plastic manufacturing, methyl tert-butyl ether/methyl tert-amyl ether (MTBE/TAME), fuel production such as petrol mixing, and dimethyl ether (DME) [6].

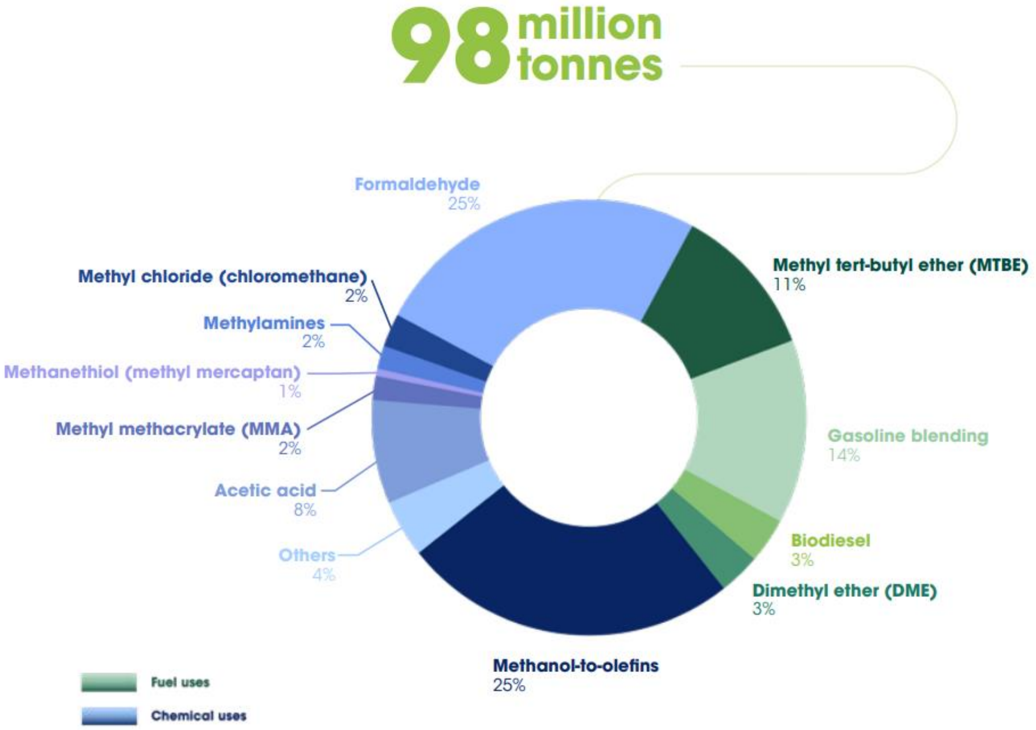

Figure 18: Global methanol demand (2019) [24].

In order to replace half of the worldwide demand for ship fuel with methanol, there would need to be a significant rise in global methanol production, reaching 328.9 million metric tonnes. This amount is three times more than the global production level in 2019. To achieve this ambitious goal, approximately 22.6 million hectares of agricultural land would need to be allocated, which is comparable to 0.46% of the total global agricultural land area.

The production costs of fossil-based methanol range from USD 18.09 to USD 45.23 per megawatt-hour (MWh), depending on the source [6]. The cost of producing bio-methanol ranges from USD 57.89 to USD 139.30 per MWh [6]. The combination of green e-methanol and bioenergy with carbon capture and storage (BECCS) is the most expensive option, with prices varying from USD 144.72 to USD 289.45 per MWh [6]. Projections indicate that the expenses associated with green methanol will steadily decrease until the year 2050, as shown in Figure 19 [6]. The manufacture of bio-methanol depends on well-established gasification technology, but it has difficulties with the availability of biomass and the scalability of production. On the other hand, the primary challenge for e-methanol is the development of carbon capture techniques that are environmentally friendly and economically viable, as they greatly impact the entire expenses of production [6].

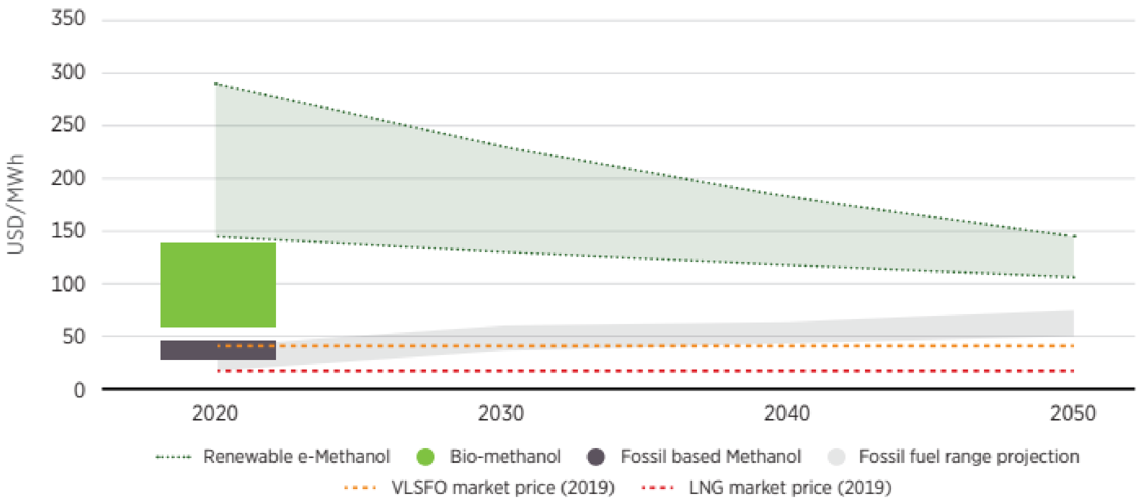

Figure 19: Methanol production cost projections [6].

2.3.1 Methanol characteristics

Methanol, a liquid at standard atmospheric conditions [24], can be stored within a temperature range of -93 to 65 °C. The volumetric energy density of methanol is approximately 4.4 MWh/m^3, which exceeds that of compressed and liquid hydrogen and ammonia, but is lower than that of LNG (6.5 MWh/m^3) and MGO (10.1 MWh/m^3) [6]. Methanol is particularly noteworthy for its high octane number, which surpasses that of petrol, averaging at 100. Methanol possesses a property that enables it to facilitate higher compression ratios in engines. As a result, it improves the efficiency of energy utilisation and thus decreases CO_2 emissions at the tailpipe, while maintaining the same power output.

