

Article

Feasibility Analysis of the New Generation of Fuels in the Maritime Sector

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Abstract: The main motivation for this paper was the lack of studies and comparative analyses on the new generation of alternative fuels in the marine sector, such as methane, methanol, ammonia and hydrogen. Firstly, a review of international legislation and the status of these new fuels was carried out, highlighting the current situation and the different existing alternatives for reducing greenhouse gas (GHG) emissions. In addition, the status and evolution of the current order book for ships since the beginning of this decade were used for this analysis. Secondly, each fuel and its impact on the geometry and operation of the engine were evaluated in a theoretical engine called MW-1. Lastly, an economic analysis of the current situation of each fuel and its availability in the sector was carried out in order to select, using the indicated methodology, the most viable fuel at present to replace traditional fuels with a view to the decarbonization set for 2050.

Keywords: decarbonization; alternative fuels; methane; methanol; ammonia; hydrogen



Academic Editor: Javier Ereña

Received: 21 March 2025

Revised: 15 April 2025

Accepted: 28 April 2025

Published: 8 May 2025

Citation: Mahía-Prados, J.M.; Arias-Fernández, I.; Romero Gómez, M.; Pereira, S. Feasibility Analysis of the New Generation of Fuels in the Maritime Sector. *Fuels* **2025**, *6*, 37. <https://doi.org/10.3390/fuels6020037>

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1. Introduction

The maritime sector is recovering from the consequences of COVID-19 and the war in Ukraine, with a rebound of 2.4% in 2023 and growth of over 2% until 2028 [1].

Throughout 2022 and 2023, this recovery continued its growth to 2.4% per year, and it maintains forecasts of over 2% between 2024 and 2028 despite the restrictions resulting from the new regulations that are continuously being generated in terms of pollutant emissions [2].

This sector is responsible for important pollutant emissions such as sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon dioxide (CO₂) and particulate matter (PM) [3].

For this reason, it is subject to multiple regulations developed by organizations such as the International Maritime Organization (IMO), with the approval of the Energy Efficiency eXisting Ship Index (EEXI), Energy Efficiency Design Index (EEDI), Energy Efficiency Operational Indicators (EEOI), Carbon Intensity Indicator (CII) or the Ship Energy Efficiency Management Plan (SEEMP) to reduce pollutant emissions [4–6].

All these indicators are intended for the improvement of the energy efficiency of ships during their design and operation, during the different phases of maintenance and, above all, in the management of the emissions emitted by them [7–10].

The revised IMO targets were set at a GHG reduction of 20% by 2030, 70% by 2040 compared to 2008 and zero emissions in 2050 [11].

To this end, IMO is expected to start imposing carbon pricing by 2027 [12,13].

All these efforts are geared towards compliance with the Paris Agreement. In fact, recent studies have shown that stabilizing the temperature increase at 1.5 °C would mean that, in the year 2150, the sea level would have risen by 17.7 cm less than with the 2 °C initially set, in addition to the fact that, in 2050, the average level could be between 25 and 30 cm more than the current level [14].

In the case of the European Union (EU), it has gone a step further with the approval of more specific measures that act on cargo and passenger ships, which are the generators of 90% of greenhouse gases (GHGs) on European coasts, approving legislation on infrastructures for the supply of alternative fuels; also significant has been the approval of specific legislation such as the FuelEU Regulation with a clear methodology for non-biological fuel production standards or the inclusion of pollutant emissions within the European Union emissions market known as the EU Emissions Trading Scheme (EU ETS) [12,15–17].

One of the best indicators of the market situation with regard to new fuels and the orientation of the maritime sector is the assessment of the order book, a methodology used in other research articles [18].

Making a comparison between the years 2021 and 2024, the shipbuilding market has evolved following the trend shown in Table 1.

Table 1. Market comparison between years 2021 and 2024.

Fuel	Operating Ships			Ships Under Contract		
	2021	2024	Δ	2021	2024	Δ
Fossil Fuel *	98.80%	98.00%	−0.80%	78.90%	72.90%	−6.00%
LNG	0.82%	1.05%	0.23%	10.77%	13.83%	3.06%
LPG	0.02%	0.12%	0.10%	1.15%	1.60%	0.45%
Battery/Hybrid	0.35%	0.80%	0.45%	8.41%	7.20%	−1.21%
Methanol	0.01%	0.03%	0.02%	0.71%	3.89%	3.18%
Hydrogen	0.00%	0.00%	0.00%	0.06%	0.17%	0.11%
Ammonia	0.00%	0.00%	0.00%	0.00%	0.42%	0.42%

* Fossil fuel includes HFO, VLSFO, MDO and MGO.

Comparing the percentage of the number of vessels using conventional fuel propulsion systems, there has been a 0.8% decline in this class of vessels in recent years, which has been absorbed between vessels operating on Liquefied Natural Gas (LNG), Liquefied Petroleum Gas (LPG), batteries and methanol.

The order book for conventionally fueled vessels has fallen sharply by six points as LNG/LPG and methanol vessels have grown, followed to a lesser extent by ammonia and hydrogen, respectively.

One of the most important aspects is the positioning of the market around batteries or hybrid ships, which has been decreasing in favor of those with more developed and proven systems and greater autonomy, with electrified ships being relegated to coastal navigation that allows them to recharge in port.

The current situation of methane as a fuel is the result of more than two decades of learning how to use it on board ships, engineering, and knowledge on the part of all the actors involved, which have made it one of the most coveted fuels when considering the propulsion of a ship, with two of the main reasons being its wide availability in the market and its low emissions in relation to fuel oil [19].

Currently, the use of fuels derived from green hydrogen is the basis for studies and predictions made by operators in the maritime sector.

Methanol, ammonia, hydrogen, synthetic fuels, biofuels, etc., form a wide range of options towards which the sector is positioning itself to meet the targets set by the IMO based on low-carbon fuels for use in internal combustion engines.

Regarding the boom in the use of ammonia within the sector, estimates made by the International Energy Agency (IEA) establish forecasts that place it as the most used fuel in the year 2050 [20,21].

These forecasts, today, clash with the reality of the sector, where the first engines that can use it as fuel are still being tested and, as it has been verified in the analysis of the order book, there are still no orders. Companies such as Wärtsilä or MAN have already signed letters of intent for the implementation of engines of this type on ships [22].

One of the main problems in this regard is the lack of regulation of ammonia as a fuel, since it is a corrosive substance, harmful towards the environment, and will require regulatory support to ensure its implementation, something that is already in place for methanol and methane, which are precisely the two types of fuel that are taking the lead in these first years of the energy transition [21].

In this sense, fuels such as methane, ammonia or methanol stand as a bridge between the most polluting fossil fuels and those that do not generate harmful emissions for the environment [18].

Hydrogen technology in the sector faces numerous problems in relation to its implementation on board ships and, as a result, such use is practically nonexistent, as shown in Table 1.

One of the main problems that hydrogen presents for its implementation lies in the lack of real knowledge of its demand, in addition to the high cost of obtaining it in a renewable form, its green designation, and its low energy density, which translates into complexity in its storage both in a liquid state and under pressure. One of the most widely used processes for obtaining green hydrogen is the electrolysis of water, although this process represents only 0.1% of world hydrogen production [21].

Based on this, if hydrogen is the raw material for ammonia, methanol and other chemical products, as well as being present in various industrial processes, the consequence of an increase in the cost of hydrogen production will also be an increase in the cost of green hydrogen derivatives.

Recent studies have compared the economics of using VLSFO and methanol for the same trip. At US prices, the cost of green methanol is three to four times higher than that of VLSFO in terms of equivalent energy, mainly due to the high cost of green hydrogen and CO₂ feedstock. A ship would need 560 tons of VLSFO to make a voyage from Louisiana to Tokyo, while it would need 2.5 times more methanol as fuel due to the difference in energy density [23].

The data used for this study, as of October 2024, are 541 EUR/ton of VLSFO and 2100 EUR/ton of methanol. In this regard, it is important to note that, although it is true that the global production of green hydrogen has increased by 3% compared to 2021, only 0.7% of all hydrogen generated in the world is considered as “low emissions”, which includes the production of 0.1% by electrolysis. The direct costs of renewable hydrogen are directly proportional to the capital costs of the electrolyzers and the cost of the electricity needed to power them. Without considering the cost of an electrolyzer, the electrical cost could be around 25–45% of the final cost of hydrogen and, in addition, the best forecasts estimate around 65–70% efficiency in electrolyzers [21].

