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Article

Assessment of Selected Alternative Fuels for Spanish Navy Ships According to Multi-Criteria Decision Analysis

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Abstract: Climate change and environmental degradation are growing concerns in today's society, which has led to greater awareness and responsibility regarding the need to adopt sustainable practices. The European Union has established the goal of achieving climate neutrality by 2050, which implies a significant reduction in greenhouse gas emissions in all sectors. To achieve this goal, renewable energies, the circular economy, and energy efficiency are being promoted. A major source of emissions is the use of fossil fuels in different types of ships (from transport ships to those used by national navies). Among these, it highlights the growing interest of the defense sector in trying to reduce these emissions. The Spanish Ministry of Defense is also involved in this effort and is taking steps to reduce the carbon footprint in military operations and improve sustainability in equipment acquisition and maintenance. The objective of this study is to identify the most promising alternative fuel among those under development for possible implementation on Spanish Navy ships in order to reduce greenhouse gas emissions and improve its capabilities. To achieve this, a multi-criteria decision-making method will be used to determine the most viable fuel option. The data provided by the officers of the Spanish Navy is of great importance, thanks to their long careers in front of the ships. The analysis revealed that hydrogen was the most suitable fuel with the highest priority, ahead of LNG, and scored the highest in most of the sections of the officials' ratings. These fuels are less polluting and would allow a significant reduction in emissions during the navigation of ships. However, a further study would also have to be carried out on the costs of adapting to their use and the safety of their use.

Keywords: alternative fuels; ships; hydrogen; multi-criteria decision analysis

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1. Introduction

The Second Industrial Revolution that began in the 19th century marked the beginning of mass production of consumer goods, and this was possible thanks to the discovery and exploitation of new fuels of fossil origin, such as coal and oil. This milestone for humanity has also had negative consequences from an environmental point of view. The most important thing is that for more than two centuries, there has been an exponential increase in harmful emissions into the Earth's atmosphere, such as greenhouse gases (GHG) and pollutants from industrial activity.

Maritime transport is one of the main reasons for the depletion of oil sources and for around 25% of greenhouse gas emissions. The share of global emissions from the shipping industry continues to increase due to the emergence of new routes and trade links [1]. Ships are becoming larger and larger, and many of them use fossil fuels with a high polluting effect. The International Maritime Organization (IMO) is a United Nations agency focused on the prevention of marine pollution from ships. In 1973, the IMO adopted the International Convention for the Prevention of Pollution from Ships (known as Marpol). This convention addresses the prevention of air pollution from ships, in addition to pollution from oil and harmful substances carried, sewage, and garbage caused by ships.

It has greatly led to an important reduction in pollution from international shipping and governs 99% of the world's merchant fleet tonnage. Annex VI of the Regulations for the Prevention of Air Pollution from Ships establishes certain Emission Control Areas (ECA), in which emissions from ships are severely limited. However, there is very little control over the journeys between these zones, so ships use highly polluting fuels [2]. In this context, the development of alternative fuels is essential to reduce pollution [3].

For that reason, it is essential to work on the development of alternative fuels to reduce pollution and mitigate the effects of climate change. Some alternatives could be of fossil origin, like liquefied natural gas (LNG), or something more eco-friendly, like biofuels or green hydrogen. These fuels can reduce the amount of greenhouse gas emissions and other pollutants that are harmful to the environment. In addition, the use of some of these alternatives also helps reduce dependence on fossil fuels, which are finite and increasingly expensive resources. Considering these aspects, it is essential to look for ways to balance current needs with those of future generations.

Sustainability not only means reducing pollution but also promoting the responsible use of natural resources and guaranteeing the well-being of people and communities affected by industrial activity. It is increasingly important to comply with environmental legislation and regulations, as well as promote social awareness about climate change and the importance of taking care of our planet for a more sustainable future [4].

A proper choice of an alternative fuel among multiple alternative marine fuels is difficult, and it requires several techniques of multi-criteria decision-making methods (MCDM) for evaluating and selecting the most suitable alternative fuel [5]. These methods evaluate the alternatives based on a certain weight that is assigned to each criteria. Among them, one of the most important is the Analytic Hierarchy Process (AHP).

The objective of this research is to identify the most promising alternative fuels and, among them, find the most suitable one in terms of effectiveness, performance, and economic sustainability. This choice will be based on a multi-criteria decision analysis for its possible implementation on the ships of the Spanish Navy.

2. Alternative Fuels

Some potential low- or zero-carbon alternative fuels can be used in marine diesel engines. In order to evaluate the most suitable alternative fuel for Spanish Navy ships, three typical alternative fuels were analyzed in this research: liquified natural gas since it has been used instead of gasoil in some Spanish Navy ships, primary alcohols as a new alternative fuel, and hydrogen due to its increasing interest. To compare these fuels, their properties will be analyzed (Table 1), as well as other relevant criteria related to safety, global availability, supply capacity, durability, adaptability, engine performance, engine emissions, and cost.

Table 1. Fuel properties [6,7].

Properties	Methanol	Ethanol	LNG	Hydrogen
Density (kg/m^3)	792	789	440	0.0838
Autoignition temperature (°C)	385	362	537	500
Flamabile limits (% *v*/*v*)	6–36	3.3–19	5–15	4–75
Gross calorific value (MJ/kg)	22.72	29.73	19.98	158.90
Octane number	99	100	>100	130
Cetane number	<5	8	−10	-
Flash point (°C)	11	13	-	-
Boiling point (°C)	78	64	−162	−252
Carbon footprint (g CO_2eq/kg)	400	1300	2760	0
C content (% wt)	38	52	75	0
H_2 content (% wt)	12	13	25	100
O_2 content (% wt)	50	35	0	0
S content (% wt)	0	0	0	0

2.1. Safety

Safety at sea and on ships is an essential factor, and it is taken into account when new naval technologies are evaluated. In alternative fuels, safety can be determined through various factors, such as their density, autoignition temperature, flammability propensity, air-fuel ratio, and octane and cetane numbers (Table 1).

Density is a critical safety factor, and in the event of a storage tank leak, hydrogen will dissipate quickly due to its low density, while methanol and ethanol will remain due to their higher density.

Another crucial characteristic is the autoignition temperature; hydrogen has the highest, followed by LNG, methanol, and finally ethanol. For autoignition, H_2 requires the highest ambient temperature, reaching 500 °C. In contrast, ethanol needs the lowest temperature, which is 362 °C.

The minimum and maximum requirements for exploding fuels are known as the flammability limits. The exact amount of fuel needed in relation to the volume of air is an indicator of flammability limits. In comparison, LNG has the most restrictive limits, ranging from 5% to 15%, while ethanol ranges from 3.3% to 19%, methanol from 6% to 36%, and hydrogen has the widest limits, ranging from 4% to 75%. The flammability of hydrogen is high due to its easy combustion with different air-fuel mixtures. The optimal air-fuel ratio varies between different types of fuel. Methanol requires the least amount of air to burn completely, while hydrogen needs the highest quantity.