In addition, mixtures of methanol and petrol demonstrate higher octane numbers and lower CO_2 emissions in comparison to petrol. When used as maritime fuel, methanol has a significantly lower environmental impact compared to petrol. It burns cleaner, leading to a reduction of over 99% in particulate matter (PM) emissions, 95% in NO_x emissions, and 60-80% in SO_x emissions [24]. The specific gravimetric density of the material ranges from 20 to 22.7 MJ/kg [2]. It is essential to exercise caution while dealing with methanol because it is very flammable (with a flammability range of 6.7-36 in air). This necessitates the implementation of proper storage, handling, and operational procedures to avoid explosions. Furthermore, methanol is highly poisonous and might fatal if ingested. The tendency of methanol to absorb moisture from the atmosphere can result in the separation of several phases when mixed with petrol. In addition, methanol displays corrosive properties towards certain metals and is not compatible with certain polymers, resins, and rubber materials. Therefore, it is important to choose appropriate materials that are compatible with methanol while handling it [24].

2.3.2 Methanol utilization in the maritime sector

Methanol's high-octane number makes it a feasible additive or substitute for petrol in ICEs [24], exhibiting an efficiency of around 42% [8]. The adaptability of this technology applies to both four-stroke and two-stroke engines, and it is equipped with advanced technology for efficient utilisation [6]. Methanol can be introduced into diesel engines either in combination with a small quantity of diesel pilot fuel or by installing glow plugs. By 2020, more than 20 big ships were either in operation or being manufactured, employing modified diesel engines that could run on both methanol and diesel. When used as the only fuel in ICEs, it is required to make changes to the size of the tank in order to achieve the same range as petrol or diesel. Engines specifically designed for methanol can allow for increased compression ratios. DME, a methanol derivative, possesses physical qualities that are similar to those of liquefied petroleum gas (LPG) fuels, which makes it ideal for utilisation due to the technological similarities between the two. It is used in compression ignition engines, specifically diesel engines, as a substitute for diesel fuel because of its high cetane number and low soot emission.

Methanol is also used in direct methanol fuel cells (DMFCs) to generate energy [24], or in solid oxide fuel cells (SOFCs) [17]. In DMFCs, it has a higher efficiency in capturing CO_2 compared to conventional combustion methods. While the efficiency of DMFC is usually approximately 40%, it can be increased to 80% by combining it with Combined Heat and Power (CHP) systems [7]. Nevertheless, the issues that arise are primarily due to the high expenses and the limited capacity [24].

Furthermore, methanol is used as a fuel in advanced hybrid vehicles and FC vehicles, where it undergoes reforming into hydrogen while being stored on-board. This method, justified by the fact that methanol has a greater amount of hydrogen per litre compared to hydrogen, avoids the requirement for expensive, high-pressure hydrogen storage and transportation systems on-board. However, there is a need for enhancements to reduce carbon monoxide (CO) levels in reformer outlets, which will help to decrease the requirement for extra treatment [24].

2.3.3 Methanol infrastructure and storage

The global availability of methanol enables its efficient distribution and storage, with millions of tonnes being transported weekly to various end-users through ships, barges, railways, and vehicles. Methanol is particularly advantageous as a fuel source in the maritime sector since it can easily be used with the existing infrastructure for transportation, storage, and refuelling [6]. The process of bunkering methanol, which retains its liquid state under normal conditions similar to conventional bunker fuel, is simple and environmentally friendly. Furthermore, the expenses associated with storing methanol are considerably less as compared to alternative options such as hydrogen and LNG [24].

Methanol tanks, usually made of aluminium, have low storage costs compared to cryogenic solutions since they require few additional components like valves or heat exchangers. The tank's volume and mass are essentially dictated by the density of the gasoline due to the simple design, which includes minimal auxiliary components and thin metal sheets [8]. Nevertheless, because methanol has a lower volumetric energy density compared to MGO, the required storage systems and tanks are generally 2.5 times larger than those needed for MGO. As a result, ships need to set aside more room for storing fuel, which leads to a decrease in the amount of cargo they can carry, in comparison to MGO or LNG storage [6]. Due to methanol's toxicity, it is necessary to pay close attention to the ventilation system in methanol storage in order to reduce the risk of injury to human respiratory health [8].

2.3.4 Summary

The following table summarize main features of methanol to be considered at the time of selecting a clean fuel for the maritime sector.

Table 7: Summary of the main features of green methanol.

Property	**Green Methanol**
volumetric energy density	4.4 MWh/m^3
gravimetric energy density	20-22.7 MJ/kg
storage conditions	-93 to 65 °C
current production cost	USD 144.72-289.45 per MWh (combination of green e-methanol and bioenergy)
flammability range in air	6.7-36%
toxicity	highly poisonous and might be fatal if ingested

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3 LITERATURE SURVEY CONSIDERING ALTERNATIVE FUELS FOR UTILIZATION IN THE MARITIME SHIPPING SECTOR

Most of the research studies considering alternative fuels is directed toward large cargo ships intended for long transoceanic voyages, often considering the use of ICE as the main propulsion system [25–30], while the use of FC has been considered as a potential alternative [31–33]. Only a few studies focus on the exclusive use of FC as the main propulsion system [7,34], while the HFO is considered the main comparison benchmark [25,27,28,31–33]. The evaluation of the considered alternative fuels is carried out according to one or more set criteria. As one evaluation criterion, the environmental aspect in the form of a global warming potential indicator or the assessment of life-cycle emissions or the technical aspect in the form of vessel performance [7] was used. The economic-environmental aspect was considered as a double evaluation criterion [28–30]. Multi-criteria evaluation is often considered, where a particular alternative fuel's technical, economic, environmental, and social aspects were considered [26,31–34].

Deniz and Zincir [26] directly compared methanol, ethanol, LNG, and hydrogen as fuels for ICE use. For the purpose of the presented study, the authors generated comparison criteria and developed a comparison methodology in order to find the most suitable alternative fuel for maritime applications. The authors considered environmental aspects, cost, safety, and expected longevity as evaluation criteria based on the fuel's structural and combustion properties. The methanol evaluation resulted in a low rating, even though methanol is a well-known fuel by marine engine manufacturers and is commercially used in other sectors. However, methanol as a fuel has significant safety concerns, bunker capability problems, engine performance reduction issues, negative effects on engine combustion chamber components, and lower cost-effectiveness. Therefore, it is concluded that methanol is currently not preferable for use on-board. Hydrogen also showed problems related to emission regulations and negative effects on engine combustion chamber components. However, all these issues are avoidable if hydrogen is to be utilized by FC, instead of ICE. Furthermore, this study confirmed that hydrogen could be used as a fuel on merchant ships.

