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An Assessment of Alternative Fuels for Ocean-Going Deep-Sea Vessels: A Case Study in IMO Maritime 2050 GHG Emission Reduction Targets

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Abstract

The International Maritime Organization (IMO) committed at the 2015 Paris Climate Summit to reducing greenhouse gas (GHG) emissions from shipping. Many studies and classification society outlooks agree that meaningful decarbonisation of deep-sea shipping will require a shift to low- or zero-carbon fuels. This research systematically evaluates three leading alternative fuels—hydrogen, ammonia, and methanol—regarded as capable of helping the sector meet the IMO's 2050 targets. Each fuel was assessed using technical, environmental, economic, and social criteria through a hybrid multi-criteria decision analysis (MCDA) approach combining the analytical hierarchy process (AHP) and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution). Criteria weights were derived from an online survey of 57 maritime experts, while secondary data from existing literature informed the TOPSIS analysis. AHP results show that environmental performance is the most important factor in fuel selection, followed by technical, economic, and social considerations. The combined AHP and TOPSIS results show that ammonia is the most suitable alternative fuel to reach IMO 2050 goals. This study's findings provide a structured and evidence-based comparison of the main deep-sea alternative fuels and offer practical guidance for maritime decision-makers seeking to identify the most suitable option for decarbonising their fleets in line with global GHG reduction goals for 2050 and beyond.

Keywords: alternative fuels; MCDA; AHP; TOPSIS; hydrogen; ammonia; methanol

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1. Introduction

At the United Nations Climate Change Conference (COP 21) on 12 December 2015, 196 parties committed to a legally binding international treaty to mitigate global climate change. During this event, the International Maritime Organization (IMO) acknowledged greenhouse gas (GHG) emissions from shipping and pledged to adopt measures to reduce them [1]. Subsequently, the IMO developed a roadmap at the 70th Marine Environmental Protection Committee (MEPC) session and adopted the Initial IMO Strategy for GHG reduction at the 72nd MEPC session, outlining targets for 2030 and 2050 [2–8].

Research [9] indicates that achieving post-2030 IMO targets will require a transition to alternative fuels. Ref. [10] reports that deep-sea vessels account for approximately 80% of global maritime CO_2 emissions, highlighting their critical role in decarbonisation. The importance of zero-carbon fuels for achieving the 2050 targets is further reinforced by [11], cited in [12]. Although multiple alternative fuels have been proposed and pilot

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projects initiated, only a limited number are feasible for deep-sea applications when production, storage, and bunkering infrastructure are considered. Despite this, no systematic assessment exists to guide stakeholders in selecting appropriate decarbonisation pathways. Ref. [13] emphasises that meeting IMO emission targets depends on the development and availability of low- and zero-carbon fuels and supporting infrastructure, a view supported by [9,12,14,15].

The maritime sector has largely adopted a reactive approach to decarbonisation, resulting in a "chicken and egg dilemma" where fuel suppliers await demand while shipowners and manufacturers await infrastructure development. Refs. [16,17] highlight this challenge using LNG as an example, noting that despite a decade of development, LNG bunkering supplies only 1% of global demand, suggesting similar challenges for other alternative fuels. Recent studies on alternative marine fuels [18–28] generally adopt a holistic approach across all vessel types. However, fuel suitability varies significantly by operational context. While batteries may suit inland or near-coastal vessels, fuels such as liquid hydrogen, ammonia, or methanol are more applicable to deep-sea vessels, though less practical for short-sea operations. Deep-sea vessels operate on long, irregular global routes and therefore require fuels that are widely available and compliant with international regulations [17,29,30] further notes that technical and commercial feasibility varies by ship type, with deep-sea vessels having fewer viable fuel options despite contributing over 80% of maritime CO_2 emissions.

This research aims to identify the most feasible alternative fuel capable of meeting the IMO's 2050 targets and supporting deep decarbonisation. While limited studies have examined deep-sea applications [26,31–33], none have comprehensively assessed technical, environmental, economic, and social factors. Consequently, a systematic evaluation of deep-sea alternative fuels is essential to address this critical gap in maritime decarbonisation research.