The octane number refers to a fuel's ability to resist autoignition during the combustion process, while the cetane number measures the fuel's ignition delay between the start of injection and the fuel's combustion and combustion efficiency. Hydrogen has the highest octane number, with a value of 130, but no cetane number. On the other hand, liquefied natural gas has an octane number higher than 100 and a cetane number of −10. For their part, ethanol and methanol have octane numbers of about 100 and cetane numbers of 8 and less than 5, respectively. This means that hydrogen is the most difficult to self-ignite, while methanol is the most likely to do so.

In terms of carbon content, it is important to note that hydrogen has no carbon content, resulting in a lower environmental footprint as it will emit fewer gases and generate less carbon waste after burning. On the other hand, LNG is the worst in terms of environmental impact, with the highest carbon footprint.

2.2. Global Availability

Global availability refers to the ease and popularity of using a fuel on a global level. It is important to note that LNG is a trend today and is available at many supply points. Spain has more than 400 LNG tankers that already burn this fuel for their propulsion. Growing confidence in the use of LNG as a fuel has resulted in the construction of 73 LNG-powered ships, along with another 80 that have already been ordered and are expected to be delivered in the near future.

In a market study [8] conducted on the Viking Energy supply vessel, it was found that the daily consumption of LNG was lower than traditional diesel, which could generate significant annual fuel savings. As demand for fuel savings increases, there will be more incentives to use LNG instead of conventional fuels. Although the price of LNG is expected to remain lower than that of fuel oil, its higher construction cost and longer payback times remain a challenge to its large-scale adoption.

Propulsion systems based on liquefied natural gas are currently being used in different maritime areas, such as in the transport of vehicles between Europe and North America using two Volkswagen freighters since 2019. A contract has also been signed between Navantia and Fred Olsen to transform ships into gas-powered systems, the first of which is a high-speed ropax ship capable of transporting passengers and goods. There are other Spanish projects that are committed to the construction of maritime units powered by LNG in different sectors [8].

The use of methanol and ethanol in diesel engines is a recent technology, which also affects its application in boats. Methanol is emerging as an attractive fuel for the marine industry, especially due to its low sulfur content and a notable increase in efficiency. Although it is easy to store under normal conditions, it requires around twice as much tank space compared to conventional fuels [9].

The use of alkaline hydrogen electrolysis does not require large areas or fuel supply, and it has been implemented by some companies on their vessels transiting British inland waterways. Although it is a proven technology and has been used for many years in land installations and vehicles, its use in ships has not been sufficiently widespread [7].

2.3. Supply Capacity

Fuel supply capacity is closely related to global availability. This is because if a large number of ships require a particular type of fuel, the supply capacity for that fuel will be high.

The supply capacity of methanol and ethanol fuel in the maritime environment is restricted [10], which negatively affects the availability of these fuels. In contrast, there is an increase in the demand for liquefied natural gas (LNG), which in turn affects its supply capacity worldwide. Despite efforts to develop LNG supply capacity, it is still not sufficient to serve the global supply network. Fortunately, there are some supply ports available, such as Incheon (Republic of Korea), Buenos Aires (Argentina), Damietta and Idku (Egypt), and several ports in Europe [11].

The use of hydrogen through an alkaline electrolysis system dispenses with the need to have an external supply of hydrogen since it is produced autonomously. However, this system requires pure water for its operation. If the vessel has a fresh water generator on board, no external supply of pure water will be required. On the other hand, if the ship does not have a fresh water generator, the supply of pure water can be carried out in any port [12].

2.4. Durability

The term durability refers to the ability of an alternative fuel to be used in the long term. This is related to global fuel reserves, global availability, fuel supply capacity, and future trends.

The main sources of global reserves of methanol and ethanol are fossil fuels, such as natural gas and coal, as well as biomass, which is the source of production of these fuels. Consequently, the production of methanol and ethanol is closely linked to the availability of global reserves of natural gas and coal, as well as the rate of biomass production. In 2014, proven reserves of natural gas reached 246,250 billion cubic meters, according to the EIA (Energy Information Administration) [13].

The amount of natural gas reserves worldwide is considerable, which guarantees its availability for several decades, even if the annual consumption of this fuel is taken into account. According to the EIA, these reserves could be enough to supply global demand for natural gas for more than 50 years. The existence of global reserves of fossil fuels has a positive effect on the durability of other fuels, such as methanol, ethanol, and LNG, whose production also depends on these resources.

In the case of hydrogen, production through an alkaline electrolysis system is an alternative that only requires pure water as a raw material. However, the availability of pure water is not usually a problem related to reserves since it is a renewable and abundant resource in most regions of the world.

2.5. Adaptability

The feasibility of adapting alternative fuel systems to new ships is greater than that of existing ships due to limited space and the necessary modifications to the main engine. For methanol and ethanol fuel systems, additional fuel tanks need to be installed or cover existing ballast tanks on board. It is also necessary to have space for separate rooms for transfer pumps and high-pressure pumps. On the other hand, supplying fuel to the main engine requires double-walled pipes in addition to additional fuel injectors and fuel pumps on the main engine to ensure fuel delivery to the cylinders [14].

Vessels powered by liquefied natural gas require special tanks as well as connection space in the tank for conditioning the LNG and providing delivery to the main engine. They also require gas ventilation space, double-walled gas pipes, specially protected bunkering stations, separation of the main engine from the engine room by walls, and a gas-safe machinery space [15]. It is important to mention that this system can be applied to a newly built ship with a preliminary evaluation.

Using hydrogen via an alkaline electrolysis system does not require a pure water tank if the boat has a freshwater generator, but a freshwater tank can be used for pure water storage if the boat does not have one. Space is needed in the engine room for the alkaline electrolysis cells and control units. Double-wall piping and minor modifications to the main engine turbocharger are required for application to a vessel. In addition to this system, safety equipment, alarms, and adequate ventilation are needed [16].

Analyzing the different systems, it can be noted that the use of LNG requires more rigorous specifications compared to systems that use methanol, ethanol, or hydrogen. Hydrogen presents the most accessible requirements to adapt to an existing ship, although some prior measures are still necessary.

2.6. Engine Performance

Engine performance can be positively or negatively affected by the use of alternative fuels. The analysis for each alternative fuel is based on Brake Thermal Efficiency (BTE) and Brake Specific Fuel Consumption (BSFC). Brake Thermal Efficiency consists of the proportion of thermal energy released in the combustion of a fuel converted into useful mechanical energy in the engine shaft. This is the efficiency of the engine to transform the chemical energy contained in the fuel into mechanical energy. On the other hand, Brake Specific Fuel Consumption is a measure that evaluates the efficiency of the engine in terms of the amount of fuel necessary to produce a given mechanical work. It is a tool to measure engine efficiency in terms of fuel consumption [7].