Gilbert et al. [25] performed an attributional life-cycle assessment (aLCA) in order to account for all upstream processes and ship operation emissions, Figure 20. By including the upstream emissions, the authors provided a comprehensive analysis of sectoral emissions by avoiding misapprehensions arising from examining operational emissions in isolation. An aLCA method provides inventory data and associated impacts of the processes used to grow and/or manufacture, distribute, use, and dispose of an alternative fuel by providing the level of upstream and operational emissions released per unit of power delivered by the engine. The authors mainly consider fossil-origin fuels with or without carbon capture technology, bio-fuels, and renewable hydrogen. Furthermore, the authors only consider ICE as the main propulsion system. The results showed that there is currently no available fuel option to be utilized by ICE and to deliver significant savings on local pollutants and GHG emissions. The authors concluded that the effort needs to be directed towards overcoming barriers to exploiting the identified low carbon potential of fuels or finding alternatives not considered within this study. Furthermore, the viability of hydrogen and other synthetic fuels crucially depends on the decarbonization of the production process.

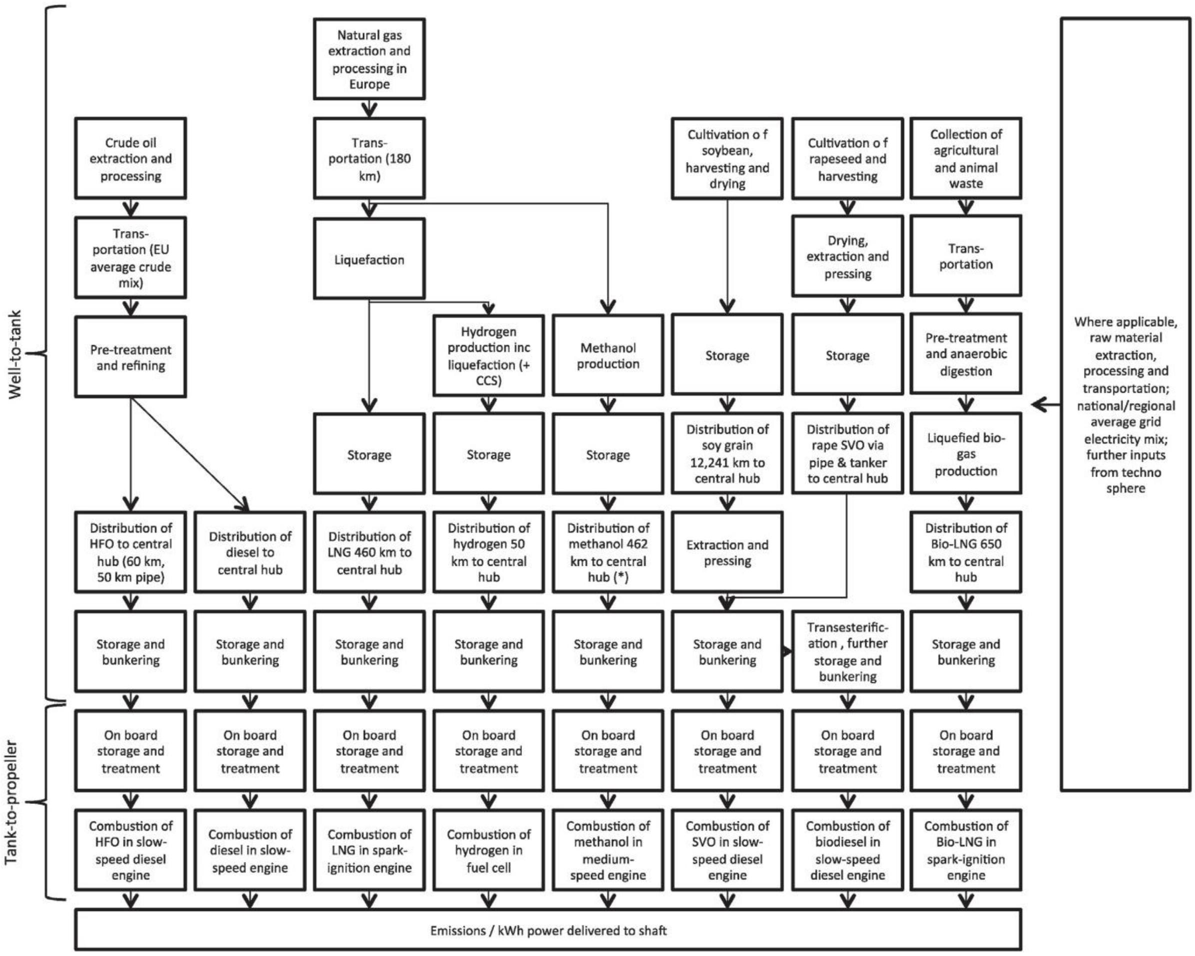

Figure 20: Life-cycle pathways of selected alternative fuels [25].

Chalaris et al. [27] performed an environmental analysis in order to determine the carbon footprint reduction potential of ammonia as a fuel for ICE. The evaluation was performed using the methodology based on the parametric trend life cycle of ammonia, where the level of environmental impact was determined based on the global warming potential. The research was combined with a comprehensive dataset of over 2061 bulk carriers and eight different ammonia production methods: steam methane reforming; photovoltaics; electrolysis via wind; biomass downdraft gasifier; biomass circulating fluidized bed gasifier system; underground coal gasification with carbon capture and storage; underground coal gasification without carbon capture; 3-step copper–chlorine cycle. The authors have concluded that in order to correctly estimate the carbon impact of ammonia as a marine fuel, the well-to-tank stage should be prioritized. Only carbon-free ammonia production processes achieve lower emissions compared to conventional marine fuels.

Hansson et al. [31] assessed the prospects for seven selected alternative fuels for deep-sea shipping by applying a multi-criteria decision analysis approach while considering the stakeholder preferences. The authors consider alternative fuels of fossil, renewable, and bio origin. The multi-criteria analysis, considering economic, technical, environmental, and social aspects, resulted in a ranking of the fuel options for different cases. The ranking was performed based on input from a panel of Swedish maritime stakeholders. Based on the ship-owner, fuel manufacturers, and engine manufacturers ranking criteria, LNG is ranked the highest, with HFO second, followed by fossil methanol. These results arrive from economic criteria, particularly fuel price, which is the top criterion for these actors. However, based on the governmental authority's criteria, renewable hydrogen resulted in the highest ranking, followed by renewable methanol, as the GHG emissions reductions and the potential to meet regulations are top criteria for governmental authorities. The authors concluded that all the renewable marine fuel options will require policy initiatives and instruments that support their introduction. Furthermore, such support should influence renewable options' performances on the relevant criteria, as a better understanding of stakeholder preferences may improve the design and implementation of policies.