In addition, there is another component to take into account in the installation of an electrolyzer for the generation of green hydrogen, and that is the proximity of water for the process. An electrolyzer located in a region of high water stress that cannot guarantee

the viability of the installation and respect for the surrounding environment is doomed to failure [24].

Another element that works against hydrogen in terms of its use as a fuel is the energy density per unit volume, since compressed hydrogen does not guarantee sufficient autonomy for a ship on long voyages [25].

According to estimates, the production of renewable fuels could reach an average of 53 million tons of fuel equivalent (Mtoe), with an average of 17 Mtoe needed in 2030 to supply the maritime sector, which is around 32% of the total [19].

This means that the remaining percentage, 68%, would have to be sufficient to supply all productive sectors worldwide, both energy and transport. At present, the share of the maritime sector is 3%, while that of the other sectors is 97%. These data make it essential to accelerate the development of new fuels, as well as energy alternatives to current generation systems.

To enable the large-scale generation of green hydrogen for the maritime industry, it is imperative to increase electricity production capacity from renewable sources. Although economies have a limit to the expansion of these sources, depending on the availability of wind and solar farms, global renewable electricity production could be sufficient to meet the green hydrogen needs of the world fleet by 2040 at the earliest, without considering the demands of other sectors. However, it is anticipated that the main constraint will lie in the availability of electrolyzers. At the same time, competition with other industrial sectors for the use of renewable electricity and green hydrogen is likely to intensify the challenges for shipping unless current supply problems are solved.

Figure 1 presents the primary sources that currently exist for mechanical, electrical and heat energy that can be obtained on board a ship, and the main characteristics of each fuel are presented in Table 2.

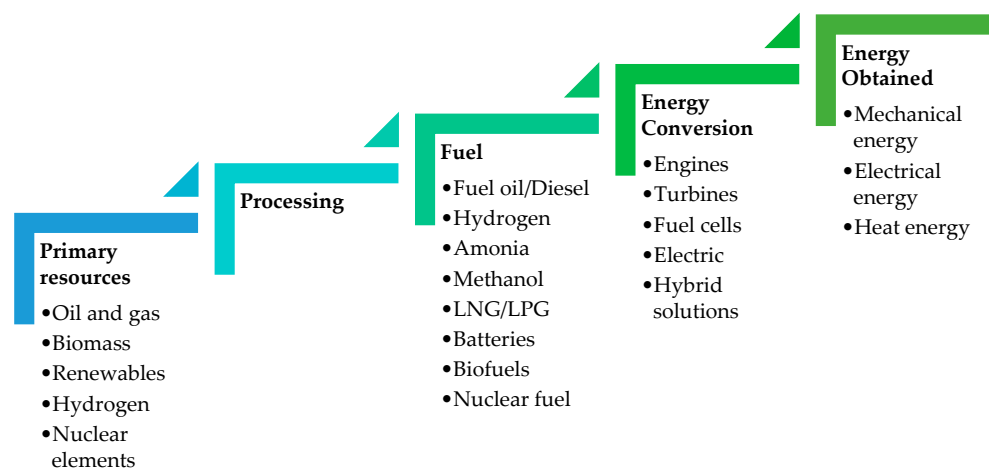


Figure 1. Energy cycle from primary resources.

Currently, there are no studies comparing those fuels that are intended to be used as an alternative to oil-based fuels, such as methane, methanol, ammonia and hydrogen. It is therefore essential to determine which of them are in the best conditions, both in terms of their technological maturity and their physicochemical characteristics, with a view to meeting the decarbonization targets set for 2050.

Table 2. Advantages and disadvantages of the new generation of fuels [18–23].

Fuel	Advantages	Disadvantages	GHG Reduction ¹
Biofuels	- Compatible with current infrastructures. - More sustainable than fossil fuels. - Allow the diversification of energy sources. - Contain little or no sulfur.	- Large-scale production is still limited, expensive, and not very efficient. - Produce greater pressure on water and soil resources. - Some biofuels have lower energy density compared to marine diesel.	30–80%
Methane	- It is the least polluting of all fossil fuels. - Operating costs tend to be lower due to the competitive price of natural gas compared to other fuels. - Dual-fuel engines using methane are more energy-efficient.	- The sliding of unburned methane. - The use of cryogenic materials. - The fuel storage tanks are 2–3 times larger than those for petroleum fuels. - Price volatility is conditioned by geopolitical situations.	20–85%
Methanol	- Liquid at room temperature, simplifying transportation and storage infrastructure. - Can be used in existing marine engines with relatively simple modifications. - Can be produced from renewable sources.	- It has about half the energy density of diesel. - It is not yet available on a large scale and is toxic and highly flammable. - Retrofits for ships to use it safely require significant upfront investment.	70–95%
Ammonia	- It does not contain carbon in its composition. - It can be liquefied at moderate pressures and temperatures, which facilitates its storage and transportation. - There is a developed global infrastructure that can be adapted.	- Generates NO_x gases in combustion. - It is highly toxic to humans and the environment. - It has a lower energy density than other fuels.	15–90%
Hydrogen	- Hydrogen produces only water as a by-product. - It can be used in fuel cells or in modified internal combustion engines. - Growing international commitments are driving its research and development.	- It must be stored at high pressures or extremely low temperatures. - It has a very low energy density per volume. - Lack of supply chain and infrastructure. - It is highly flammable and presents explosion risks.	15–100%

Table 2. Cont.

Fuel	Advantages	Disadvantages	GHG Reduction ¹
Electrification	- Electric ships generate no emissions. - Electric propulsion systems are quieter than diesel engines. - The cost of electricity is generally lower than that of fossil fuels. - Electric systems are more efficient than combustion engines.	- Significant size and weight of equipment and batteries. - High power requirements for charging and battery capacity limit autonomy. - High initial investment. - Batteries have a limited lifetime.	100%
Nuclear	- Very high energy density. - Nuclear reactors do not emit CO₂ or other pollutant emissions. - Although initial construction and maintenance costs are high, long-term operating costs due to high efficiency and long fuel life are very low.	- A negative perception among the public about nuclear safety and disasters. - The production of radioactive waste. - The technology to employ nuclear fusion energy technology is still under development.	100%

¹ GHG reduction is estimated as a reduction in CO_x, SO_x, NO_x and PM over the use of petroleum-derived fuels such as heavy fuel oil, marine diesel oil/marine gas oil or very-low-sulfur fuel oil.

To this end, a comparison will first be made of the physicochemical characteristics of each fuel and their behavior during combustion in an engine, which will be the same for all the fuels, in order to verify the differences between them. Next, an analysis of the maturity of the market for each of the fuels and their projections for their implementation in the sector will be carried out. Finally, it will be established which fuel is the most mature for its implementation as an alternative fuel in the maritime sector.

2. Description of the Model Ship

To analyze the impact of fuels on the sector, it is essential to carry out the study on a model ship, since the equipment and systems will have to be adapted to the new fuel both in terms of storage and operation.

We decided to choose a container ship type with the following characteristics shown in Table 3:

Table 3. Ship data.

L (m)	284.4	V (knots)	19.5
Lpp (m)	273	GT	90,835
B (m)	43	DWT (tons)	68,530
D (m)	26	C (m ³)	135,049
T (m)	12	P (MW)	28

It is assumed that methane is considered its main fuel, since it is considered the bridge to decarbonization until new fuels and technologies are viably developed, as shown by the demand for this type of vessel in the order book shown in Table 1. In addition, the vessel is considered to operate in European Economic Area waters.

The propulsion plant scheme is shown in Figure 2.

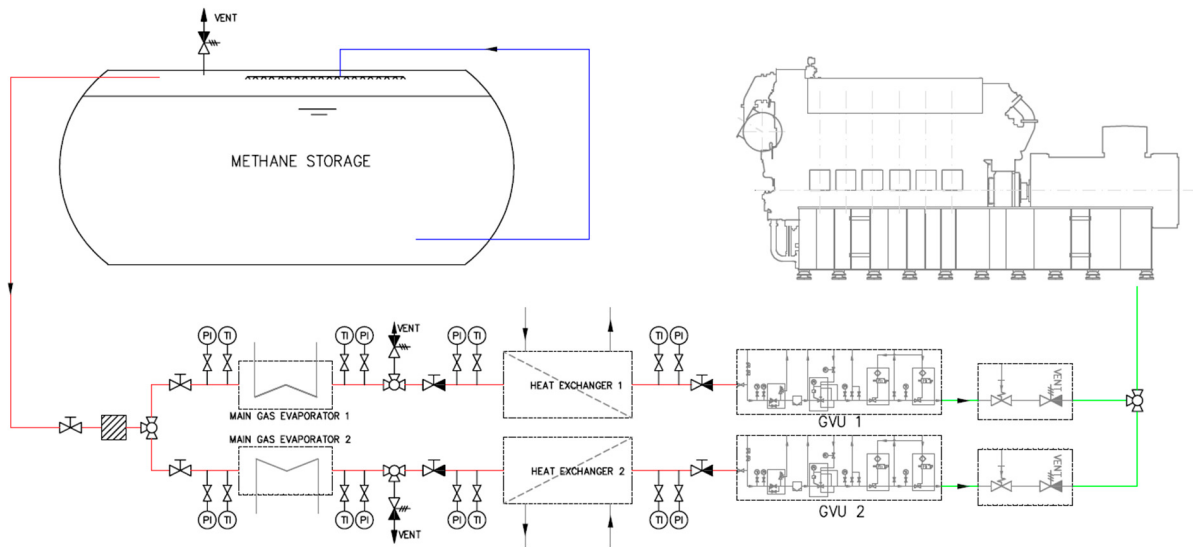


Figure 2. Diagram of the propulsion plant [26].