2. The State of the Art

2.1. The 2050 Future Fuel Mix

There is a wide array of low-carbon fuel choices on which studies have been conducted, and pilot projects have been launched to test these fuels on vessels to determine their technical and economic viability [12]. However, each alternative fuel and energy source has drawbacks in global availability, onboard storage, energy density, and support infrastructure [13]. Ref. [16] elaborates on economic, environmental, infrastructural, safety, and technical challenges by comparing 12 different types of alternative fuels. The study mainly focuses on the financial considerations of the fuels and does not consider the 'hidden cost' of fossil fuels. Ref. [16] concludes that the choice of alternative fuel should be a "ubiquitous product", and the potential candidates include LNG, methanol, hydrogen, and ammonia for deep-sea shipping. Ref. [23] reports a similar study comparing the challenges of alternative marine fuels and identified economic opportunities. However, the study is limited to fuels used for IC engines and does not consider other options, such as fuel cells, which could be viable propulsion options for 2050 and beyond.

Much of the research suggests that LNG would act as a bridge fuel, while methanol, ammonia and hydrogen are likely to be adopted as the fuels of the future [31,32,34–36]. Clarkson's research on 'Potential Net Zero' scenarios predicts that hydrogen, ammonia and methanol will be the dominant alternative fuel options for deep-sea applications by 2050 [37]. As an alternative fuel, LNG is incapable of attaining the IMO's 2050 emission ambitions due to its GHG potential, as it would be a fuel still derived from fossil fuels. Moreover, alternatives such as biodiesel could be deemed net-zero fuels. However, biodiesel production would cause a diversion of crops and could aggravate food shortages around the globe. Accordingly, hydrogen, ammonia and methanol would be the most feasible alternative fuel options for 2050 and beyond. Table 1 presents the various characteristics of hydrogen, ammonia and methanol.

Table 1. Characteristics of alternative fuels. Source: [20,29,38–41].

Alternative Fuel Characteristics	Hydrogen	Ammonia	Methanol
Chemical Composition	H_2	NH_3	CH_3OH
Boiling Point, °C @ 1 Bar	−253	−33	65
LHV, MJ/kg	120.2	22.5	19.9
Auto Ignition Temperature, °C	535	630	440
Flammable range, % Vol in air	4~74%	15~33.6%	6.0~36%
Energy Density, MJ/lt	9.2	12.7	15.7
Liquid Density, kg/m^3	70.8	600	798
Volume Comparison Heavy Fuel Oil (HFO) (Energy Density)	4.33	2.55	2.54
Carbon Content	0	0	0.375
Carbon Content Reduction (Compared to HFO)	100%	100%	56%
CO_2, Kg CO_2/kWh	0	0	0.2486
CO_2, Kg CO_2/kWh Reduction (Compared to HFO	100%	100%	11%
Low Flash Point	Yes	No	Yes
Toxicity	Not Toxic	Highly Toxic	Low Acute Toxicity

2.2. Hydrogen

Hydrogen offers ship owners a low-carbon, low-emission fuel, which could be used in either internal combustion engines or fuel cells [39]. Compared to incumbent marine fossil fuels exported from resource-rich countries, hydrogen could be produced in any part of the world, leading to a secure and independent energy ecosystem [16]. Among the potential alternative energy options, hydrogen (H2) is a much-preferred fuel because of its environmental impact [42,43]. It is the cleanest marine fuel in terms of combustion emissions. Burning H2 in oxygen produces only water, making it a clean fuel. However, when it is burned in air, the high heat creates nitrogen oxides (NOx) which are air pollutants. Heat and water vapour are also generated, eliminating some CO_2 and soot but introducing NOx concerns, requiring emissions controls for practical use [13,33,44].

Unlike fossil fuels, hydrogen is deemed an energy carrier [20,45–47] rather than a fuel source. It is considered to have the highest energy content per unit mass of 120.2 MJ/kg compared to other chemical fuels, such as marine diesel oil (MDO), by 2.8 times. However, hydrogen has a very low volumetric energy density (9.93 GJ/m3) and will require about 4.1 times the volume of MDO to create the same energy content [17].