Xing et al. [33] performed a review of alternative marine fuels, including their physicochemical properties, combustion and emissions performance, as well as feedstock, production, transportation, storage, and end uses. The main aim of the study was to determine the most likely alternative fuel for low-carbon maritime transportation towards 2050 based on the performed literature review, as well as to propose a multi-dimensional decision-making framework. Furthermore, the study aimed to identify the crucial barriers for each considered fuel, whether the fuel is used for ICE or FC. The fuels considered were evaluated based on technical, environmental, cost, and safety aspects. The fuels were also evaluated for different voyage applications: domestic inland; domestic costal; international short sea; international deep sea (Figure 21). The authors concluded that the adoption of alternative marine fuels is inevitable, as it is difficult to achieve low-carbon shipping through technological and operational measures. Hydrogen and ammonia are evaluated as ideal fuels for inland and coastal shipping in certain regions. However, more national or regional incentives are necessary to encourage local low-carbon development strategies, as the current costs are high and existing infrastructure is insufficient. Furthermore, the infrastructure constructions should consider the recycling utilization of intermediate products for the production of alternative marine fuels and by-products, as well as the cogeneration of cooling, heating, and power, in order to reduce the production cost of alternative marine fuels.

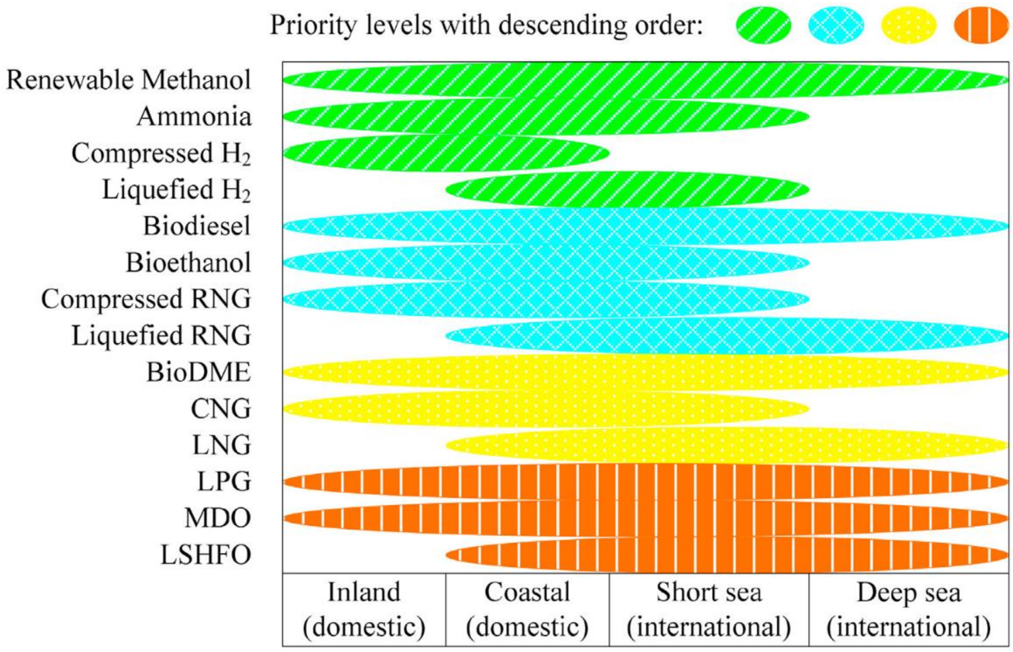

Figure 21: Priority levels and potential applications of different marine fuels [33].

Prussi et al. [32] performed an analysis based on the current body of knowledge by presenting other technical and non-technical aspects. The authors considered fossil-origin fuels, renewable fuels, and biofuels for utilization via ICE or FC where it was applicable. The study showed that among the alternative fuels proposed, only a few can today rely on a large-scale production capacity. Therefore, by comparing the broad volumes required by certain segments could give a more realistic picture of the potential contribution of a specific solution. Even though the maritime sector is usually described as homogeneous, the authors point out the significant difference between ships regarding engine types and fuel consumption. Therefore, this study compares the consumption of each sub-segment with the information currently available for each alternative fuel considered. The analysis showed that even if cost and GHG saving are fundamental enablers the fuel uptake, other aspects, such as technical maturity, safety regulations, operators' expertise, etc., are not sufficiently analysed for certain solutions. The existing reliable infrastructure needs to support an alternative fuel demand. However, this is not the case for most of the proposed solutions.

Kanchiralla et al. [17] did a study that specifically examined green fuels such as hydrogen, methanol, and ammonia. The study focuses on evaluating environmental impacts and costs through the use of life cycle assessment and cost evaluation methodologies while considering both ICE and fuel cell-powered propulsion systems. Three case study ships are chosen to demonstrate the range of ship functions: deep-sea shipping tankers; RoPax ferries; service vessels. The analysis suggests that compressed hydrogen is not feasible for the tanker and RoPax vessel due to the reduced energy density of the energy carrier and the significant energy consumption during bunkering. Additional protective measures are required to ensure the safety of crew members in ammonia and methanol cases. The most significant reduction potential for the tanker cases was exhibited by ammonia when utilized in an SOFC, followed by methanol. The RoPax vessel, which has the most yearly energy usage, has the potential to gain additional cost savings through improvements in life cycle energy efficiency.

McKinlay et al. [7] examined the volume and mass specifications for storing different alternative fuels on large-scale international vessels: methanol; ammonia; hydrogen. The researchers used shipping data from LNG01 (a typical long-distance vessel mainly using LNG as a steam turbine engine fuel). The analysis presumed that the data gathered from LNG01 effectively reflected the requirements of all long-haul shipping. In addition, three alternative approaches were examined to calculate fuel storage: shaft power approach; design range approach; shaft power and design range combination approach. The dataset in the study comprises data from 108 journeys carried out over 38 months. The Shaft power strategy calculated the total amount of energy delivered for each voyage. The Design range technique utilized the longest journey of LNG01 to ascertain the vessel's range and evaluate the capabilities of alternate fuels. The study also considered the storage infrastructure needs for each fuel by evaluating their energy densities, covering the complete system, except methanol and ammonia. Methanol is recognized as more convenient to store and requires less volume compared to hydrogen. Considering fuel storage, it indicates that methanol would pose the least number of technological difficulties for immediate adoption compared to the other two fuels. Ammonia is a compelling alternative, ranking closely behind methanol among the three choices. Although hydrogen is commonly disregarded for this purpose because of its perceived poor volumetric energy density, the results suggest that the necessary volume is not substantial enough to eliminate it as an option. Based on the evidence, cryogenic storage seems to be a more feasible alternative to compressed hydrogen storage.