Methanol and ethanol are commonly used as fuels in internal combustion engines. However, these fuels reduce the BTE due to their lower energy content than gasoline since they contain oxygen in their composition. In addition, its compression ratio is different from that required by gasoline, which can further decrease its thermal efficiency. Another important factor is their high latent heat of vaporization, which means that they require more heat to vaporize and mix properly with air before combustion (Table 1). On the other hand, methanol and ethanol increase the BSFC due to their lower net heating values [17]. There are no studies that directly compare the effect of these alternative fuels on engine performance. Then, it is not possible to establish their relative importance precisely.

Differently, the addition of LNG and hydrogen in diesel engines can improve BTE and decrease BSFC. This is because they have a higher calorific value and better combustion characteristics than conventional diesel fuel [18–20], since higher calorific values release more heat, increasing engine efficiency. Rajak et al. [21] have investigated the engine performance of hydrogen combined with diesel, concluding that it improves the combustion characteristics and decreases the ignition delay.

2.7. Engine Emissions

The main objective of using alternative fuels on board ships is to reduce emissions generated by maritime transport, which may differ depending on the type of fuel used. Figure 1 shows the effect of alternative fuels on engine emissions with respect to fossil fuels. As it can be seen, methanol and ethanol decrease the emission of nitrogen oxides (NOX), sulfur oxides (SOX), and minor particles (PM), while increasing the emission of carbon dioxide and monoxide (CO_2 and CO). LNG reduces CO_2, NOX, SOX, and PM emissions, although it increases CO emissions. Hydrogen has the lowest carbon footprint possible of all alternative fuels (Table 1).

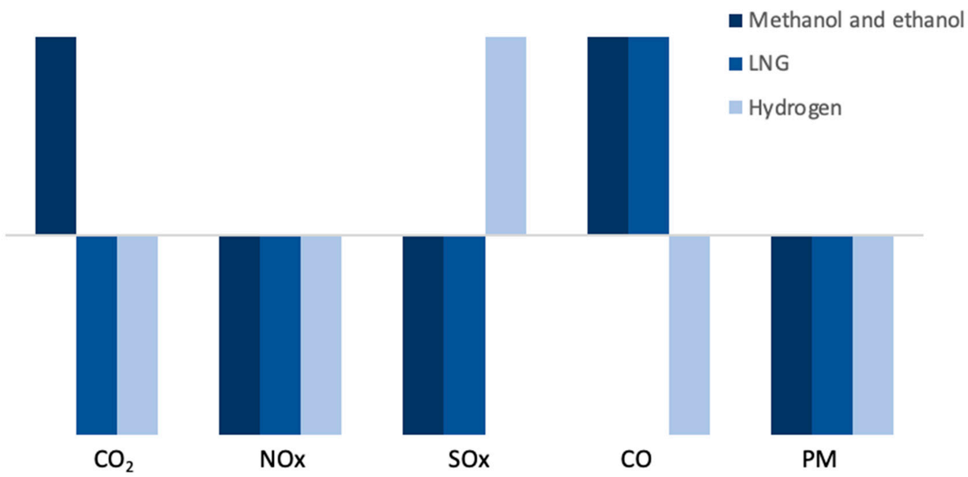

Figure 1. Effect of alternative fuels on engine emissions with respect to fossil fuels.

However, when LNG is used as fuel, a phenomenon known as "methane leak" occurs, which nullifies the effect of reducing CO_2 emissions. This phenomenon has been eliminated in two-stroke diesel engines and reduced to minimum levels in four-stroke diesel engines, thanks to technological development. Because of this, the release of methane is overlooked when performing the evaluation [22].

On the other hand, hydrogen helps reduce CO_2, CO, and PM emissions, although its impact on NOX emissions varies depending on engine operating conditions. International emissions standards are linked to the global MARPOL regulation, which sets limits for emissions that are covered by this regulation [10].

2.8. Cost

The main disadvantage of hydrogen is the cost of production and storage due to cryogenic storage, which is an economic problem [1]. An economically competitive fuel option requires low production, transportation, and storage. Although hydrogen production is expensive compared to other fuels, its price may become more competitive as new production technologies are developed and economies of scale are achieved. In the short term, hydrogen is expected to be more expensive than natural gas, but its price may improve in the future with the possibility of reducing its price [23].

Liquefied natural gas has a relatively low production cost since it is extracted from natural gas reserves. Compared to other alternative fuels, it has an advantage in terms of infrastructure, as LNG-powered vehicles can use the same supply network as diesel vehicles. However, the infrastructure cost of installing LNG fueling stations can be high. LNG can help close the gap between the current fossil fuel-based economy and the future hydrogen-based economy. Furthermore, it is possible to create a mixture of hydrogen and natural gas and allow it to be transmitted through existing pipeline systems [1].

Ethanol and methanol are biofuels that can be produced from renewable sources such as corn, sugar cane, biomass, and agricultural waste. The production cost of these biofuels depends largely on the raw materials used and the production technology used. In general, producing ethanol is cheaper than methanol production. However, biofuel production can also have negative effects on food availability and land use, which can increase the total cost of fuel [24].

3. Multi-Criteria Decision Making Methods

Multi-criteria decision-making methods (MCDM) consist of a multi-step process with the aim of structuring and formalizing a decision to solve a problem. These methods analyze a series of criteria (cost, efficiency, environment, etc.) that are relevant for the problem and determine the best alternative according to the selected criteria. Many MCDMs have been developed and applied in different fields [25]. The most commonly used are Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), and Complex Proportional Assessment (COPRAS), with the AHP being the most popular [26]. Each multi-criteria decision-making method presents advantages and disadvantages that must be considered.

AHP is suitable for qualitative analysis and allows for the evaluation of alternatives against alternatives. TOPSIS can be used in qualitative or quantitative analysis and evaluates the distance of alternatives with respect to an ideal point. PROMETHEE makes qualitative or quantitative analyses using specific software. COPRAS is only suitable for quantitative analyses, and the alternatives have to be sorted in descending order [25]. The aim of this research is to select the best alternative fuel for Spanish Navy ships. AHP was considered the most suitable for this research for being a qualitative analysis that compares among different alternative fuels, but taking into account that it depends heavily on the accuracy and consistency of pairwise comparisons, which can be subjective as well as influenced by individual biases.