According to [14,20], the current global production of H2 amounts to about 55 million tonnes per year. At present, approximately 95% of this H2 is produced from fossil fuels, while the remaining 5% is generated through renewable electrolysis. Hydrogen production from a replenishable feedstock and renewable energy is considered 'green hydrogen' [22,42]. Hydrogen production through electrolysis using solar or wind turbines has been analysed using sustainable energy [20,28,39,45,48]. The world's largest green hydrogen production plant is proposed to be built by 2025 and is designed to produce 650 tons of hydrogen daily, utilising 4 GW of renewable energy [33,49]. The EU aims to install a 6 GW renewable energy electrolyser by 2024, producing one million tons of green hydrogen annually. The EU strategy plans to increase electrolyser capacity to 40 GW by 2030 to produce 10 million tons of green hydrogen [50]. The global hydrogen market is projected to grow from 70 million tons in 2019 to 120 million tonnes in 2024 [51]. Australia is anticipating exporting one million tons of hydrogen by 2030, projecting a GDP growth of AUD 11 billion by 2050 [52].

As a marine fuel, hydrogen can generate power by combustion in internal combustion (IC) engines or gas turbines [53]. Alternatively, it can be used directly in fuel cells like the PEM [52,54–56]. Hydrogen is easily ignitable, but IC engines require special modification due to the low heat capacity and density [22]. Conventional IC engines will be required to be retrofitted to enable LH2 operation by injection of a pilot fuel such as MDO [42]. Fuel cells are expected to develop an electrical efficiency of about 50%~60%, which is considerably higher than that of utilising hydrogen in an IC engine (between 40%~50%) [9,17,29].

The major challenge for hydrogen fuel would be the high production cost and the lack of bunkering infrastructure [20]. On the other hand, Ref. [39] also identifies that, among other challenges, advanced storage requirements and fire hazard mitigation are factors that require due attention. Hydrogen can be stored as a compressed gas or a cryogenic liquid at −253 °C. In gas form, hydrogen requires high-pressure tanks, and due to its low volumetric density, it would require 4 times the storage space compared to conventional fuels. On the contrary, a study carried out on long-distance shipping [31] concluded that the volume requirement for pressurised or liquified hydrogen is not significantly high to be considered infeasible. If stored in liquid form, the storage volume would be less, but the tank would need to withstand cryogenic temperatures.

With current technological advancements, hydrogen as a marine fuel is limited to short-sea voyages due to constraints in storage volume on board [8,17,20].

2.3. Ammonia

Owing to its low energy density, hydrogen as an alternative fuel poses challenges concerning storage and transportation. This can be resolved by utilising a hydrogen carrier like ammonia which has a higher energy efficiency than compressed hydrogen or LH2. Refs. [46,57,58] claim that ammonia has a 3-times higher energy density than hydrogen. However, a report [59] indicates that ammonia has a comparable energy density of 22.5 MJ/Kg when compared to methanol (22.7 MJ/Kg), but a lower value than LNG (55 MJ/Kg and MDO (45 MJ/Kg). By weight, 18% of ammonia consists of hydrogen; thus, ammonia contains 50% more hydrogen than LH2 [33,58,60]. Hence, ammonia is an effective hydrogen carrier, containing 107 kg of hydrogen in 1 m^3 of ammonia.

Ammonia has a reliable production, storage, and distribution infrastructure due to industrial applications and fertiliser production for agriculture [47]. In 2019, 150 million tons of ammonia were produced globally [59]. Bulk quantities of ammonia are usually stored at −33 °C and atmospheric pressure [13,61]. Pressurised liquid ammonia (10 bar) can be stored at ambient temperature in thermal stress relief vessels [31,58,62]. Thus, the storage of ammonia is more convenient than the storage of hydrogen.

Presently, nearly 90% of ammonia is produced by synthesising hydrogen and nitrogen in a process known as the Haber–Bosch method [22,33,62–64]. When the hydrogen and the nitrogen for the Haber–Bosch method are acquired from renewable energy sources, the ammonia generated is termed 'green ammonia' [59,60,65]. However, this is an energy-intensive process [31,60,63]. Ammonia can also be generated using carbon-free routes such as cryogenic distillation column, pressure swing adsorption, and membrane separation [66]. Ref. [60] convincingly argues that the technology readiness level (TRL) for green ammonia is of concern, and the obstacles with the production techniques need to be overcome for viable commercial production.