According to Figure 2, the methane is stored in a two-phase mixture at a pressure of between 5 and 8 bars and at temperatures between $-163\text{ }^{\circ}\text{C}$ and $-90\text{ }^{\circ}\text{C}$. The conditions in the storage tank are regulated by spraying the liquid methane charge to cool the uppermost layers of the storage tank by means of sprays.

For fuel supply, the methane passes through the main gas evaporator changing the phase of the fuel and then heating it to the injection temperature. Afterwards, the pressure is adjusted through the GVUs and finally injected into the engine.

The main functions of the Gas Valve Units (GVUs) are to filter the gas, regulate its pressure to the pressure of the consumers and monitor its condition.

The engine under study, which has been designated MW-1, is a theoretically designed engine whose combustion operates according to the equations and methodology described in Section 3, and has the characteristics shown in Table 4:

Table 4. MW-1 engine characteristics.

Bore	840 mm
Stroke	3150 mm
RPM	76
Power	28 MW
Mean effective pressure (MEP)	19 bar
$v_{\text{mean speed}}$	8 m/s
$V_{\text{combustion chamber}}$	0.125 m^3
V_{cylinder}	1.75 m^3
$A_{\text{injection}}$	$4.52 \cdot 10^{-6}\text{ m}^2$
$v_{\text{injection}}$	250 m/s

3. Analysis Model and Methodology

3.1. Combustion Modeling

Mass conservation equation:

$$m_{\text{air}} + m_{\text{fuel}} = m_{\text{products}} \quad (1)$$

where m_{air} is the mass of air introduced into the combustion chamber, m_{fuel} the mass of fuel injected and $m_{products}$ the mass of products generated after combustion.

First law of thermodynamics:

$$\Delta_Q - \Delta_W = \Delta_U \quad (2)$$

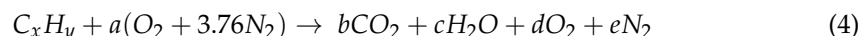
where Δ_Q is the heat released by the combustion of the fuel, Δ_W the work done by the gases during their expansion in the cylinder to move the piston, and Δ_U the change in internal energy.

Ideal gas law:

$$P \times V = n \times R \times T \quad (3)$$

where P is the pressure of the gas inside the cylinder, V its volume, n the number of moles of gas, R the universal gas constant and T the temperature of the gas inside the cylinder.

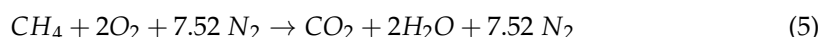
Stoichiometry of combustion: Applying Equation (1) to a hydrocarbon combustion reaction in the engine combustion chamber, the stoichiometric combustion ratio is obtained (4).



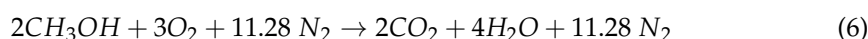
In the case of an ideal combustion of pure hydrogen with air, the hydrogen reacts with the oxygen in the air to form water vapor. The composition of the air is, approximately, 21% oxygen, 78% nitrogen and 1% other gases.

It is necessary to differentiate the combustion of a hydrocarbon from those fuels that are not, such as ammonia or pure hydrogen. Methanol (CH_3OH) and methane (CH_4) are combusted in the presence of carbon, while ammonia (NH_3) and hydrogen (H_2) are not.

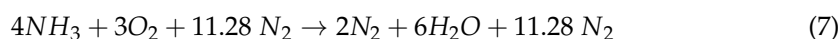
The stoichiometric reaction of methane combustion is as follows:



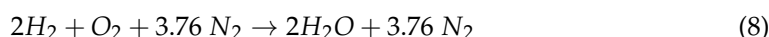
The stoichiometric reaction of methanol combustion is as follows:



The stoichiometric reaction of ammonia combustion is as follows:



The stoichiometric reaction of hydrogen combustion is as follows:



Engine combustion modeling: To make an approximation to the engine MW-1, from the unified models of the premixed phase of combustion using the Wiebe model, and the diffusive phase using the Watson and Pilley equations [27].

The total fraction of fuel burned as a function of crankshaft angle is the sum of the contributions of both phases (9).

$$mf_{combustion}(\theta) = f_{premix}(\theta) + f_{diffusion}(\theta) \quad (9)$$

In the case of the premixed phase, the Wiebe model is used in Equation (12):

$$f_{premix} = m_f \times \left(1 - \left[1 - \left(\frac{\theta}{\Delta\theta} \right)^{C1} \right]^{C2} \right) \quad (10)$$

In the case of the diffusive phase, the Watson and Pilley model is used, stated in Equation (13):

$$f_{diffusion}(\theta) = m_f \times \left(1 - e^{-a \left(\frac{\theta - \theta_0}{\Delta\theta} \right)^{m+1}} \right) \quad (11)$$

where m_f is the mass of fuel injected, e is the Euler number, a is the parameter that controls the shape of the curve (generally between 5 and 7 for diesel engines), m is the exponent that controls the slope of the curve related to the speed of combustion, θ is the crankshaft angle and $\Delta\theta$ is the combustion time of this phase measured in degree variation.

As the combustion takes place in a transient way changing from premixing to diffusion, a smoothing function can be defined that connects both phases in a continuous way, ensuring that there are no abrupt jumps in the burned fraction or in the heat release rate as a function of the crankshaft angle. For this purpose, obtaining Equation (12).

$$mf_{combustion}(\theta) = (\alpha(\theta) \times f_{premix}(\theta) + (1 - \alpha(\theta)) \times f_{diffusion}(\theta)) \quad (12)$$

where $\alpha(\theta)$ is a function that decreases from 1 to 0, with 1 being the complete premix phase and 0 the complete diffusion phase.

It is important to note that the equations are a function of the crankshaft angle, since this will be the variable that will allow us to evaluate at each moment the combustion state of the engine by the piston position.

Modeling of the fuel injection law and the combustion chamber: The combustion that takes place inside a cylinder of a compression ignition engine can be divided into three phases [27]:

- The first phase begins with the injection of the fuel and extends until the moment when the autoignition of the mixture begins. In this stage, physical processes play an important role by facilitating the atomization and evaporation of the fuel, as well as its mixing with the surrounding air. Simultaneously, the first chemical reactions of combustion take place, which, although not very exothermic, progress thanks to the temperature exceeding the self-ignition threshold.
- The second phase is activated when the evaporated fuel mixed with the air reaches autoignition. This autoignition manifests itself through an initial very exothermic reaction, and at the end of this stage, the highest combustion pressures are achieved.
- The third and final stage corresponds to the combustion by diffusion of the fuel that remains to be burned. This includes both the fuel that did not evaporate and was not completely mixed in the first stage and the fuel that is injected later. This stage does not have an exact end, as it depends on the amount of fuel injected, which varies according to the injection law and engine load.

The main combustion, controlled by the rate and manner of injection of the remaining fuel, occurs at the same time, and follows the injection law, which is fundamental to optimize engine performance and behavior. The injection law represents the amount of fuel injected as a function of crankshaft angle (13).

$$\frac{dm_f}{d\theta} = f(\theta) \times \dot{m}_f \quad (13)$$

where $f(\theta)$ is a function defining the shape or pulse of fuel injection, and $(\dot{m}_f)$ the fuel injection mass flow rate.