Atilhan et al. [34] performed a techno-economic and environmental analysis of renewable and fossil-based liquid hydrogen production technologies with a specific focus on the utilization of hydrogen in the shipping industry. The authors have concluded that conventional routes for grey hydrogen production are economically competitive, with a vast infrastructure and almost no tank-to-propeller carbon footprint. However, the well-to-tank carbon footprint of grey liquid hydrogen is substantial. From the health and safety perspectives, there are both advantages and disadvantages when it comes to using liquid hydrogen, as although it is nontoxic, it can lead to asphyxiation if not handled correctly. Furthermore, the high energy density is advantageous from a shipping perspective, while the other chemical properties regarding fire safety should be considered. The authors concluded that the present production cost of green hydrogen is 3-4 times that of grey hydrogen and that the supply chain of the hydrogen economy is mostly dependent on the hydrogen production route. Moreover, there is a need for improvement of the cargo containment systems, as well as the establishment of the globally accepted liquefied hydrogen standards and regulations concerning the safe operation of loading-transit-offloading routines.

A summary of reviewed literature considering alternative fuels for utilization in the maritime shipping sector is given in Table 8.

Table 8: Summary of reviewed literature considering alternative fuels for utilization in the maritime shipping sector.

Author	**Propulsion**	**Fuels considered**	**Evaluation criteria considered**	**Conclusions**

Gilbert et al. 2018 [25]	ICE	HFO MDO LNG Hydrogen Methanol Bio-fuels	**Attributional life-cycle assessment** (assessment of upstream processes and ship operation emissions; considered emissions are greenhouse gasses and local pollutants, namely CO_2, CH_4, NO_x, SO_x, and PM)	There is no available GHG emission and local pollutant-free fuel option for use within ICE. In order to achieve the long-term sustainability of the maritime sector, there are needed actions across other sectors, considering both industry and policy. Potential alternative fuel options need to fulfil full life-cycle emission-free criteria.
Xing et al. 2021 [33]	FC ICE	HFO MDO LNG Hydrogen Ammonia Methanol Bio-fuels	**Technical aspect** (availability in terms of commercial level; on-board and off-board infrastructure; infrastructure maturity level; reliable fuel supply) **Safety** (based on the each considered fuel properties: flashpoint; flammability; toxicity level) **Environmental aspect** (effect on air pollution; effect on climate changes) **Cost** (evaluated based on overall capital costs and operational costs)	The multi-criteria optimization does not provide a solid solution, due to the uncertainties surrounding involved stakeholders' criteria preferences. Hydrogen and ammonia are evaluated as good alternative fuel choices for inland and coastal shipping.
McKinlay et al. 2021 [7]	FC	Methanol Ammonia Hydrogen	**Performance** (based on the real long-distance vessel energy consumption data and physical properties of each alternative fuel considered; energy requirements were determined based on the shaft power data, and design range; simulations	Results show significant fuel option requirement variations based on the evaluation approach taken. Considering only one criterion may lead to misleading results.

			were performed using Python software)	
Atilhan et al. 2021 [34]	FC	Hydrogen	**Technical aspect** (storage) **Safety** (evaluation performed based on: potential health issues; flammability; instability; special hazards) **Environmental aspect** (assessment of upstream processes equivalent CO_2 emissions) **Cost** (production costs)	Hydrogen is one of the few alternative fuel options to meet the carbon emission reduction goals. The creation of global scale demand and utilization hydrogen supply chain is essential in order to reach ambitious CO_2 reduction goals.
Deniz and Zincir 2016 [26]	ICE	LNG Methanol Ethanol Hydrogen	**Safety** (based on the each considered fuel properties: density; flammability; auto-ignition temperature; octane number; cetane number; stoichiometric air-fuel ratio) **Expected longevity** (evaluated based on global availability, reserves, bunker capability, future trends) **Environmental aspect** (effect on engine emissions; compliance with emission regulations) **Cost** (evaluated based on capital cost and operational costs)	Methanol and ethanol have safety concerns, environmental concerns, and lower cost-effectiveness, and as such are evaluated as not preferable for on-board use. LNG was evaluated as difficult to apply, due to complex system structure, tank design, environmental concerns, and overall system safety. Hydrogen evaluation shows an inadequacy in compliance with emission regulations when used as a fuel for ICE. Limited ship application.
Chalaris et al. 2022 [27]	ICE	Ammonia	**Environmental aspect** (global warming potential indicator)	In order to estimate the carbon impact of ammonia as a marine fuel, the well-to-tank should be prioritized. Only carbon-free

				ammonia production processes achieve lower emissions compared to conventional marine fuels.
Hansson et al. 2019 [31]	FC ICE	HFO LNG Hydrogen Methanol Bio-fuels	**Technical aspect** (reliable fuel supply; available infrastructure) **Environmental aspect** (effect on climate changes; effect on health impact; acidification impact) **Cost** (overall on-board associated costs; operational costs; fuel associated costs) **Social** (safety, evaluated based on fuel properties, and potential health hazards; upcoming legislation, evaluated based on the possibility for meeting known regulations)	Ship owners and ship companies prioritize the economic aspects when selecting fuel, with the fuel price as the top priority. LNG is ranked highest by stakeholders. Governmental authorities prioritize environmental and social aspects, the overall GHG emission impact, and the potential to meet regulations. Green hydrogen is ranked highest by the governmental authorities.
Prussi et al. 2021 [32]	FC ICE	HFO LNG Hydrogen Ammonia Methanol Bio-fuels	**Technical aspect** (available infrastructure; reliable fuel supply; ports infrastructure; fuel maturity level for maritime use) **Environmental aspect** (well-to-tank and tank-to-propeller, regulatory framework evaluation) **Cost** (costs associated with the fuel usage) **Social** (expertise, on-board handling for ship owners and operators) **Expected longevity** (future market trends;	Evaluation parameters such as technical maturity, safety regulations, operators' expertise, etc. are still not sufficiently analysed, unlike the GHG emission savings and cost. The existing reliable infrastructure needs to support an alternative fuel demand. However, this is not the case for most of the proposed solutions. In the future, technology improvements, cost,