Experimental tests have investigated the feasibility of using ammonia in an IC engine with minor modifications [67]. The potential of green ammonia to emit a third less GHG in an IC engine than in an MDO-operated IC engine has been noted [60]. However, the low flame speed (7 cm/s at atmospheric conditions) and high auto-ignition temperature (630 °C) make ammonia impossible to use as a single fuel and would require a pilot fuel with a dual-fuel injection configuration in IC engines [60]. Detailed studies [67] have explored how advanced injection can improve the overall efficiency of an ammonia dual-fuel engine. Ref. [68] also identifies high heat vaporisation and toxicity as drawbacks of ammonia. Moreover, the combustion of ammonia will generate high levels of NOx, which can be mitigated by employing selective catalytic reduction systems [17,31].

Ref. [17] claims that the use of ammonia as a feeder for hydrogen fuel cells is of growing interest and requires further development of technology. Ref. [31] acknowledge that ammonia could be used with solid-oxide fuel cells to generate electricity, which is in contrast to PEM (proton exchange membrane) electrolysis or alkaline fuel cells, which require hydrogen.

Ammonia is a corrosive and toxic substance in a concentrated form. It is a strong alkaline solution and may irritate tissues in the skin, eyes and respiratory system. The toxicity of ammonia mainly depends on its concentration, duration of exposure and physical form [58]. Lower concentrations in the range of 50 ppm to 100 ppm may irritate the eyes, nose and throat, while inhalation of ammonia at elevated concentrations may result in suffocation or rapid corrosive burning of the respiratory system and may lead to death [58,60]. Skin contact with cold-service ammonia might result in skin burns [60,62,64]. A sustainability white paper [38] states that the odour threshold of ammonia could be as low as 0.037 ppm to 1.0 ppm; thus, its pungent odour can be detected by humans before it reaches levels that could cause health risks. The report suggests that OSHA recommends a safe maximum threshold limit value (TLV) of 50 ppm in 8 h.

Ammonia has a relatively lower flammable range of about 15%~33% in dry air and an auto-ignition temperature of 630 °C. Thus, the risk of an ammonia-rated fire is much lower than other marine alternative fuels [38]. Since ammonia is much lighter than air and highly soluble in water, it makes it easy to control in case of a fire or explosion [60].

The authors of [40] have published a guide to provide insight into ammonia fuel vessels in terms of design, construction and surveys. The guide outlays a detailed description of ammonia-related safety measures and precautions.

2.4. Methanol

Due to its complex storage and distribution requirements, the implementation of hydrogen as an energy carrier has been hindered. Hence, methanol and ammonia have emerged as viable indirect energy storage mediums [22,62]. Among the alternative fuel choice for deep-sea shipping, ammonia and methanol appear to be favourable due to their cost, capability to integrate with existing technology, and current availability [22]. According to [41,69], methanol draws interest in oceangoing, short-sea and inland waterway vessel shipowners due to its CO_2 reduction potential. According to [70], the popularity of methanol is drawn due to its ease of handling, operation safety, and engine compatibility.

Methanol (CH_3OH) is considered the simplest form of alcohol. It is a volatile, colourless, and flammable liquid which emits a distinct odour at ambient temperature [70,71]. A report on methanol by [72] states that methanol readily dissolves in water and is biodegradable.

At present, the large-scale production of methanol consists of two steps. In the first step, the carbonaceous feedstock is gasified into a mixture of carbon monoxide and hydrogen known as 'syngas'. Subsequently, the syngas is converted to methanol [70]. Methanol production from fossil feedstock, such as natural gas and coal, has a well-established global infrastructure [70,71]. Alternatively, methanol could also be produced by utilising renewable feedstocks or as an electro-fuel [40,72,73]. Ref. [70] states that an abundant biomass feedstock is available in Southeast Asia, and methanol production is more favourable through this pathway. However, the study concludes that the future methanol supply would be produced by hydrogen generated from renewable energy sources and direct capture of CO_2 from the atmosphere [70].

Methanol could be used as fuel for IC engines or as a fuel source for fuel cells onboard ships [69,71]. According to a study by [70], methanol is an oxygen-rich fuel that could be combusted in IC engines. The combustion emits water and CO_2 as by-products with no SOx and negligible amounts of NOx. The study further claims that a methanol slip will not cause global warming as it is prone to photochemical reactions or bacterial digestion.