The function defining the shape of the injection can be of three different shapes:

- Rectangular: it is constant throughout the injection (14).

$$f(\theta) = 1 \quad (14)$$

- Linear or ramped: injection increases continuously and steadily throughout the process (15).

$$f(\theta) = \frac{\theta - \theta_{start}}{\theta_{end} - \theta_{start}} \quad (15)$$

- Trapezoidal: injection increases at the beginning, remains constant in the central part, and then decreases (16).

$$f(\theta) = \begin{cases} \frac{\theta - \theta_{start}}{\theta_{peak} - \theta_{start}} & \text{If } \theta_{start} \leq \theta \leq \theta_{peak} \\ 1 & \text{If } \theta_{peak} \leq \theta \leq \theta_{end} \\ \frac{\theta_{end} - \theta}{\theta_{end} - \theta_{peak}} & \text{If } \theta_{end} \leq \theta \leq \theta_{end} \end{cases} \quad (16)$$

For this case, the trapezoidal shape is chosen as it is the one that best fits the reality of injection.

The fuel flow rate as a function of injection pressure can be calculated with Equation (17):

$$P_{injection} = \frac{m_f}{A_{injector} \times v_{injection}} \quad (17)$$

where $A_{injector}$ is the area of the injector orifice and $v_{injection}$ is the speed at which the fuel is injected into the cylinder.

As for the compression ratio that exists between the cylinder volume and the combustion chamber, it is defined by Equation (18):

$$r_C = \frac{V_{cylinder} + V_{combustion\ chamber}}{V_{combustion\ chamber}} \quad (18)$$

Engine efficiency calculation: In the context of internal combustion engines, the first law of thermodynamics is fundamental to understand how the chemical energy of the fuel is converted into mechanical work to produce power. This efficiency expresses the proportion of the chemical energy of the fuel that is converted into useful work (19) and will be the criterion for evaluating different types of fuel in an engine of similar characteristics.

$$\eta = \frac{W}{Q_{comb}} = \frac{W}{m_{f_{comb}} \times LHV} = 1 - \frac{Q_{lost}}{Q_{comb}} \quad (19)$$

where W is the useful work done; Q_{comb} is the energy released as heat when the fuel is completely burned in the presence of oxygen or, equivalently, the product of the modeled mass of fuel injected and burned in the cylinder times the Lower Heating Value (LHV) of the fuel, which would also be the definition of Power; and Q_{lost} is heat that is lost and not converted into useful work such as heat transfer losses to the cylinder walls, exhaust gas losses and frictional and frictional losses.

Calculation of the Mean Effective Pressure: The Mean Effective Pressure (MEP) of an engine is defined as the ratio between the work produced in a cycle and the cylinder volume in which this work is performed. Based on this, and on Equation (3), and on the density ratio between mass and volume, the MEP could be defined as follows:

$$MEP = \frac{\rho_f \times \dot{V}_f \times PCI}{V_{cylinder}} \quad (20)$$

3.2. Methodology for Evaluating Results

To perform a neutral analysis on the characteristics of the fuels, the adapted and simplified Likert model was chosen, which uses options ranging from 1 to 4, where 1 represents the most unfavorable option and 4 the most favorable. This format eliminates

the neutral option, making it necessary to take a clear position on one or the other fuel objectively based on the evidence shown [28].

4. Analysis and Discussion

The fuels to be evaluated in the MW-1 engine will be methane, methanol, ammonia and hydrogen, whose main characteristics for the calculation are shown in Table 4. Furthermore, the calculations have been carried out in the absence of friction, under ideal conditions and with criteria for equal conditions for all fuels, without the need for injection pressure equipment or any other additional element to be able to compare them. Table 5 was produced with the above data and equations.

Table 5. Data obtained from the combustion in the MW-1 engine.

Fuel	Density (kg/m ³)	R (kg Air/kg Fuel)	LHV (kJ/kg)	Vf (m ³ /s)	MEP (Bar)	IP (Bar)	Z
Methane	0.66	17.2	52.500	0.81	160.38	471.98	5
Methanol	0.79	6.46	22.700	1.56	159.86	1091.58	10
Ammonia	0.59	6.07	18.600	2.55	160	1332.19	16
Hydrogen	0.07	34.22	131.000	3.05	159.82	189.15	19

R is the air/fuel ratio under stoichiometric conditions, LHV is the Lower Heating Value of the fuel, Vf is the volume of fuel injected, and Z is the number of cylinders for these fuels.

4.1. Combustion Analysis

4.1.1. Analysis of the Stoichiometry of Combustion

According to Table 6, R varies significantly among the four fuels, reflecting the differences that exist in their chemical compositions and the amount of oxygen required for complete combustion. Likewise, we fixed the mass of fuel injected as standard to evaluate the behavior of each fuel according to the need for injected air, and we observed the variations for each fuel.

Methane has an intermediate air/fuel ratio, with 17.20 kg of air per kilogram of fuel, and for methanol and ammonia, both have lower and quite similar air/fuel ratios of 6.46 kg and 6.07 kg, respectively. Of the four, hydrogen has the highest ratio, with a value of 34.22 kg of air per kilogram of fuel, mainly due to its low molar mass and the fact that it does not have oxygen in its molecular structure, making it necessary to provide large amounts of oxygen for the formation of water, because water can be generated even if the H₂ is not completely burned, with air being a limitation to be taken into account.

These considerations have important implications for the design and operation of combustion systems, including engines, burners and turbines. Hydrogen requires larger intake systems or fans to supply sufficient air, while methanol and ammonia offer more efficient combustion with lower air demand, although they also need air support systems.

As for methane, it is the most balanced of the fuels under study. Its air/fuel ratio is lower than that of hydrogen but much higher than that of methanol and ammonia, making it an intermediate choice in terms of air requirements.

4.1.2. Analysis of Emissions

As discussed in Section 4.1, air is made up of a set of gases. However, under conditions of temperature and pressure during combustion, as well as the possibility that fuel combustion may not be complete, gases may appear in the products that cause the greenhouse effect, such as NO_x or CO_x, among others, although the most important problem with incomplete combustion is the loss of efficiency.

Although it is true that the previous section dealt with the complete combustion of fuels, it is necessary to deal with cases in which incomplete combustion takes place,

favoring the appearance of polluting elements in all the fuels under study. The combustion of methane and methanol is quite similar.

Ammonia combustion produces mainly nitrogen and water under conditions of complete combustion, since nitrogen is inert and does not oxidize. However, when oxygen is insufficient, nitrogen monoxide and other oxides can form pollutants and contribute to smog and acid rain, as NO_x .

NH_3 generates nitrogen oxides that are an environmental concern, especially at high temperatures, so its use in engines or combustion systems must be well controlled to minimize NO_x emissions. In addition, its combustion has the advantage of not generating carbon dioxide, which makes it a potential candidate for low-climate-impact fuels, although NO_x formation remains a challenge.

The incomplete combustion of hydrogen is uncommon due to its strong ability to burn under poor conditions, although in extreme cases of oxygen deficiency, trace amounts of hydrogen monoxide (HO) may be formed. Furthermore, although hydrogen does not contain nitrogen, when burned in the presence of air, which contains nitrogen, nitrogen oxides can be formed if combustion occurs at temperatures above 1200°C .

In terms of emissions, the cleanest fuels are hydrogen and methane when burned completely, since their main products are water and carbon dioxide in the case of methane, but with minimal emissions of pollutants compared to methanol.

However, it should be mentioned that hydrogen emissions have an influence on terrestrial methane. Recent studies have shown that hydrogen's potential as a clean fuel could be compromised due to its ability to react with the hydroxyl radical (OH) in the atmosphere, which is responsible for breaking down methane. If hydrogen emissions exceed a certain point, this reaction could increase the accumulation of atmospheric methane, aggravating the problem of global warming [29].

4.1.3. Analysis of the Fuel Injected

This section will be approached from two points of view: as a function of the mass injected and the volume of the combustion chamber. If a calculation is made at the same injected mass of the four types of fuel of 0.0129 kg/cycle , a combustion duration of 38 degrees of crankshaft rotation is established [30].

The graph in Figure 3 is based on the equations in Section 3 and the data in Tables 5 and 6.