			competition with other low-carbon technologies)	GHG emission reduction potential, and availability will determine the usage of fuels in the maritime sector.
Solakivi et al. 2022 [28]	ICE	HFO MDO LNG Hydrogen Ammonia Methanol Bio-fuels	**Environmental aspect** (CO_2 equivalent emission factor) **Cost** (fuel cost, forecast based on overall production cost and input raw material cost changes)	Forecast results show that the cost of alternative fuels will remain considerably higher for a long time, compared to fossil fuels. The alternative fuels are expected to take longer to become cost-effective for the current engine technologies.
Loennechen et al. 2024 [29]	ICE	MDO LNG Hydrogen Ammonia Methanol Bio-fuels	**Environmental aspect** (global warming potential indicator) **Cost** (total cost of ownership, each considered scenario determines comprising cost components)	Methane, methanol, and ammonia are found as favourable abatement options when produced from renewable energy sources or biomass.
Lagemann et al. 2022 [30]	ICE	MDO LNG Hydrogen Ammonia Methanol Bio-fuels	**Environmental aspect** (global warming potential indicator) **Cost** (total cost of ownership, comprising: newbuild cost; retrofit cost; cost of fuel; lost opportunity cost)	Optimization results showed that bio-fuels are more cost-effective, compared to electro-fuels, without considering fuel availability. Hydrogen storage system cost is required to increase hydrogen retrofit appeal.
Kanchiralla et al. 2023 [17]	FC ICE	Hydrogen Ammonia Methanol	**Technical aspect** (available infrastructure; reliable fuel supply; fuel availability)	Liquid hydrogen in fuel cells has the highest GHG reduction potential for the RoPax ferries

			Environmental aspect (life-cycle assessment) **Cost** (life cycle costing, considering capital, maintenance, repair, and disposal costs) **Social** (safety, evaluated based on fuel properties, and potential health hazards)	and the service vessel cases. The higher capital cost and shorter lifetime for FCs and batteries have a significant effect on the cost competitiveness of these technologies.

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4 OVERVIEW OF PROJECTS CONSIDERING ALTERNATIVE FUELS FOR UTILIZATION IN THE MARITIME SHIPPING SECTOR

The **ZemShip** project started near the end of 2006 and ended in mid-2010 [35]. The main project objectives were to design, build, and test an inland passenger vessel using a hybrid FC-battery propulsion system for commercial use in the Hamburg urban area. The ship was implemented by two 48 kW PEMFC systems and seven lead-gel battery packs, while the hydrogen was stored on-board within 12 storage tanks at 350 bar. A fully charged hydrogen storage tank unit provided enough energy for approximately three days of operation [35]. Linde supplied the hydrogen until 2013, when the supply was terminated for economic reasons.

FellowSHIP was a project from 2007 until mid-2010, with the objectives to develop and perform off-board and on-board testing of 320 kW prototype molten carbonate fuel cell (MCFC) with LNG as the fuel [35]. The LNG reformation was performed internally within the MCFC system, which excluded the need for an external reforming system. The feasibility of an all-electric vessel was demonstrated on the retrofitted offshore supply vessel, the Viking Lady.

The **Nemo H2** project was started by five companies in early 2006 with the aim of developing, constructing, and testing a hydrogen passenger boat with a 100-person capacity in the city of Amsterdam [35]. The boat was implemented with a 65 kW PEMFC system and an on-board 8-cylinder 350 bar pressure hydrogen storage unit. The risk assessment and on-shore and on-board tests proved that the safe operation of hydrogen boats is possible [35].

SF-BREEZE (San Francisco Bay Renewable Energy Electric vessel with Zero Emissions) project started in 2015 with the main objectives to design, build, and operate a 150-passenger high-speed ferry using a PEMFC and liquid hydrogen as fuel [35]. The project aimed to investigate the techno-economic and environmental aspects of building and operating a high-speed hydrogen passenger ferry and hydrogen refuelling station in the San Francisco Bay area. The ship was to operate at 35 knots, driven by 4.92 MW PEMFC, utilizing liquid hydrogen from a 1200 kg capacity storage unit [35].

Stena Germanica is a 1500-passenger and 300-car ferry retrofitted to be powered by methanol [36]. It was put in service in mid-2015 on the line between Gothenburg, Sweden, and Kiel, Germany [36]. The majority of methanol used by Stena is produced in Europe from Norwegian natural gas [23].

HySeas III was a Horizon 2020 project that ran from mid-2018 up until mid-2022 [37]. The project aimed to design, construct, and deliver a prototype of a small to mid-sized hybrid gaseous hydrogen-battery RoPax ferry to operate on the Kirkwall – Shapinsay ferry line in Scotland, UK, capable of transporting 16 cars and 100 passengers. The ferry is powered by 6 individual FC modules, 100 kW peak power each, and 4 individual Li-ion battery packs, with a total capacity of 692 kWh [38,39]. The FC and battery systems are able to deliver a 1 MW power output.

The **FLAGSHIP** project started at the beginning of 2019 and will last until the end of March 2025 [40]. The main project objective is to build two new hydrogen-fuelled ships, a RoPax ferry and a push boat. Both ferry and push-boat will be equipped with 600 kW and 400 kW PEMFC systems for propulsion via hydrogen utilization, respectively. The new RoPax ferry will be able to accommodate 199 passengers and 60 cars, while the daily hydrogen consumption is estimated to be 500 kg/day during a 17 h/day operation schedule [41]. The RoPax ferry is to operate for at least 18 mounts in the Stavanger area, Norway, while the push boat is set for at least 18 mounts of operation in the Lyon area, France.

The **FASTWATER** project started in mid-2020 and continued until mid-2024 [42]. The main project objectives were to demonstrate the overall feasibility of methanol under operational conditions during demo testing and to develop the next generation of methanol-fuelled engines [43]. Therefore, unlike previously mentioned projects, FASTWATER considers the MD95-ICE as a main propulsion system. The proposed concept was to be tested via pilot boat [42,43].

In mid-2023, a Norwegian operator, **Norled**, deployed in service a liquid hydrogen ferry MF Hydra [44]. The ferry has an 80-car and 299-passenger capacity, servicing a triangular route between Hjelmeland, Skipavik, and Nesvik in Norway [44,45]. The vessel is implemented by two 200 kW FC, a 1.5 MWh battery, and an 80 m^3 liquid hydrogen storage tank (4000 kg). The hydrogen storage and FC are placed on top of the ferry. The hydrogen systems were supplied by Linde Engineering, Germany, while the FC was developed by Ballard, Denmark [44].