3.1. Analytic Hierarchy Process (AHP)

Thomas L. Saaty [27] developed a mathematical and psychological tool called the Analytical Hierarchy Process (AHP). This method is used to make complex decisions in situations where there is little information or it is difficult to evaluate the available data. The AHP offers solutions that meet the needs and understanding of the problem and is widely applied in various fields, including business, economics, and research. This tool is characterized by its great academic rigor, given that it is based on psychological and mathematical foundations and has various empirical verifications.

Saaty [28] proposes converting subjective evaluations of relative importance into a set of total weights, which will be used to select the best alternative. To apply this method, the problem must be decomposed into the following steps: define the problem, identify it, and select alternatives. Develop a hierarchical framework. Construct a pairwise comparison matrix, calculate the eigenvector, and determine the importance of the alternatives. Assess consistency and select the best alternative (Figure 2).

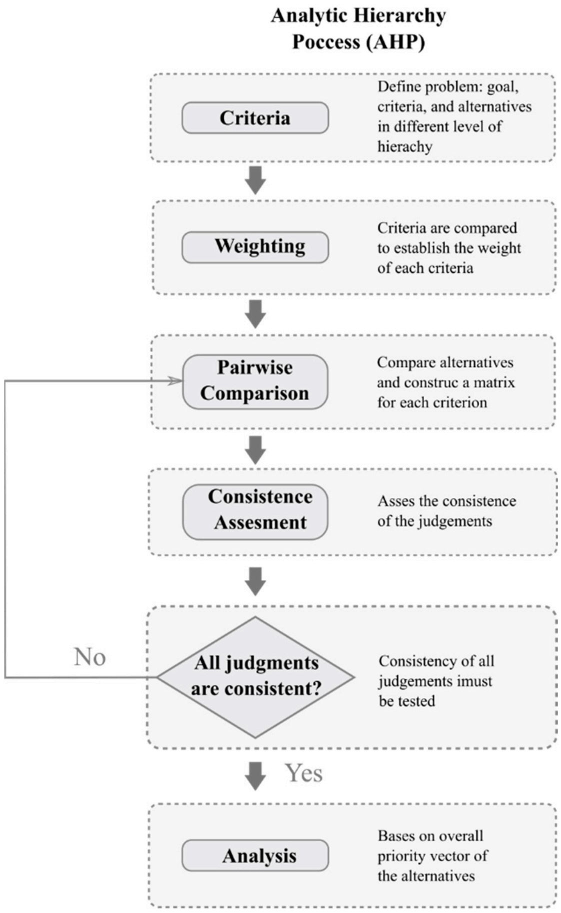

Figure 2. Steps of the analytic hierarchy process.

3.1.1. Problem Hierarchy

Firstly, a hierarchical framework is created in which the objective to be achieved is placed at the top, followed by the main criteria necessary to reach the goal, the sub-criteria at the intermediate levels, and the alternatives at the lowest levels (Figure 3). In addition, it allows possible contradictions between them to be handled to reach a more objective and clear decision.

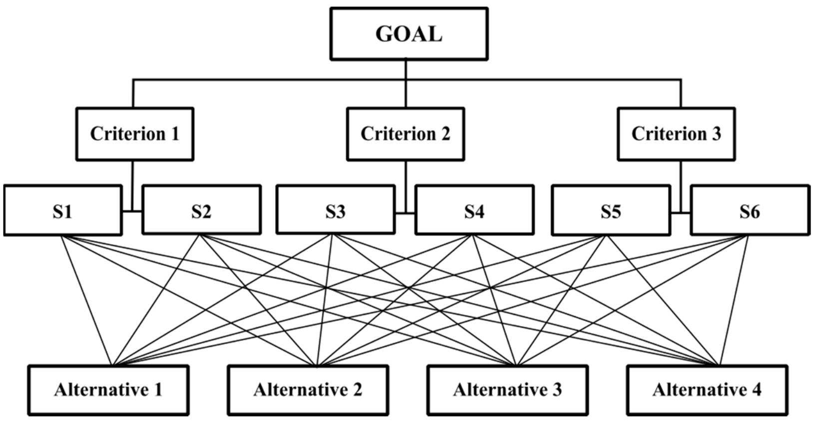

Figure 3. Hierarchical framework of the problem.

3.1.2. Pairwise Comparison Matrix

This matrix determines the importance of the criteria or alternatives, providing a comparison among them. To determine their importance, the alternatives are compared to each other and assigned a corresponding number. The procedure will be as follows: first, a value of 1 is assigned to the alternative that is considered less important compared to the other. Then, using Saaty's paired comparison scale (Table 2), it is evaluated how much more important the alternative is compared to the other. In this way, a ranking of importance can be established for each alternative and facilitate decision analysis. It is crucial to be clear and precise in assigning scores to ensure that the results are reliable and useful.

Table 2. Saaty's scale of relative importance for criterion pairs.

Rating	Definition	Explanation
1	Equal importance	Both elements contribute equally
2	Weak	Between equal and moderate
3	Moderate importance	Judgment and previous experience give a slightly advantage one element over another
4	Moderate plus	Between moderate and strong
5	Strong importance	Judgment and previous experience give a significant advantage one element over another
6	Strong plus	Between strong and very strong
7	Very strong importance	An element exerts significant dominance which has been demonstrated in practice
8	Very, very strong	Between very strong and extreme
9	Extreme importance	One element prevails over the other with the highest possible level of affirmation

This process is carried out individually for each of the alternatives. In this way, a matrix C of size $n \times n$ is constructed where " $a\_(ij)$ is the element (i, j) of A, for $i = 1, 2, \ldots n$ and $j = 1, 2, \ldots n$ with n being the number of alternatives to use, where each element of the matrix is the measure of preference of the alternative in row i compared to the alternative in column j [29]. It is important to take into account that the main diagonal of the matrix is equal to one since each alternative is being compared with itself ($c_{ii} = 1$). Furthermore, it is only necessary to make comparisons above the main diagonal, as comparisons below are simply the inverse of these ($c_{ij} = 1/c_{ji}$). It is important to take into account that the main diagonal of the matrix is equal to one since each alternative is being compared with itself ($c_{ii} = 1$). Furthermore, it is only necessary to make comparisons above the main diagonal, as comparisons below are simply the inverse of these ($c_{ij} = 1/c_{ji}$). It is important to take into account that the main diagonal of the matrix is equal to one since each alternative is being compared with itself ($c_{ii} = 1$). Furthermore, it is only necessary to make comparisons above the main diagonal, as comparisons below are simply the inverse of these ($c_{ij} = 1/c_{ji}$).

$$C = \begin{pmatrix} 1 & c_{12} & \cdots & c_{1n} \\ c_{21} & 1 & \cdots & c_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ c_{n1} & c_{n2} & \cdots & 1 \end{pmatrix} \text{ it is verified that : } c_{ij} \times c_{ji} = \frac{1}{C} = \begin{pmatrix} 1 & c_{12} & \cdots & c_{1n} \\ \frac{1}{c_{12}} & 1 & \cdots & c_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{1}{c_{1n}} & \frac{1}{c_{2n}} & \cdots & 1 \end{pmatrix} \quad (1)$$

Consequently, matrix C meets the requirements of reciprocity, homogeneity, and consistency, defined as follows:

Reciprocity: If $c_{ij} = x$, then $c_{ji} = \frac{1}{x}$, with $1/2 \leq x \leq 2$.