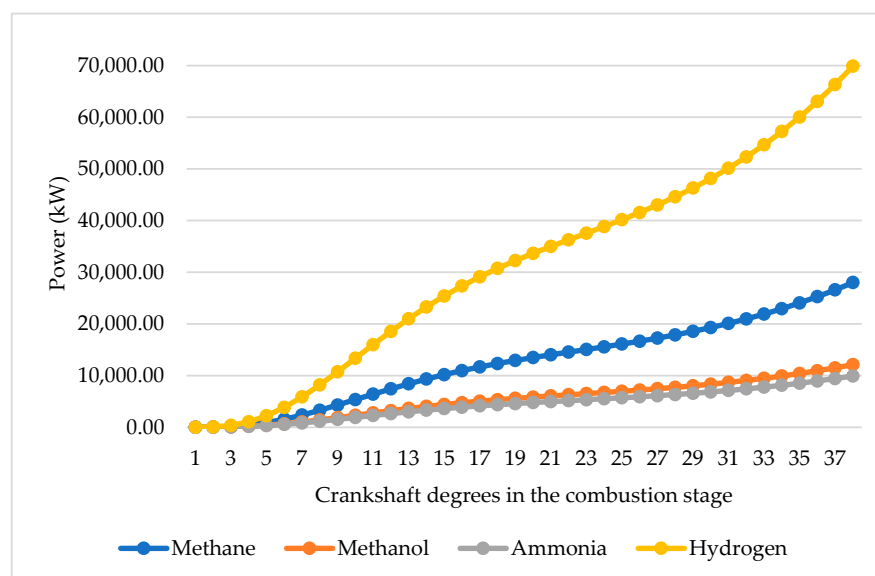


Figure 3. Power developed as a function of the crankshaft degree of rotation.

At the same mass injected, the high calorific value of hydrogen allows this fuel to generate more power than the others, followed by methane, ammonia and methanol, in that order.

All other things being equal and in an ideal environment, hydrogen would produce around 70,000 kW of power compared to the 12,100 kW generated by methanol, the 9920 kW by ammonia or the 28,000 kW by methane. This confirms that the fuel with the highest LHV, hydrogen, requires less mass to deliver the same amount of energy.

If calculations are made for use in internal combustion engines, the mass injected will be limited by the capacity of the combustion chamber, with the physical geometry of the cylinders coming into play and, thus, conditioning the final size that the engine may have.

According to Equations (1), (4) and (18) and the data in Table 5, the overall volume of the combustion chamber was calculated independently of the fuel used. For this purpose, it was averaged according to the ranges of the usual compression ratios (rC) depending on the fuel [31–42]:

- Methane: 12-18:1;
- Methanol: 10-16:1;
- Ammonia: 12-18:1;
- Hydrogen: 12-20:1.

Next, the lower and upper ranges were averaged, these being 11.5 and 18, respectively. If the arithmetic average of these two values is taken, the average compression ratio of the four fuels is 14.75. The common compression ratio is taken as 15:1 by rounding up.

Evaluating this compression ratio for each fuel, Table 5 shows the number of cylinders that would be necessary to obtain the same power depending on the fuel used.

Analyzing the data presented in Table 5, it is important to highlight that the number of cylinders obtained is different for all the fuels analyzed, so that, with an equal number of cylinders, the fuel injection systems will have to be different according to the fuel in order to increase the volume of fuel injected and reduce the number of cylinders required.

In the more specific case of hydrogen, its low density means that a high number of cylinders is required to provide the same power output.

The type of fuel has a direct impact on the number of cylinders required for each engine and, therefore, on the final geometry and volumes that an engine can occupy depending on the type of fuel used, as well as its weight.

By varying the compression ratio from 12 to 16, but keeping the rest of the parameters, as can be seen in Figure 4, methane is the fuel that best withstands the variations, followed by methanol. Ammonia and hydrogen, with a variation of five points in the compression ratio, need five more cylinders for the same power; although the number of cylinders for ammonia is lower, they do have similar behavior.

4.1.4. Analysis of Mean Effective Pressure

The MEP depends on the fuel as it is linked to its density, its calorific value and the volumetric flow rate injected into the cylinder. According to Table 5, since the same power is set for all fuels, the MEP varies around 160 bar. Precisely, hydrogen, having a higher fuel volume, requires a lower MEP, while methane requires a higher MEP. However, the differences in pressure are negligible, so this indicator could be negligible when comparing the different fuels.

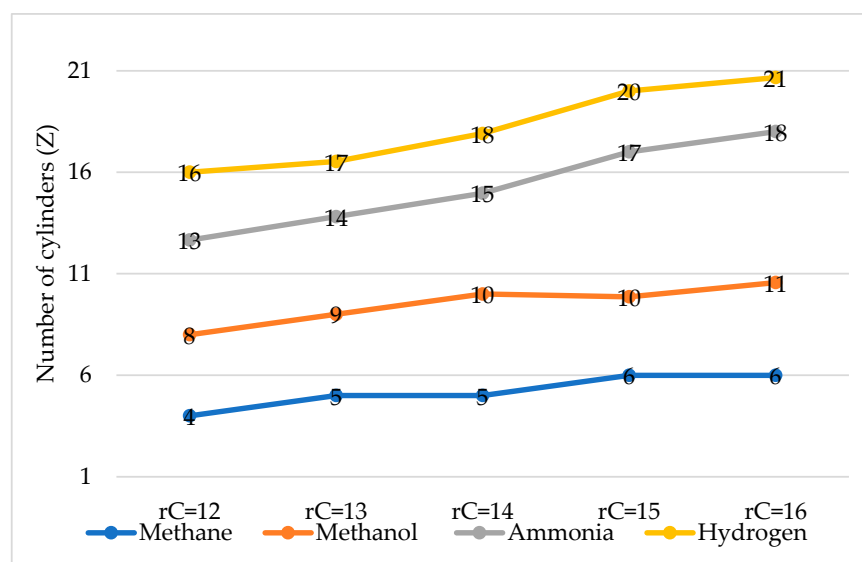


Figure 4. Evolution of the number of cylinders as a function of the compression ratio.

4.1.5. Analysis of Flammability Range

The flammability range describes the concentration of fuel in air within which combustion can be maintained and is a key parameter for the design of injection systems and combustion chambers. The flammability characteristics of each fuel are listed in Table 6:

Table 6. Flammability characteristics by fuels [32–35].

Fuel	Lower Flammability Limit (LFL) (% vol.)	Upper Flammability Limit (UFL) (% vol.)	Flammability Range (% vol.)	Reactivity
Methane	5.00	15.00	10.00	Moderate
Methanol	6.00	36.00	30.00	High
Ammonia	15.00	28.00	13.00	Low
Hydrogen	4.00	75.00	71.00	Very high

According to the flammability range, methane has a more restricted flammability range (5% to 15%), which results in greater stability when used as a fuel, since its moderate range ensures combustion control, reducing the risk of pre-ignition.

Methanol has an intermediate flammability range of thirty points, from 6% to 36%. Its high proportion of intrinsic oxygen due to the alcohol composition facilitates its complete combustion and reduces the formation of contaminating particles, but it requires careful control of the mixture and operating conditions to avoid problems related to the accumulation of flammable vapors and the risks associated with this.

Ammonia, with a range of 15% to 28%, presents its main challenge in maintaining combustion due to low reactivity. This results in the need for very advanced injection systems or the use of auxiliary mixtures to favor its reaction.

As for hydrogen, it has a very wide flammability range of more than 70 points and a high reactivity, which allows it to burn even in very poor mixtures. These wide ranges give rise to dangerous characteristics in terms of its handling and use as a fuel, since a small leak can very easily create flammable atmospheres.

4.1.6. Analysis of Injection Pressure (IP)

The relationship between the LHV of the fuel and the pressure required in the engine is derived from the basic principles of thermodynamics and injection system design contained in Equations (2), (17) and (19).

If the required power output is fixed, the LHV directly affects the amount of fuel to be injected and, therefore, the pressure required to ensure efficient combustion inside

the cylinder. The design of the injection system must ensure that the fuel enters the combustion chamber with sufficient pressure to atomize and mix with the air. It follows that the injection pressure depends on the mass flow and the characteristics of the system, such as the diameter of the injectors and the injection speed.

A higher mass flow due to a fuel with a lower LHV implies that the injection pressure needs to be increased to ensure efficient fuel delivery.

Several readings can be extracted from Table 6 about this. For sizing an injection system based on the LHV of the fuel, those with a higher LHV, such as methane or hydrogen, require lower mass flow, which allows relatively low injection pressures or smaller injector sizes. Conversely, fuels with lower LHV, such as methanol and ammonia, require higher mass flow for the same power output, resulting in increased pressure required to atomize the fuel and maintain injection timing.

Fuel choice directly affects injection system design and engine efficiency. Fuels with a high LHV such as methane and hydrogen are more suitable for systems that prioritize efficiency and simplicity in their design, while methanol and ammonia may require significant adjustments to the injection system to handle their higher flow and injection pressure needs.