Ref. [72] claims that methanol is often overlooked as an alternative fuel despite having many advantages, such as global availability and the ability to be produced with various fossil and renewable feed stocks. The report states that the existing bunkering infrastructure will require minor modifications to accommodate methanol owing to its low flashpoint. Moreover, unlike hydrogen, it does not have cryogenic complexity and is in liquid form under ambient temperatures rendering it simple to handle and bunker [69,73].

On the contrary, alcohol fuels such as methanol have a lower energy density content than traditional marine fuels. Methanol will require approximately twice the volume of MDO to produce the same amount of energy [72,74].

From a safety perspective, flames propagating from methanol are hazardous, mainly as they burn at low temperatures, with no smoke and an invincible flame in daylight. Thus, a fire outbreak from methanol can go undetected until the flame propagates to adjacent materials. Methanol has a flammable range between 6~36.6% and potentially creates an explosive environment. Methanol can burn with a water emulsion of 25% by volume. This will require unique fire stick machine practices like alcohol-resistant forms. The authors of [73] have published a guide for the arrangement, installation and construction of vessels intending to operate with methanol or ethanol.

2.5. Previous Research: Data Sources, Methodology & Findings

Only a limited number of studies have been carried out to compare alternative marine fuels. The most recent study was carried out by the authors of [26], which evaluated alternative marine fuels through sustainability criteria. An in-depth systematic literature review utilizing secondary data and a detailed survey evaluated these fuels. The study concluded that the most important criteria for alternative fuels would be regulatory compliance, followed by LCA performance, cost, air pollution potential, and safety. However, the study's relevance is applicable to fuel options that could meet the IMO's 2030 emission targets and it does not emphasize 2050 emission targets. Ref. [32] reports a case study using an LNG tanker, using secondary data from the literature and MySQL simulations. The study identifies key engineering challenges anticipated with the integration of hydrogen, ammonia and LNG. The findings state that hydrogen was the favoured option among the other fuel options. It was also proposed that ammonia and hydrogen have a promising potential for decarbonization in the future.

Ref. [75] evaluates alternative fuel options for autonomous vessels regarding environmental regulations and cost-effectiveness. The challenges and opportunities of waste plastic oil (WPO), tyre pyrolysis oil (TPO), biodiesel, ammonia, vegetable oil (VO), and waste lubricant oil (WLO) as alternative marine fuels such as have been widely explored in [23] through systematic analysis. The findings indicate that neat WPO and TPO emission performances were poorer than those of fossil diesel.

A lifecycle assessment (LCA) analysis of LNG, liquified petroleum gas (LPG), methanol and bio-methanol was performed in [74]. The study utilized secondary data from the academic literature for the analysis. The conclusion suggested that, from an environmental perspective, methanol and methane do not show any significant improvement over each other when sourced from the same raw material. Ref. [24] has evaluated the application of alternative fuels in the entire transport sector, including shipping. The comprehensive case study concludes that zero-carbon energy carriers such as hydrogen or ammonia offer the most promising pathways to low-carbon shipping.

A systematic literature review using secondary data was undertaken by the authors of [25]. The report's conclusion emphasizes that the demand for alternative fuels should be supported by reliable infrastructure and identifies the need for a quantitative modelling approach to determine the future fuel mix of the industry. An environmental and economic assessment of alternative fuels is presented in [76] utilizing secondary data and the analytical hierarchy process (AHP) method. It was concluded that methanol and ethanol were not among the preferred choices, while LNG was evaluated as the most suitable alternative fuel. Hydrogen was considered a replacement for LNG in the future.

An MCDA approach using fuzzy logarithmic least squares and fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) to determine the sustainability of marine fuels is presented in [77]. However, the study only included LNG, hydrogen and methanol as alternatives. Hydrogen was recognized as the most sustainable fuel, followed by LNG and methanol. Additionally, [19,21] report a comparison of seven marine fuels, including hydrogen and methanol. However, ammonia was not considered as an alternative in this analysis. Both these studies incorporated stakeholders from Sweden consisting of authorities, fuel suppliers, ship owners and engine makers. The MCDA analysis revealed that the ship owners, engine makers and fuel suppliers preferred LNG, while the authorities ranked hydrogen as their most preferred choice of fuel.

The recent studies identified above on alternative marine fuels did not consider the IMO's 2050 ambitions, instead focusing on the 2030 GHG emission targets. LNG is not seen as a viable option for 2050 and beyond; thus, the results concluded in these studies would not be valid beyond 2030.