Homogeneity: If elements i and j are considered equally important then $c_{ij} = c_{ji}$, and $c_{ii} = 1$ for all i.

Consistency: It is satisfied that $c_k \cdot c_{kj} = c_{ij}$ for all $1 \leq i, j, k \leq q$.

3.1.3. Calculation of the Eigenvector

Once the paired comparison matrix is obtained, the following steps are carried out to determine the weight of each of the alternatives, which will be called the eigenvector.

Step 1: The matrix D is obtained as a result of multiplying C by itself.

$$\mathrm{D} = \mathrm{C} \times \mathrm{C} = \begin{pmatrix} 1 & d_{12} & \cdots & d_{1n} \\ d_{21} & 1 & \cdots & d_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ d_{n1} & d_{n2} & \cdots & 1 \end{pmatrix} \quad (2)$$

Step 2: The values of each column are then added.

$$p_1, p_2, \ldots p_n = \sum_{1}^{n} c_i \quad (3)$$

Step 3: The matrix D is normalized (matrix E).

$$\mathrm{E} = \begin{pmatrix} \frac{1}{p_1} & \frac{d_{12}}{p_2} & \cdots & \frac{d_{1n}}{p_n} \\ \frac{d_{21}}{p_1} & \frac{1}{p_2} & \cdots & \frac{d_{2n}}{p_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{d_{n1}}{p_1} & \frac{d_{n2}}{p_2} & \cdots & \frac{1}{p_n} \end{pmatrix} = \begin{pmatrix} e_{11} & e_{12} & \cdots & e_{1n} \\ e_{21} & e_{22} & \cdots & e_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ e_{n1} & e_{n2} & \cdots & e_{nn} \end{pmatrix} \quad (4)$$

Step 4: The eigenvector (V), the weight of each alternative, is calculated from the average of each row. Its value is on a scale from 0 to 1.

$$\mathrm{V} = \begin{pmatrix} \frac{1}{n}\sum_1^n e_{1j} \\ \frac{1}{n}\sum_1^n e_{2j} \\ \vdots \\ \frac{1}{n}\sum_1^n e_{nj} \end{pmatrix} = \begin{pmatrix} v_1 \\ \vdots \\ v_n \end{pmatrix} \quad (5)$$

3.1.4. Consistency Assessment

Consistency is very important to contrast the opinions of specialists in a particular discipline with the information provided. The method indicates that if consistency is acceptable, the decision-making process can move forward. If not, the individual responsible for decision making should review the evaluations of the paired comparisons before continuing with the analysis. When the consistency is equal to zero, it can be said that the consistency is total. The consistency was determined as follows:

Step 1: The original matrix C is multiplied by the eigenvector (V), obtaining the total row vector (T):

$$\mathrm{T} = \begin{pmatrix} 1 & c_{12} & \cdots & c_{1n} \\ c_{21} & 1 & \cdots & c_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ c_{n1} & c_{n2} & \cdots & 1 \end{pmatrix} \times \begin{pmatrix} v_1 \\ \vdots \\ v_n \end{pmatrix} = \begin{pmatrix} t_1 \\ \vdots \\ t_n \end{pmatrix} \quad (6)$$

Step 2: Each value of the total row vector is divided by the corresponding value of the eigenvector, obtaining the quotient (Q):

$$\mathrm{Q} = \begin{pmatrix} \frac{t_1}{v_1} \\ \vdots \\ \frac{t_n}{v_n} \end{pmatrix} \quad (7)$$

Step 3: The largest eigenvector ($\lambda_{\max}$) is obtained from the quotients.

$$\lambda_{\max} = \frac{\left(\frac{t_1}{v_1} + \cdots \frac{t_n}{v_n}\right)}{n} \quad (8)$$

Step 4: The consistency index (CI) is determined as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{9}$$

Step 5: The consistency relationship (CR) can be obtained with the following equation:

$$CR = \frac{CI}{RI} \tag{10}$$

The random index (RI) is selected from Table 3 for the matriz of three. This value is calculated from a large number of randomly generated positive reciprocal matrices of order n. The literature provides random indices for a limited matrix [30].

Table 3. Random index of AHP.

Matrix Sixe (n)	2	3	4	5	6	7	8	9	10
Random index (RI)	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

The value of CR should be less than 0.05 (for a matrix size of 3) to obtain a consistent matrix. If CR > 0.05, the original paired comparison matrix should be reviewed and the weight of the alternatives recalculated [31].

3.1.5. Select Best Alternative

The AHP method enables decision-making taking into account the importance of the alternatives and established criteria. If the matrix results are consistent, the process can continue. To select the best alternative, the weight of each alternative (V) must be multiplied by the weight of the criteria normalized (S), obtaining the overall priority vector of the alternatives.

4. Results and Discussion

4.1. Comparison Criterions

The relevant criteria were selected after an extensive literature review [7,32,33], for their relevance in the evaluation and comparison of fuels in terms of their effectiveness, performance, and economic sustainability. This allowed for the creation of the problem hierarchy, placing the objective of finding the best alternative fuel at the highest level, followed by the criteria and the alternatives at the lower level. The criteria and alternatives for the decision process are presented in Figure 4.

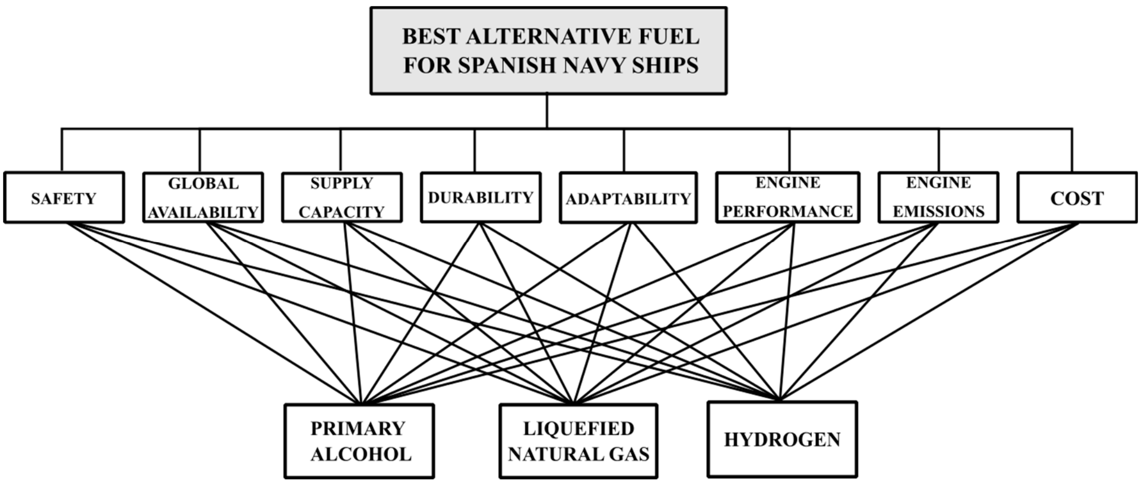

Figure 4. Hierarchical model for selection of best alternative fuel for Spanish Navy ships.