4.2. Feasibility Analysis

Methane, methanol, ammonia and hydrogen have emerged as viable options due to their physicochemical properties as alternative fuels in the maritime sector; however, their implementation, regardless of their characteristics, will depend on the infrastructure that guarantees their supply and competitive prices in the fuel market. Therefore, the economic and availability study of these fuels worldwide is fundamental to understanding their practical feasibility in the maritime context.

Each of these fuels presents unique characteristics in terms of their production, distribution, storage and use, as well as the associated costs.

This analysis focuses on assessing both the economic and global availability of these fuels, considering factors such as production trends, infrastructure development and demand projections in the industry.

For this purpose, use was made of the Alternative Fuels Insight (AFI) database of the classification society Det Norske Veritas (DNV) and the Argus database.

4.2.1. Availability and Production Analysis

According to Figure 5, presenting the sector's projections, methane continues to consolidate its position as the most widely used alternative fuel. Its infrastructure, with 115 terminals in operation and 82 in the pipeline, reflects a fuel that has solid projects and prospects for its use as a marine fuel. This fuel offers a cleaner alternative to traditional fossil fuels, thanks to its ability to significantly reduce CO₂ emissions and other pollutants.

Methanol, on the other hand, is emerging as an increasingly relevant option for the decarbonization of maritime transport. With 120 terminals in operation and 10 more under development, this fuel has gained popularity due to its lower emissions and its compatibility with existing engines, which reduces propulsion system conversion costs. Although its growth is more moderate compared to methane, the gradual expansion of its bunkering infrastructure supports its potential as a viable long-term alternative.

In contrast, ammonia and hydrogen face more compromised situations in terms of their infrastructure development. Ammonia, with 8 active terminals, including supply to other sectors, but with 263 under development or in evaluation, has considerable potential due to its ability to completely eliminate CO₂ emissions during combustion. However, its implementation as a fuel is mainly hampered by the technologies required for its safe use. Hydrogen, although the cleanest fuel, is at an early stage of development with only two

terminals in operation and none in the pipeline, reflecting the difficulties associated with its production, storage and distribution, similar to ammonia. Despite this, both fuels have promising prospects as technologies advance and the necessary infrastructure materializes.

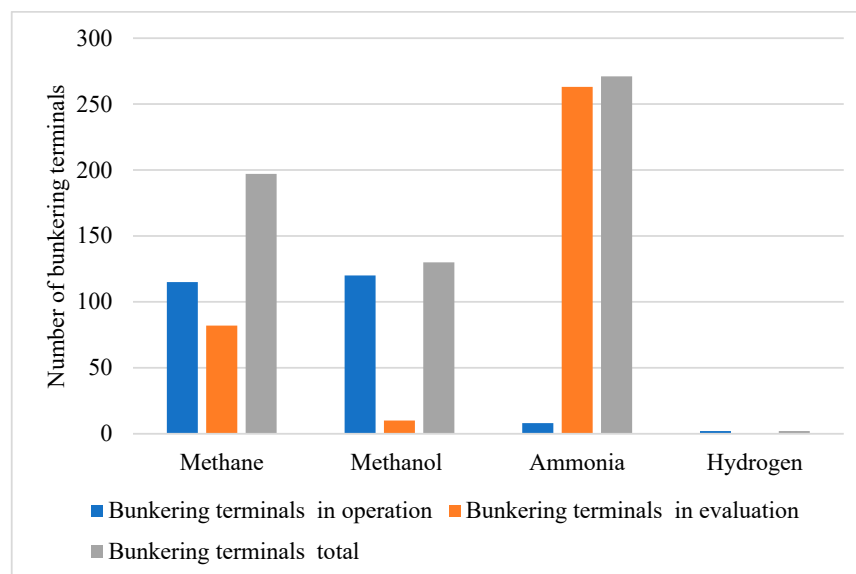


Figure 5. Bunkering terminals at 2024 closing by AFI.

An analysis of the projects underway and planned for the maritime sector, as shown in Figure 6, reveals a transformation in the energy landscape, with very marked differences between fuels in terms of their role and future potential. Methane, although growing steadily, remains a transitional option due to its lower environmental impact compared to traditional fossil fuels. However, its sustained growth compared to the exponential increase in other alternatives reflects a loss of prominence as the industry seeks more sustainable solutions.

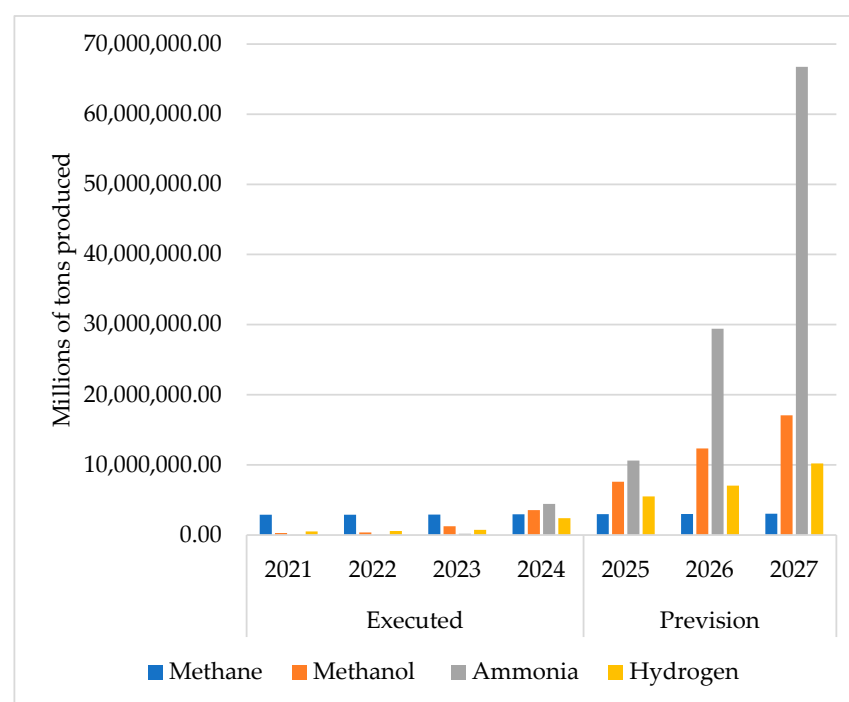


Figure 6. AFI's estimated volume of fuel infrastructure development (blue and e-fuel).

Methanol shows accelerated growth, driven by its ability to reduce emissions and by investments in infrastructure and technology that are positioning it as a viable solution in the medium and long term. On the other hand, ammonia, with a much more pronounced increase, is emerging as a strategic fuel in the energy transition, particularly for its ability to not generate CO₂ during its use. However, its adoption is going to depend on overcoming the barriers already discussed above, as well as ensuring that it is produced sustainably, especially by using green hydrogen in its manufacture.

Although hydrogen does not appear to be positioned as a direct fuel for the maritime sector due to the difficulties associated with its storage and transportation, it plays a key role as a building block in the production of cleaner fuels such as ammonia and methanol. Its use in the form of green hydrogen is key to ensuring that these fuels are truly sustainable, which reinforces its importance within the energy transition. Taken together, these dynamics reflect a shift towards alternative fuels that integrate hydrogen as an essential component, with methane playing a transitional role and methanol emerging as the most viable solution to meet the decarbonization goals of the power and maritime sectors.

4.2.2. Economic Analysis and Forecasts

Looking at the data in Table 7, methane continues to be the dominant fuel among the fuels under study, although there is a slight decrease in its percentage share of the total number of ships. In 2025, 86.69% of ships using alternative fuels will be powered by methane. Although the number of vessels operating with it continues to increase from 814 in 2025 to 996 in 2028, its share of total alternative fuels gradually decreases, reaching 76.79% in 2028. This trend reflects an increase in the adoption of other alternative fuels, such as methanol, but methane remains the most widely used option due to its accessibility, existing bunkering infrastructures and its environmental advantage compared to other fossil fuels.

Table 7. Forecast of contracted vessels operating with new fuels by AFL.

Fuel	2025		2026		2027		2028	
	Number of Ships	Percentage	Number of Ships	Percentage	Number of Ships	Percentage	Number of Ships	Percentage
Methane	814	86.69%	916	78.63%	988	73.90%	996	76.79%
Methanol	100	10.65%	213	18.28%	318	23.78%	277	21.36%
Ammonia	4	0.43%	20	1.72%	26	1.94%	13	1.00%
Hydrogen	21	2.24%	16	1.37%	5	0.37%	11	0.85%

As for methanol, considerable growth is shown during this period. In 2025, only 10.65% of ships will operate with methanol, but this percentage increases in the following years. In 2026, the share of methanol will increase to 18.28%, and in 2027, the forecast is for a 23.78% increase, underlining the growing interest in this fuel. Although in 2028 there is a slight drop in its share, reaching 21.36%, the total number of ships using methanol will continue to grow, driven by the increasing investment in bunkering infrastructures and the development of engines capable of using methanol efficiently.