MF Ole Bull is a car ferry between Valestrand and Breistein, north of Bergen, Norway [46]. The aim of the project was to demonstrate the feasibility of hydrogen FC for marine electric propulsion and to test hybrid operation together with Li-ion batteries [46]. The ferry was implemented with 200 kW PEMFC and 100 kWh battery, while the estimated daily hydrogen consumption is 150 kg/day [39,46]. The hydrogen was supplied by GreenStat, which was produced by electrolysis in the Breistein area, Norway [46].

A summary of past and ongoing projects considering alternative fuels for utilization in the maritime shipping sector is given in Table 9.

Table 9: Summary of past and ongoing projects considering alternative fuels for utilization in the maritime shipping sector.

Project	**Location**	**Type of vessel**	**Fuel**	**Propulsion**	**Fuel storage**	**Battery**
FellowSHIP	-	Offshore supply vessel, Viking Lady	LNG	MCFC (320 kW)	-	-

ZemShip	Hamburg, Germany	Small passenger ship	Compressed hydrogen	PEMFC (2×48kW)	50 kg 350 bar	560 V 360 Ah
Nemo H2	Amsterdam, Netherlands	Small passenger ship	Compressed hydrogen	PEMFC (65 kW)	40 kg 350 bar	30 – 50 kW
SF-BREEZE	San Francisco, USA	High-speed passenger ferry	Liquid hydrogen	PEMFC (4.92 MW)	1200 kg	-
HySeas III	Kirkwall – Shapinsay, Scotland	RoPax ferry	Compressed hydrogen	FC (600 kW)	1000 kg	692 kWh
FLAGSHIPS	Stavanger, Norway	RoPax ferry	Compressed hydrogen	PEMFC (600 kW)	-	-
	Lyon, France	Push boat		PEMFC (400 kW)	300 – 350 kg 300 – 350 bar	
Stena Germanica	Gothenburg, Sweden – Kiel, Germany	RoPax ferry	Methanol	4×Sultzer 8ZA40S	-	-
FASTWATER	-	Pilot boat	Methanol	MD95-ICE	-	-
MF Hydra, Norled	Hjelmeland, Norway	RoPax ferry	Liquid hydrogen	FC (2×200 kW)	80 m^3 4000 kg	1.5 MWh
MF Ole Bull	Valestrand – Breistein, Norway	Car ferry	Hydrogen	PEMFC (200 kW)	-	100 kWh

5 EVALUATION OF ALTERNATIVE FUELS FOR UTILIZATION IN THE MARITIME SHIPPING SECTOR

Green fuels such as green hydrogen, ammonia, and methanol have numerous advantages compared to conventional fossil fuels. However, the use of green fuels has obstacles that must be addressed in order to encourage wider adoption and maximise their beneficial environmental effects. The following evaluation criteria system was set based on the performed literature survey and similar projects considering alternative fuels for utilization in the maritime shipping sector. The evaluation criteria consider technical, economic, environmental, and social aspects. The technical aspect considers on-board and off-board available infrastructure and the possibility of reliable fuel supply. The economic aspect considered fuel price, operational cost, and investment cost of an on-board and off-board infrastructure. The environmental aspect was evaluated through the climate change potential and acidification, while the social aspect was evaluated based on the toxicity of the fuel and safety in regard to hazard potential. The evaluation was carried out in the context of using considered alternative fuels on small passenger ships.

The reliability of considered alternative green fuels supply directly depends on the reliability of green hydrogen production. Therefore, it would only be fair to rate all of the fuel options considered equally in that regard. The cost of green hydrogen will be directly correlated with the cost of electricity [47]. The liquefied hydrogen will be more expensive than compressed hydrogen due to additional costs and energy requirements for the liquefaction process. The production of green ammonia and green methanol starts with the production of green hydrogen and continues with the respective synthesizes process, which requires additional energy, plant, labour, etc. Therefore, green ammonia and green methanol are going to be more expensive compared to green hydrogen. The production of green methanol requires a substantial source of CO_2, which would tend to suggest that green methanol plants are best suited next to other plants emitting so-called green CO_2, even though the meaning of green CO_2 is unclear at best [38].

The available on-board infrastructure could also be considered somewhat equal for all fuels considered (in regards to using FC technology as the main propulsion system), as very few conventional vessels are designed to accommodate electric drive-trains, and retrofitting them would require significant changes to the vessel architecture [38]. Furthermore, each of the considered fuels introduces new types of safety hazards that existing vessels are not designed to manage. Although each possible hazard can be safely managed, doing so requires new approaches to vessel design to satisfy all safety regulations. However, since such safety provisions do not exist in conventional vessels, implementing them would significantly change vessel architecture [38]. Therefore, changing a power system and undertaking safety-relevant architectural changes will not come cheap, regardless if it is a matter of retrofitting an existing conventional vessel or building an entirely new one.

The ammonia and methanol off-board infrastructures have an advantage over hydrogen due to already existing commercial need for both ammonia and methanol [48,49]. Ammonia has a well-established network throughout transportation routes, port terminals, storage units, etc. [48], with the only drawback in the infrastructure being the lack of a green hydrogen-ammonia production plant. Although hydrogen lacks the off-board infrastructure comparable to ammonia or methanol off-board infrastructure, some suggest that the already existing LNG infrastructure could be used or retrofitted to some degree for hydrogen [50]. However, the existing levels of off-board infrastructure would significantly reduce the required capital investments.

All of the considered alternative fuels have a low environmental impact when utilized with the associated FC technology, where only methanol utilization emits some amount of CO_2. However, the distinctive difference in the environmental effect of each considered fuel can be made if, for some reason, the fuel is released into the environment. The hydrogen is lighter than air and would immediately disperse into the atmosphere without adversely affecting the environment. On the other hand, ammonia and methanol could have a health hazard effect on the environment due to their toxic and corrosive nature. Furthermore, the high-level toxicity of ammonia and methanol is a major concern regarding human safety. For instance, even a small exposure to ammonia will cause a loss of consciousness [51]. Therefore, it is of utmost importance that the ammonia does not come into direct contact with humans [7]. Furthermore, it may be deemed necessary to further increase existing safety protocols for the use of ammonia on-board the passenger vessel. Like ammonia, methanol is also highly toxic to humans and, as such, requires high safety standards. Furthermore, the IMO suggests that methanol storage would require more monitoring systems, even though the methanol storage technology is considered mature [23]. Unlike ammonia and methanol, hydrogen is not toxic to humans. However, it poses a potential safety hazard due to its highly flammable properties and the possibility of asphyxiation if a high-concentration atmosphere is created within a confined space. However, this could be avoided if a hydrogen storage tank were placed on top of the vessel, as was demonstrated by the MF Hydra project [44].