Afterwards, the criteria were presented to high-ranking officers assigned to the Spanish Navy ships to explore qualitatively the suitable selection criteria, and finally, a survey was carried out in order to establish comparison criteria and the weight of each criterion. Officers assigned to the engine service of the Spanish Navy ships were invited to take part in this study voluntarily. They had to rank in order of importance from highest to lowest the following aspects: safety, global availability, supply capacity, durability, adaptability, engine performance, engine emissions, and cost. Table 4 collects the weight of each criterion normalized (S).

Table 4. Weight of each criterion normalized.

Nomenclature	Criterion	Ranking	Weight
C1	Safety	1	0.0278
C2	Global availability	6	0.1667
C3	Supply capacity	7	0.1944
C4	Durability	8	0.2222
C5	Adaptability	5	0.1389
C6	Engine performance	2	0.0556
C7	Engine emissions	3	0.0833
C8	Cost	4	0.1111

4.2. Pairwise Comparison Matrix of Alternative Fuels

The values of Saaty's scale were assigned according to the discussion presented in Section 2, and they are summed up as follows and presented in Table 5:

Safety: hydrogen has been given the highest score (9); LNG has received a moderate score (3); both methanol and ethanol have been ranked with the lowest score (1).

Global availability: LNG obtains a pretty good rate (8). Hydrogen is classified as moderate (3) because it is an already proven technology, although recent, as it is beginning to be implemented in ships. Finally, methanol and ethanol are new technologies with limited maritime application, which places them at the lowest level of availability (2).

Supply capacity: hydrogen's supply capacity assessment would obtain a fairly high rating (8), as its only drawback is the need for fresh water. In the case of LNG, it would be classified as a moderate level (3) due to the existence of supply areas, although these are not adequate to satisfy demand in its entirety. Finally, methanol and ethanol would be located at the worst level (2) due to their limited fuel supply capacity.

Durability: hydrogen presents a moderate score (4); LNG has received a weak score (3); primary alcohols have been ranked with the lowest score (2).

Adaptability: hydrogen is given a pretty good rating of (5). Methanol and ethanol are classified has having a weak level (2) since they require modifications of a certain magnitude. LNG obtains a weak rating, although it does not reach the worst rating, since significant changes are required in existing vessels to adapt it (1).

Engine performance: the highest rating is given to LNG and hydrogen (9), due to their positive impact on engine performance, while methanol and ethanol receive the worst red rating due to their negative impact (1).

Engine emission, hydrogen, has been given the highest score (9). LNG, methanol, and ethanol have received a moderate score (3).

Cost: The final evaluation gives a moderate rating to both LNG and ethanol and methanol (3). Liquefied natural gas is relatively cheap to produce thanks to the availability of natural gas and existing infrastructure, while the cost of ethanol and methanol depends largely on the feedstock and technology used, with ethanol being cheaper than methanol. In contrast, hydrogen is rated with the lowest score (1) since its production is the most expensive compared to other fuels due to its high price.

Table 5. Values of Saaty's scale assigned.

Criterion	Etanol (A1)	LNG (A2)	H_2 (A3)
Safety (C1)	1	3	9
Global availability (C2)	2	8	3
Supply capacity (C3)	2	3	8
Durability (C4)	2	3	4
Adaptability (C5)	2	1	5
Engine performance (C6)	1	9	9
Engine emissions (C7)	3	3	9
Cost (C8)	3	3	1

The values in Table 5 were used to construct a pairwise comparison matrix (3 × 3) for each criterion, for a total of 9. The pairwise comparison matrix of criteria is shown in Table 6.

Table 6. Pairwise comparison matrix for all criteria.

	C1			C2			C3			C4		
	A1	A2	A3	A1	A2	A3	A1	A2	A3	A1	A2	A3
A1	1	1/3	1/9	1	1/8	1/3	1	1/3	1/8	1	1/2	1/4
A2	3	1	1/3	8	1	2	3	1	1/2	2	1	1/3
A3	9	3	1	3	1/2	1	8	2	1	4	3	1
	C5			**C6**			**C7**			**C8**		
	A1	A2	A3	A1	A2	A3	A1	A2	A3	A1	A2	A3
A1	1	2	1/2	1	1/9	1/9	1	1/3	1/9	1	1	3
A2	1/2	1	1/5	9	1	1	3	1	1/3	1	1	3
A3	2	5	1	9	1	1	9	3	1	1/3	1/3	1

4.3. Consistency Assessment of Alternative Fuels

Taking into account that the comparisons among alternative fuels were carried out through subjective judgments, it is necessary to ensure that the judgements are consistent. The first step was to obtain the eigenvector for each criterion from the pairwise comparison matrix according to Equations (2)–(5). The values are collected in Table 7.

Table 7. Eigenvector of alternative fuels for each criterion.

Fuel	C1	C2	C3	C4	C5	C6	C7	C8
A1	0.0769	0.0864	0.0864	0.1365	0.3090	0.0526	0.0769	0.4286
A2	0.2308	0.6282	0.2854	0.2385	0.1095	0.4737	0.2308	0.4286
A3	0.6923	0.2854	0.6282	0.6250	0.5816	0.4737	0.6923	0.1429

From the obtained values of the eigenvector, it can be said that:

For the first criterion (safety), hydrogen (A3) obtains the highest score, with a value of 0.6923, being the safest one among the studied alternative fuels.

This pattern is not repeated for criterion two, where LNG (A2) has a greater weight with a value of 0.6282. This indicates that LNG has the highest global availability.

According to the third (supply capacity), fourth (durability), and fifth (adaptability) criteria, hydrogen (A3) is the best qualified. Hydrogen is obtained by water electrolysis, and this resource is available around the world and is easy to store on board.

Considering the sixth criterion (engine performance), there is a tie between alternatives 2 and 3 (LNG and hydrogen), both with a weight of 0.4737.

The seventh criterion (engine emissions) gives the highest score to hydrogen (A3) since it only emits water vapor.