Ammonia is experiencing more modest growth compared to methane and methanol, but its market share is estimated to increase gradually. In 2025, 0.43% of ships consuming new fuels will use ammonia, with four ships operating on this fuel. However, in 2026, its share increases to 1.72%, and in 2027, it rises to 1.94%, reflecting an increase in the research and development of technologies adapted to the use of ammonia. The total number of ships operating with ammonia remains very small, mainly because the lack of bunkering infrastructures and the technical difficulties in adapting marine engines to the use of ammonia, and the toxicity of ammonia as a fuel, slow down its adoption. In 2028, its

share drops to 1.00%, which may indicate a certain slowdown due to the challenges it still faces to become a viable option in the fleet.

Finally, hydrogen shows a somewhat irregular evolution. In 2025, 2.24% of alternative fuel ships will use hydrogen, reflecting an initial interest in this clean fuel. However, its adoption does not follow an upward line, but experiences a steep drop in the following years. The decline in hydrogen adoption is largely due to high production costs, the lack of adequate bunkering infrastructure and the technical challenges associated with its storage and use in marine engines.

As for price developments, addressed in Figure 7, between 2021 and 2024, the overall trend for methane was for a gradual increase in prices driven by several factors. The post-pandemic economic recovery, Brexit, and the Russia–Ukraine conflict, in addition to the increase in global gas demand, are key factors influencing this growth. In addition, the expansion of bunkering infrastructures and the improvement of methane engine technologies have contributed to the stabilization of its price, albeit with slight fluctuations due to variations in global natural gas markets.

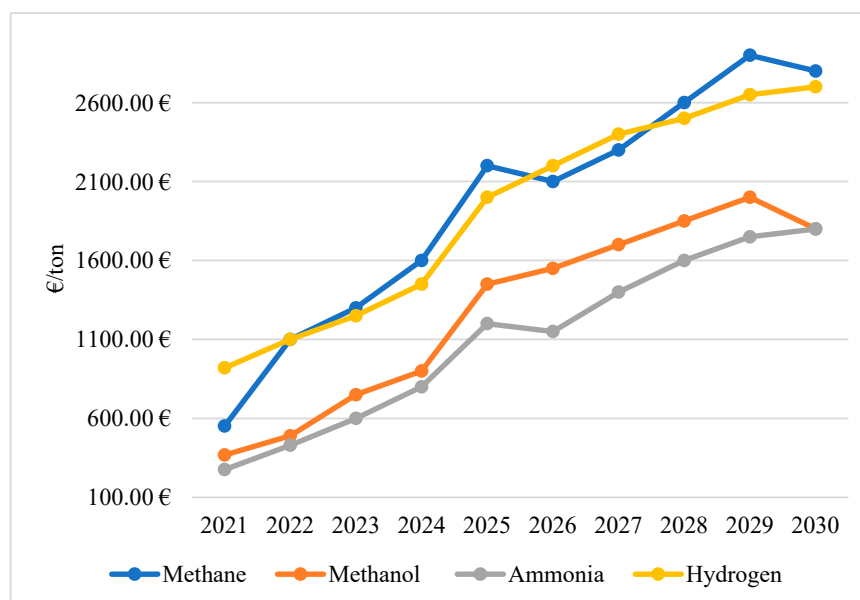


Figure 7. Marine fuel price forecast and evolution by AFI.

Between 2025 and 2030, the trend towards a higher price is evident. This is due to the growing investment in technology associated with natural gas, coupled with an increase in demand for more sustainable solutions in the maritime sector. However, methane's price will also be influenced by fluctuations in international energy markets, especially variations in gas production and energy policies that encourage the use of cleaner sources.

Methanol is becoming an increasingly viable alternative fuel for marine propulsion, largely due to its low environmental impact in terms of sulfur and nitrogen oxide emissions. Between 2021 and 2024, there was an increasing trend in prices, driven mainly by fluctuations in the cost of the raw materials used for its production, such as natural gas. For the 2025–2030 period, demand for methanol as a greener alternative to diesel will continue to rise. This will lead to an increase in prices, supported by greater investment in methanol production from renewable sources and an increase in the adoption of systems using this fuel. However, despite the upward trend, forecasts indicate that prices will remain volatile due to feedstock availability and costs, as well as challenges related to the expansion of the global methanol bunkering infrastructure.

On the other hand, ammonia is still in the development stages for use as a marine fuel, expectations are high due to its potential as a clean energy source. Between 2021 and 2024, ammonia prices increased moderately, mainly due to the growing interest in its adoption, driven by the need to reduce the emissions of polluting gases. However, the lack of infrastructure and the need to develop specific equipment and services for its use in engines limit its insertion in the fuel market, which may generate price fluctuations. From 2025 to 2030, ammonia is expected to become an increasingly attractive option, but price fluctuations will be related to advances in the production of sustainable ammonia and its viability on board.

Finally, as for hydrogen, if it is used as a fuel, it faces problems related to its storage and distribution, resulting in the high prices observed between 2021 and 2024. During this period, prices follow a moderate upward trend, driven by the growing demand for sustainable solutions and the lack of infrastructure for large-scale production and distribution.

As we move into the 2025–2030 period, hydrogen will likely play a key role in the decarbonization of the maritime sector. Prices are expected to continue to rise, albeit with more pronounced fluctuations, driven by the expansion of hydrogen production and storage infrastructure, and the rise in methane, by comparison, will also be driven by taxes on carbon-polluting emissions, which will drive up demand for hydrogen.

4.3. Discussion

In accordance with the methodology described in Section 3.2, in order to establish a homogeneous evaluation of the results, Sections 4.1 and 4.2 were evaluated numerically from 1 to 4, with 1 being the most unfavorable option and 4 the most favorable. On this basis, Tables 8–10 were obtained.

Table 8. Combustion analysis.

Fuel	4.1.1— Stoichiometric Air	4.1.2—Emissions	4.1.3—Fuel Injected	4.1.4—MEP	4.1.5— Flammability	4.1.6— IP	Total
Methane	2	1	4	1	4	3	15
Methanol	3	2	3	3	3	2	16
Ammonia	4	3	2	2	2	1	14
Hydrogen	1	4	1	4	1	4	15

Table 9. Feasibility analysis.

Fuel	4.2.1—Availability and Production Analysis	4.2.2—Economic Analysis and Forecasts	Total
Methane	4	4	8
Methanol	3	3	6
Ammonia	2	2	4
Hydrogen	1	1	2

Table 10. Final evaluation of the analyses.

Fuel	4.1—Combustion	4.2—Feasibility	Total
Methane	15	8	23
Methanol	16	6	22
Ammonia	14	4	18
Hydrogen	15	2	17

Table 8 reflects the six analyses that were carried out within Section 4.1 and that evaluate the combustion of each fuel using the scoring system described above. Table 9 shows the scoring of the analysis related to fuel production and fuel price. Table 10 is a summary table of the scores obtained in Tables 8 and 9, summing them up:

Overall, although methane's characteristics are not the best in terms of combustion, its availability and viability as a fuel within the maritime sector make it the highest-scoring

fuel in the overall assessment. With good flammability, moderate pollutant emissions and being a widely available and economical fuel, with well-developed infrastructure for its production and distribution, it is a viable and economical option. However, its problems with fugitive emissions suggest that it still requires technological improvements to reduce its environmental impact.

As for methanol, it has the best characteristics in terms of combustion analysis. In terms of emissions, it is less polluting than fossil fuels, although it still produces CO_2 , which limits its attractiveness as a completely clean alternative within the sector, and, although it is an accessible option as a fuel, it does not have the supply infrastructure of methane. Yes, it is relatively inexpensive and available, but its large-scale production, especially from biomass or natural gas, is not competitive. It is presented as an environmentally friendly alternative to fossil fuels, but its viability does not make it the industry's first choice. Its cost and infrastructure limit its use, although with improvements in this aspect, it could become a much more attractive solution.

Ammonia has a complex combustion performance. Its need for air is not excessive, but it requires high temperatures and tends to generate NO_x , which has a negative impact on its emissions, even though it is capable of not generating CO_x . In terms of feasibility, ammonia faces difficulties in both availability and cost. Although it is produced at the industrial level, its infrastructure for use as a fuel is very limited and its economic competitiveness is low, due to the high costs of production, storage and distribution. All this is without even considering that, of the four fuels, its high toxicity is what poses the greatest challenges for its implementation as a fuel in the sector.