After a thorough review and evaluation of the green alternative fuels considered, compressed hydrogen was evaluated with the highest rating. This evaluation outcome was decided on safety and environmental impact, along with the advantages of lower production costs. Table 10 shows the evaluation summary based on the set criteria by highlighting each considered alternative fuel's positive and negative impacts.

Table 10: Evaluation summary based on the set criteria by highlighting each considered alternative fuel's positive and negative impacts. The scale goes from the most positive impacts (value of 5 and dark green color) to the most negative impacts (value of 1 and red color).

Evaluation criteria		**Alternative green fuel**			
		GH2	**LH2**	**MeOH**	**Ammonia**
Economic	Fuel price	3	2	2	2
	Operational cost	3	2	2	2
	Investment cost (on-board infrastructure)	1	1	1	1

5
4
3
2
1

	Investment cost (off-board infrastructure)	2	1	3	4
Technical	Available infrastructure (on-board)	1	1	1	1
	Available infrastructure (off-board)	2	2	4	4
	Reliable fuel supply	2	2	2	2
Environmental	Climate change	5	5	3	4
	Acidification	5	5	5	5
Social	Toxicity	5	5	1	1
	Safety	4	3	2	2

GH_2 – gaseous hydrogen, compressed hydrogen

LH_2 – liquid hydrogen

MeOH – methanol

6 CONCLUSIONS

Hydrogen and hydrogen-based fuels (such as methanol and ammonia) offer tremendous potential for the decarbonisation of the worldwide maritime fleet. This study includes a comprehensive evaluation of the feasibility and potential environmental impacts of using hydrogen as a fuel source for marine transportation, including screening of existing solutions and assessing their applicability for the project in terms of environmental impact and operational requirements. The analysis included four fuels, namely compressed hydrogen, liquid hydrogen, methanol and ammonia, and the screening process involve considering a range of factors, such as availability, safety, costs, and infrastructure requirements.

However, it is difficult to identify the most viable and sustainable fuel system, as it depends on the size and autonomy of the ship, as also demonstrated by a study performed for HydrogenEurope [52] and shown in Figure 22.

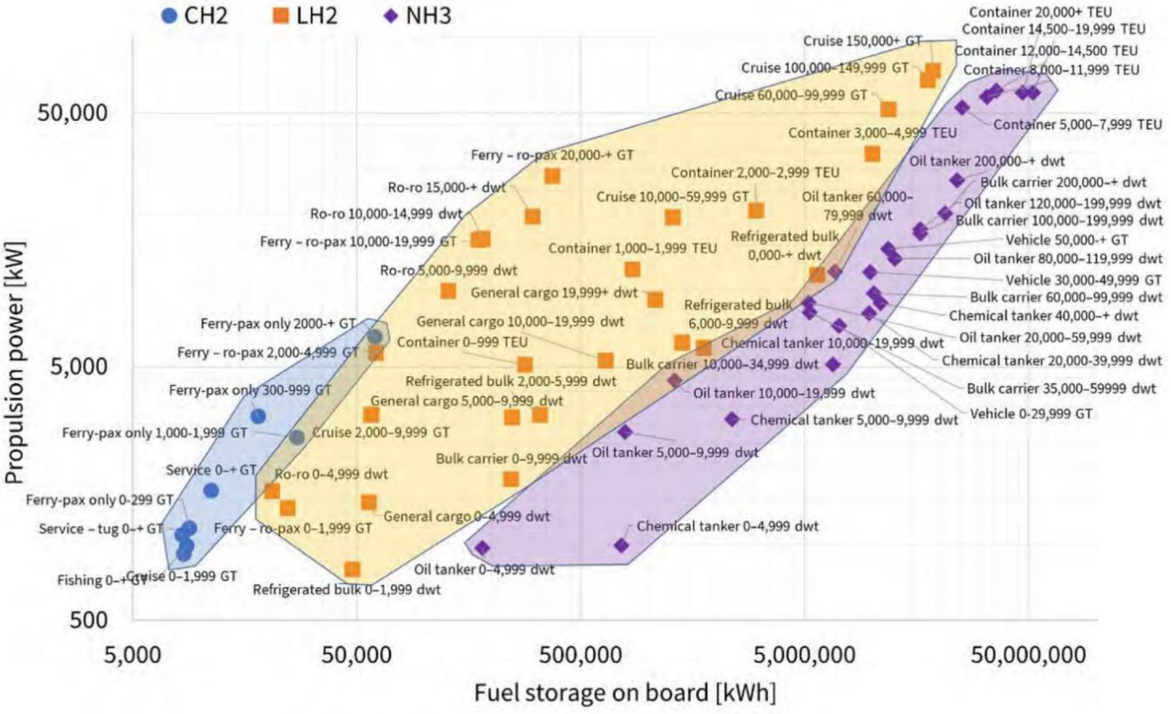

Figure 22: Optimum zero-emission propulsion option for various ship types [52].

This study concluded that compressed hydrogen with PEMFC is the most cost-effective option for relatively small ships with an operational profile that allows for frequent refuelling. Ammonia with SOFC is the best for deep-sea shipping applications or smaller vessels with high-value cargo (e.g. chemical tankers), and liquefied hydrogen with PEMFC for every ship in between.

Selection of the best climate neutral fuel for a particular ship must also take into consideration local fuel availability and infrastructure as well as technical difficulties related to handling the refuelling process.

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For this project, as it involves relatively small ship with operational profile that allows for frequent refuelling, the best option would be compressed hydrogen. Although, currently there is no infrastructure in Croatia for any of the considered fuels, securing supply of compressed hydrogen would be relatively easy. Hydrogen, if properly handled, does not have significant environmental impact through the entire supply chain – from production, through transport, storage and utilization. Also, again if properly handled, hydrogen does not pose significant safety hazard in spite of its perception. Many studies and its record prove that hydrogen is not more dangerous than other fuels. Nevertheless, hydrogen's environmental impact will be assessed in this project through Task 5.2 Environmental studies, and hydrogen safety considerations will be addressed in Task 5.4 Safety assessments, hazard mitigation & demonstration study for the H2 ship.

7 ANNEXES

Annex I: Example

Annex II: Example

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