Finally, in the last criterion (cost), the same result was obtained between primary alcohols (A1) and LNG (A2) with a value of 0.4286.

The second step is to calculate the largest eigenvector (λ_{max}), the consistency index (CI), and the consistency ratio (CR) using Equations (6)–(10). The summary results are presented in Table 8. It can be observed that the values of CR are less than 0.05, indicating that the judgment matrix is consistent and can be used to identify the best alternative fuel.

Table 8. Consistency for alternatives.

	C1	C2	C3	C4	C5	C6	C7	C8
λ_{max}	3.0000	3.0092	3.0092	3.0183	3.0055	3.0000	3.0000	3.0000
CI	0.0000	0.0046	0.0046	0.0091	0.0028	0.0000	0.0000	0.0000
CR	0.0000	0.0079	0.0079	0.0158	0.0048	0.0000	0.0000	0.0000

4.4. Select Best Alternative Fuel

The overall priority vector of the alternatives was obtained by multiplying the weight of each alternative (V) by the weight of the criteria normalized (S) as follows:

$$\begin{pmatrix} 0.0769 & 0.0864 & 0.0864 & 0.1365 & 0.3090 & 0.0526 & 0.0769 & 0.4286 \\ 0.2308 & 0.6282 & 0.2854 & 0.2385 & 0.1095 & 0.4737 & 0.2308 & 0.4286 \\ 0.6923 & 0.2854 & 0.6282 & 0.6250 & 0.5816 & 0.4737 & 0.6923 & 0.1429 \end{pmatrix} \times \begin{pmatrix} 0.0278 \\ 0.1667 \\ 0.1944 \\ 0.2222 \\ 0.1389 \\ 0.0556 \\ 0.0833 \\ 0.1111 \end{pmatrix} = \begin{pmatrix} 0.1636 \\ 0.3280 \\ 0.5085 \end{pmatrix} \quad (11)$$

The obtained results indicate that hydrogen has the highest value (0.5085) in comparison with LNG (0.3280) and primary alcohols (0.1636). According to Saaty [27], the alternative with the highest value would achieve the goal. Hydrogen has great potential as a promising fuel due to its high energy density and fast charging capacity, which makes it suitable for heavy or long-distance transportation applications. Then, hydrogen can be the best alternative fuel to be used in Spanish Navy ships, according to the selected criteria in this research. Similar results were obtained by Ren and Liang [34], who found that hydrogen was the most suitable fuel among the other alternatives.

5. Conclusions

This study aims to explore the viability of adopting alternative fuels on Spanish Navy ships with the purpose of establishing sustainable propulsion systems on their platforms and thus contributing to the fight against climate change. The implementation of this measure could reduce greenhouse gas (GHG) emissions and other pollutants derived from the burning of fossil fuels and maritime navigation, which would make an important contribution to mitigating their effects worldwide. Moreover, the amount of CO_2 emitted can be reduced, and emissions harmful to the atmosphere can even be completely eliminated. Reducing all these emissions could have a significant impact on air quality and, therefore, the health of the population. Thus, the transition towards more sustainable energy sources and improving the energy efficiency of ships could have a significant environmental impact.

The analytical hierarchy process was used for selecting the most suitable alternative fuel for Spanish Navy ships based on eight criteria in terms of their effectiveness, performance, and economic sustainability. The criteria were selected after an extensive literature review, and they were validated and ranked by officers of the Spanish Navy. The great experience of the naval officers who have participated in this study has played a high role in the result, since they have provided very valuable information on the needs of the Spanish Navy.

The analysis revealed that hydrogen was the most suitable fuel, with the highest priority. The results of the analysis show an overall rating of H_2 as a fuel far superior to LNG, with an achieved value of 0.5085 versus 0.3280 for LNG, mainly due to its high energy density and fast charging capacity. In terms of economics, it is important to consider both the short- and long-term costs of implementing alternative fuels on Navy ships. Although the initial cost may be high, especially in the case of hydrogen, in the long term, the cost of maintaining and operating ships could be significantly reduced. However, the study of the cost of implementing this fuel on Navy ships has not been carried out, leaving it for future research.

As a future line of this work, the study of the implementation of these better valued fuels is proposed. This is a complex task, whether the aim is to adapt conventional propulsion systems from diesel to H_2 or LNG or to replace them. It would imply the need for an in-depth economic study of existing ships as well as those under construction. But in addition, and also very important, a rigorous study on both structural and operational safety with these fuels would be necessary.

Finally, it would be interesting to conduct this study with data from officers of the navies of other countries and compare the results. The objective would be to see what evaluations they provide to the different sections and compare the results with those obtained from the Spanish Navy data.

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References

1. Al-Enazi, A.; Okonkwo, E.C.; Bicer, Y.; Al-Ansari, T. A Review of Cleaner Alternative Fuels for Maritime Transportation. *Energy Rep.* **2021**, *7*, 1962–1985. [CrossRef]
2. Fitzmaurice, M. The International Convention for the Prevention of Pollution from Ships (MARPOL). In *Research Handbook on Ocean Governance Law*; Edward Elgar Publishing: Northampton, MA, USA, 2023.
3. Islam Rony, Z.; Mofijur, M.; Hasan, M.M.; Rasul, M.G.; Jahirul, M.I.; Forruque Ahmed, S.; Kalam, M.A.; Anjum Badruddin, I.; Yunus Khan, T.M.; Show, P.L. Alternative Fuels to Reduce Greenhouse Gas Emissions from Marine Transport and Promote UN Sustainable Development Goals. *Fuel* **2023**, *338*, 127220. [CrossRef]
4. Torres Camprubí, A. Securitization of Climate Change: The Inter-Regional Institutional Voyage. *Yearb. Int. Environ. Law* **2016**, *27*, 82–105. [CrossRef]
5. Shao, M.; Han, Z.; Sun, J.; Xiao, C.; Zhang, S.; Zhao, Y. A Review of Multi-Criteria Decision Making Applications for Renewable Energy Site Selection. *Renew Energy* **2020**, *157*, 377–403. [CrossRef]
6. Astbury, G.R. A Review of the Properties and Hazards of Some Alternative Fuels. *Process Saf. Environ. Prot.* **2008**, *86*, 397–414. [CrossRef]
7. Deniz, C.; Zincir, B. Environmental and Economical Assessment of Alternative Marine Fuels. *J. Clean. Prod.* **2016**, *113*, 438–449. [CrossRef]
8. Caro, R.V. Buques Impulsados Por Gas Natural Licuado. Entrada En Vigor Del Código IGF. *Rev. Gen. Mar.* **2017**, *273*, 465–479.
9. Argüelles Alonso, Á. Estudio Sobre La Situación Actual Del Metanol Como Combustible En La Industria Marina. Master's Thesis, University of Cantabria, Cantabria, Spain, 2021. Available online: http://hdl.handle.net/10902/22814 (accessed on 30 November 2023).
10. OMI. *Convenio Internacional Para Prevenir La Contaminación Por Los Buques, MARPOL 73/78*. 2017. Available online: https://www.imo.org/es/About/Conventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx (accessed on 30 November 2023).
11. Svanberg, M.; Ellis, J.; Lundgren, J.; Landälv, I. Renewable Methanol as a Fuel for the Shipping Industry. *Renew. Sustain. Energy Rev.* **2018**, *94*, 1217–1228. [CrossRef]
12. Gilbert, P.; Walsh, C.; Traut, M.; Kesieme, U.; Pazouki, K.; Murphy, A. Assessment of Full Life-Cycle Air Emissions of Alternative Shipping Fuels. *J. Clean. Prod.* **2018**, *172*, 855–866. [CrossRef]