Ammonia has great potential in terms of CO_2 emission reduction, but its complex combustion and low viability make it less attractive in the short term.

Lastly, there is hydrogen, which, although standing out for its clean combustion, presents many more limitations than the other fuels in terms of its management as a fuel, despite its high calorific value. Its low energy density is a handicap that other fuels do not have. In terms of infrastructure, hydrogen is the least developed of them all; its availability is very low and its costs are extremely high due to the lack of production, especially when obtained from renewable sources, whose market value is skyrocketing.

Hydrogen has excellent environmental potential due to its zero emissions, but its economic and technological difficulties make it unfeasible.

Only 2% of ships can currently run on low- or carbon-neutral fuels, an insufficient percentage to have a direct impact on the reduction in polluting emissions, although the maritime sector is only responsible for 3% of GHG emissions in the world. All this without taking into account the problem of the availability of new fuels and the competition that will arise with other sectors for this.

Moreover, if one takes into account the high costs of obtaining green hydrogen, and that it is absolutely essential to obtain green ammonia, green methanol or other by-products, this will lead to a rise in the price of green hydrogen derivatives.

As for fuels such as methane, ammonia or methanol, they stand as a transition bridge between the most polluting fossil fuels and those that do not generate harmful emissions for the environment, with hydrogen being positioned as an energy vector that allows obtaining non-biological fuels that are neutral in polluting emissions, as shown both by its situation in the order book and in the fuels market.

There is currently no demand for green hydrogen. Global hydrogen production rose by 3% compared to 2021, and only 0.7% of all the hydrogen generated in the world was considered "low emissions", including the 0.1% produced by electrolysis.

In terms of combustion analysis, methane is reasonably efficient, but, under incomplete combustion conditions, it can generate pollutants such as carbon monoxide, formaldehyde

and fugitive emissions, making it a problem for engines seeking to comply with the strictest environmental regulations. On a safety level, methane has a more limited flammability range than hydrogen, between 5% and 15%, making it less dangerous from a reactivity standpoint. In addition, methane behaves more stably in the face of compression ratio variations, which makes it suitable for engines with greater operating flexibility.

As for methanol, it has a lower air/fuel ratio than hydrogen and methane (6.46 kg of air per kilogram of fuel). This means that it requires less air for combustion, which allows for smaller intake systems. Its ICP is 19,700 kJ/kg, so it generates less power than hydrogen and methane. In terms of efficiency, methanol tends to generate excess air during combustion, which lowers the combustion temperature and reduces its thermal efficiency. A major disadvantage of methanol is its tendency to generate pollutants such as formaldehyde and carbon monoxide when it does not burn completely. In addition, methanol has a flammability range between 6% and 36%, which makes it relatively safe.

A particular characteristic of ammonia is its tendency to form nitrogen oxides in the event of incomplete combustion. This NO_x contributes to the formation of smog and acid rain, which is a problem from an environmental point of view. In terms of safety, ammonia has a flammability range of 15% to 28%, which makes it safer than hydrogen but less stable than methane. Ammonia requires a specific injection system design because, like methanol, it needs a higher injection pressure to ensure combustion. In addition, its low LHV means that, despite its lower air requirement, engines must be adapted to adjust their efficiency.

Hydrogen stands out for having the highest air/fuel ratio due to its low molar mass and the lack of oxygen in its molecular structure. This characteristic means that engines using hydrogen must have much larger air intake systems. In terms of emissions, hydrogen has the advantage of being almost clean when burned completely, producing mainly water vapor. However, at high temperatures, it can form nitrogen oxides, contributing to air pollution. Although incomplete combustion is rare in the case of hydrogen, the risks associated with its wide flammability range are a concern in terms of safety.

Economic and availability analysis of fuels, carried out based on industry estimates, defines that from the period 2021 to 2030, clear and significant trends are being observed in terms of the price evolution and adoption of the new generation of fuels.

As global energy transition policies intensify, the maritime industry is undergoing a gradual transformation towards more sustainable and environmentally friendly sources, but it still faces severe problems in terms of supply infrastructure, technology and the production of these fuels, which still underpins the procurement of new ships with fuels that generate polluting emissions such as those derived from fuel oil, or that use methane as fuel.

In terms of prices, a clear upward trend is anticipated, especially for the more environmentally friendly fuels such as methanol, ammonia and hydrogen. These fuels show a price evolution influenced by investments in new technologies and the construction of bunkering infrastructures, which increases costs in the short and medium term.

In the case of methane, although it is expected to remain a predominant fuel in the maritime industry, prices will be increasingly affected by global energy transition policies.

As restrictions on fossil fuels increase and demand for cleaner options grows, the price of methane could experience variations that, while not completely displacing it, will affect its competitiveness against other cleaner options, this being dependent on the regulations and standards that define what is a clean fuel and what is not.

Nevertheless, of all of the alternative fuels, methane remains the most widely used in the maritime sector. Although, in absolute terms, the number of ships using methane as fuel continues to grow, its percentage share within the alternative fuel market has started to gradually decline.

The maritime sector is in the midst of a transition to alternative fuels, with methane as the main option. However, its dominance is expected to decline progressively as other alternative fuels emerge, although it remains the majority choice due to its established infrastructure ensuring its availability and its relatively low cost compared to other fuels.

Methanol is emerging as the main competitor to methane and is set to grow in the coming years. Its attractiveness lies in its lower environmental impact, the feasibility to comply with regulations via its use, and the development of bunkering infrastructure. These advantages are increasing its adoption, positioning it as a key alternative for the decarbonization of the sector.

Ammonia, on the other hand, is advancing more moderately. Its potential lies in its ability to reduce CO₂ emissions, but it faces problems such as toxicity and lack of infrastructure. Despite its slow growth, it is still considered a long-term option.

Hydrogen, although promising as a clean fuel, faces barriers that are currently insurmountable in the maritime sector. Lack of infrastructure, high production costs and technological difficulties prevent its expansion in the market, resulting in a reduced market share in the coming years on its own, but it will be a vital part of green fuels.

5. Conclusions

We must not lose sight of the fact that what is really important is to reduce polluting emissions as soon as possible in order to achieve climate neutrality by 2050.

At present, in view of the analyses carried out, the most promising trend is the use of methane as a fuel, followed by methanol. The most viable strategy, focused only on the use of new fuels and without taking nuclear energy into account, would be to use methane or green methane obtained synthetically, with the lowest possible carbon content, during the next decade (2025–2035) to reduce CO₂ emissions into the atmosphere and increase control over fugitive emissions of unburned methane (slip). This would reduce carbon emissions by reducing the use of fuels or gas oils, gaining time while the systems with which the fuels that do not have carbon in their composition operate are optimized enough to make their retrofitting in existing ships profitable. During those years, methanol-fueled engines will reach a technological and efficiency level mature enough to continue reducing pollutant emissions by initiating the transition from methane to methanol, just as is currently occurring from fuel oil to methane, using green hydrogen for its production.

Ammonia is very difficult to implement; even if engines are developed that can use it as a fuel, the safety measures that will be required to tackle the problems related to its toxicity and handling, and the position adopted by classification societies, will finally decide whether this fuel will be viable or not.

As for hydrogen, although current barriers slow its adoption, it is a promising option in the long term, especially if technological advances and infrastructure investments can reduce its costs and improve its viability, so its future is more likely to be linked to being part of the new generation of fuels as a component, rather than as a fuel per se.

However, it is necessary to maintain the perspective that not everything is worthwhile regarding reducing CO₂ emissions; hydrogen emissions can influence the concentration of methane in the atmosphere through its reaction with the hydroxyl radical, so an excess of hydrogen would reduce the availability of OH, raising methane levels and generating an adverse climate impact in the long term. Similarly, increased demand for methane-powered ships could increase methane emissions from unburned methane, which, even if CO₂ is reduced in compliance with the Paris Agreement, would aggravate global warming by raising the atmospheric methane concentration.

It is necessary to address, with a global strategy, the volume of emissions that each fuel would generate within the maritime sector with a view to its implementation so that

the adoption of one or the other is not a solution to the current carbon emission problems, but would alleviate global warming in the future.

Author Contributions: Conceptualization, J.M.M.-P. and I.A.-F.; validation, M.R.G. and S.P.; formal analysis, J.M.M.-P.; writing—original draft preparation, J.M.M.-P.; writing—review and editing, J.M.M.-P. and M.R.G.; supervision, I.A.-F. and M.R.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Dataset available on request from the authors.

Conflicts of Interest: The authors declare no conflict of interest.

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