3. Method

To assess these fuels, qualitative and quantitative data were analysed. Many of the primary and secondary data utilized for this research were quantitative, while the remainder were qualitative data. As the data utilized for the analysis were both qualitative and quantitative, a mixed methodological approach was most suited.

This research has employed a combination of AHP and TOPSIS to assess the criteria for three main marine alternative fuels. The first step was to determine the alternatives and assessment criteria from a wide array of alternative marine fuels. This was achieved through a detailed and systematic literature review. The technical, environmental, economic and social attributes of alternative fuels—hydrogen, ammonia and methanol—were compared. Several sub-criteria for each of these attributes were identified. The performance values for each alternative corresponding to its attributes were compiled using secondary data obtained through a literature review. The secondary data consisting of performance values of the assessment criteria (sub-criteria) were a combination of quantitative and qualitative by nature. Each of the qualitative performance data was converted to a quantitative value using a 5-point linguistic conversion scale. Primary data for the calculation of local and global weights of assessment sub-criteria were acquired through a pairwise comparison online survey formulated through a Google survey. Subsequently, AHP was utilised to determine the local and global weights for the assessment sub-criteria. Finally, aggregation of the alternative fuels was performed through TOPSIS. The flow process of the intended research is depicted in Figure 1.

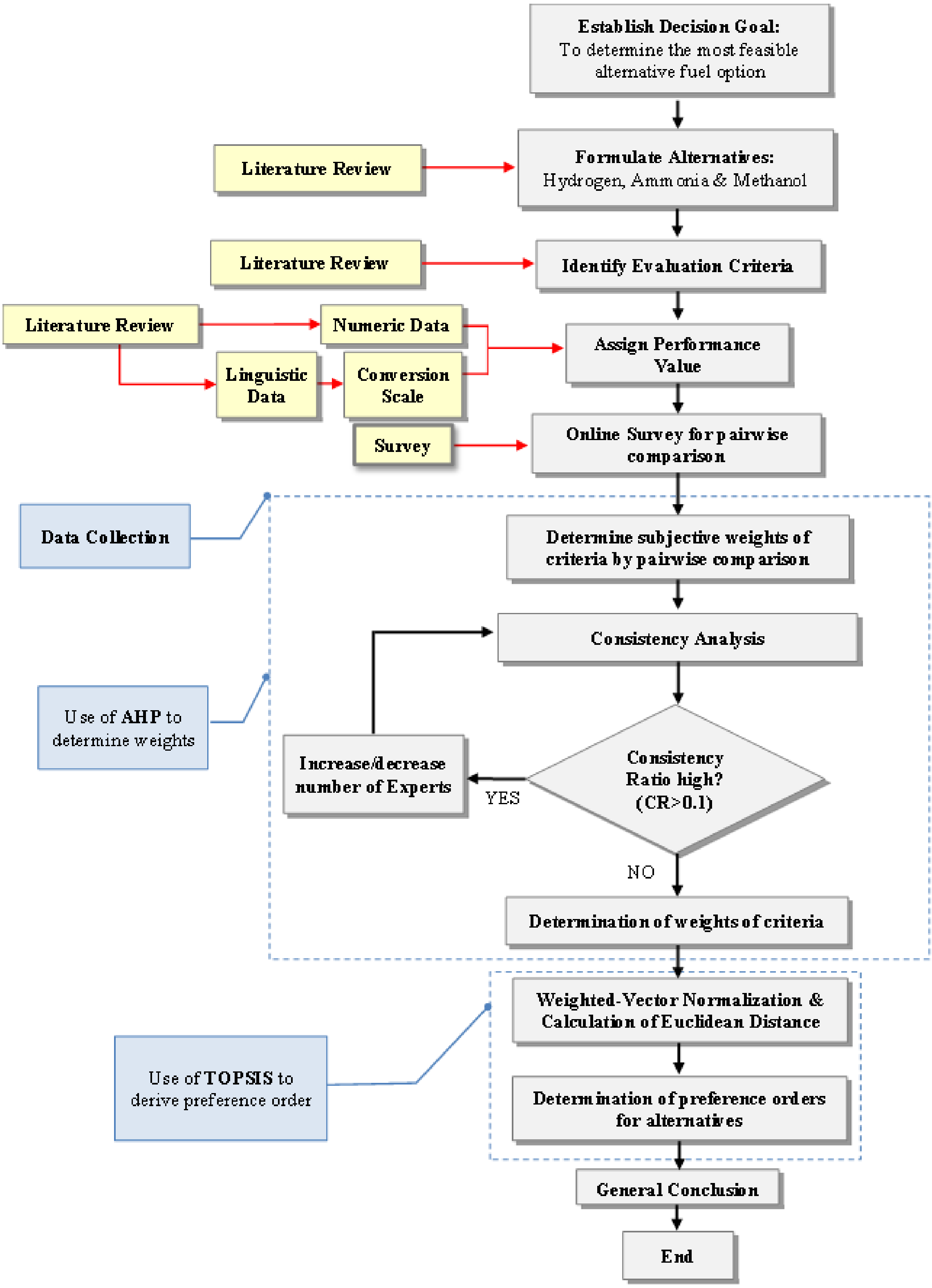

Figure 1. Flow chart of the study.

The primary data were used to determine the criteria weights using AHP. Upon computing the criteria weights, TOPSIS was utilized to evaluate and aggregate the alternatives with secondary data.

3.1. Multi-Criteria Decision Making

Ref. [48] claims that multi-criteria decision analysis (MCDA) methods are popular in decision-making for the sustainable energy sector due to their multi-dimensionality and complexity. Ref. [78] used MCDA to assess fuel cell types for ships using multi-criteria decision analysis. The study employed AHP with a weighted sum model (WSM) for the analysis. Literature reviews on MCDA used for renewable energy analysis, and application in supply chain management have been performed in [79,80]. A study on the various normalisation techniques used for MCDA was carried out in [81].