13. Troderman, J. Renewable Identification Number Prices for Ethanol and Biomass-Based Diesel Remain High. U.S Energy Information Administration. July 2022. Available online: https://www.eia.gov/todayinenergy/detail.php?id=53019 (accessed on 30 November 2023).
14. Li, Z.; Wang, Y.; Wang, Y.; Yin, Z.; Gao, Z.; Ye, Z.; Zhen, X. Effects of Fuel Injection Timings and Methanol Split Ratio in M/D/M Strategy on a Diesel/Methanol Dual-Fuel Direct Injection Engine. *Fuel* **2022**, *325*, 124970. [CrossRef]
15. EMSA. *Final Report—European Maritime Safety Agency (EMSA)—Study on Standards and Rules for Bunkering of Gas-Fuelled Ships*; EMSA: Lisboa, Portugal, 2013; Available online: https://www.emsa.europa.eu/publications/reports/item/1714-study-on-standards-and-rules-for-bunkering-of-gas-fuelled-ships.html (accessed on 30 November 2023).
16. Veldhuis, I.J.S.; Richardson, R.N.; Stone, H.B.J. Hydrogen Fuel in a Marine Environment. *Int. J. Hydrogen Energy* **2007**, *32*, 2553–2566. [CrossRef]
17. Sayin, C.; Ozsezen, A.N.; Canakci, M. The Influence of Operating Parameters on the Performance and Emissions of a DI Diesel Engine Using Methanol-Blended-Diesel Fuel. *Fuel* **2010**, *89*, 1407–1414. [CrossRef]
18. Cheenkachorn, K.; Poompipatpong, C.; Ho, C.G. Performance and Emissions of a Heavy-Duty Diesel Engine Fuelled with Diesel and LNG (Liquid Natural Gas). *Energy* **2013**, *53*, 52–57. [CrossRef]
19. Poompipatpong, C.; Cheenkachorn, K. A Modified Diesel Engine for Natural Gas Operation: Performance and Emission Tests. *Energy* **2011**, *36*, 6862–6866. [CrossRef]
20. Selvi Rajaram, P.; Kandasamy, A.; Arokiasamy Remigious, P. Effectiveness of Oxygen Enriched Hydrogen-Hho Gas Addition on Direct Injection Diesel Engine Performance, Emission and Combustion Characteristics. *Therm. Sci.* **2014**, *18*, 259–268. [CrossRef]
21. Rajak, U.; Nashine, P.; Verma, T.N.; Veza, I.; Ağbulut, Ü. Numerical and Experimental Investigation of Hydrogen Enrichment in a Dual-Fueled CI Engine: A Detailed Combustion, Performance, and Emission Discussion. *Int. J. Hydrogen Energy* **2022**, *47*, 32741–32752. [CrossRef]
22. Nair, A.; Acciaro, M. Alternative Fuels for Shipping: Optimising Fleet Composition under Environmental and Economic Constraints. *Int. J. Transp. Econ.* **2018**, *45*, 439–460. [CrossRef]
23. Martins, J.; Brito, F.P. Alternative Fuels for Internal Combustion Engines. *Energies* **2020**, *13*, 4086. [CrossRef]
24. Campos martín, J.M.; Chica, A.; Domine, M.; García, T.; Pawelec, B.; Luis, J.; Rojas, S.; Serra, J.M.; Suelves, I. Biocombustibles Biofuels. *Bol. Grupo Español Carbón* **2020**, *58*. Available online: https://www.gecarbon.org/boletines/articulos/BoletinGEC_058-art6.pdf (accessed on 30 November 2023).
25. Zlaugotne, B.; Zihare, L.; Balode, L.; Kalnbalkite, A.; Khabdullin, A.; Blumberga, D. Multi-Criteria Decision Analysis Methods Comparison. *Environ. Clim. Technol.* **2020**, *24*, 454–471. [CrossRef]
26. Taherdoost, H.; Madanchian, M. Multi-Criteria Decision Making (MCDM) Methods and Concepts. *Encyclopedia* **2023**, *3*, 77–87. [CrossRef]
27. Saaty, R.W. *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation (Decision Making Series)*; Mathematical Modelling; McGraw-Hill International Book Company: New York, NY, USA, 1980.
28. Saaty, R.W. The Analytic Hierarchy Process—What It Is and How It Is Used. *Math. Model.* **1987**, *9*, 161–176. [CrossRef]
29. Berumen, S.A.; Redondo, F.L. La Utilidad de los Métodos de Decisión Multicriterio (omo el AHP) en un Entorno de Competitividad Creciente. *Cuad. Adm.* **2007**, *20*, 65–87.
30. Velmurugan, R.; Selvamuthukumar, S.; Manavalan, R. Multi Criteria Decision Making to Select the Suitable Method for the Preparation of Nanoparticles Using an Analytical Hierarchy Process. *Pharmazie* **2011**, *66*, 836–842. [CrossRef] [PubMed]
31. Martínez Gómez, J. Uso de Métodos Multicriterio de Toma de Decisiones para la Selección de Biomasa en Reactores Fischer Tropsch. *Ingenius Rev. De Cienc. Y Tecnol.* **2016**, 27–36. [CrossRef]
32. Moshiul, A.M.; Mohammad, R.; Hira, F.A. Alternative Fuel Selection Framework toward Decarbonizing Maritime Deep-Sea Shipping. *Sustainability* **2023**, *15*, 5571. [CrossRef]
33. Andersson, K.; Brynolf, S.; Hansson, J.; Grahn, M. Criteria and Decision Support for a Sustainable Choice of Alternative Marine Fuels. *Sustainability* **2020**, *12*, 3623. [CrossRef]
34. Ren, J.; Liang, H. Measuring the Sustainability of Marine Fuels: A Fuzzy Group Multi-Criteria Decision Making Approach. *Transp. Res. D Transp. Environ.* **2017**, *54*, 12–29. [CrossRef]