An MCDA involves alternatives, criteria, and criteria weights, where m alternatives are evaluated against n of criteria. This information is graphically represented in a grouped decision matrix. Figure 2 depicts a typical decision matrix used in MCDA. X_{ij} is considered as the 'performance value' of the j-th criteria of the i-th alternative. w_j is the weight of the criteria j, while n would be the number of criteria, and m would be the number of alternatives.

$$
\begin{array}{ll}
 & \begin{array}{cccc} \textit{Criteria} & C_1 & C_2 & \ldots & C_n \\ \textit{Weights} & w_1 & w_2 & \ldots & w_n \end{array} \\
\textit{alternatives} & \text{-----------------} \\
\begin{array}{c} A_1 \\ A_2 \\ \ldots \\ A_m \end{array} & \begin{pmatrix} X_{11} & X_{11} & \ldots & X_{1n} \\ X_{21} & X_{11} & \ldots & X_{2n} \\ \ldots & X_{11} & \ldots & \ldots \\ X_{m1} & X_{m2} & \ldots & X_{mn} \end{pmatrix}_{m \times n}
\end{array}
$$

Figure 2. Multi-criteria decision making matrix. Source: [82].

3.2. Analytical Hierarchy Process for Assigning the Relative Weights

AHP is a multiple-criteria decision-making approach which Saaty initially proposed [83–86]. It is a support tool in decision making that can assist in solving complex decisions. It uses a multi-level hierarchical structure comprising objectives, criteria, sub-criteria, and alternatives [82]. AHP is used to obtain relative weights for each of the criteria and sub-criteria for the decision-making process. It is based on an eigenvalue approach to its pairwise comparison [87].

Refs. [86,87] state that to make an informed decision, the decision problem needs to be decomposed into the following steps:

(a) Define the problem and research background knowledge.
(b) Identify the objectives of the problem or decision.
(c) Build a decision hierarchy structure with the goal of the decision on the top, the objectives followed by the decision criteria at intermediate levels and the alternatives at the lowest level.
(d) Evaluate the relative importance of each decision criteria by constructing a pairwise comparison matrix.
(e) Perform normalisation for comparison matrix and subsequently calculate the weights for each of the criteria and priorities.

(f) Calculate the maximum eigenvalue, consistency index (CI), and consistency ratio (CR) and analyse the consistency.

Analytical Hierarchy, Pairwise Comparison, and Criteria Weighting

The application of AHP commences with the decision problem being decomposed into a logical hierarchical structure. This enables the problem to be analysed more easily and independently compared [86,87]. Figure 3 depicts a typical logical hierarchy structure as proposed by Saaty.

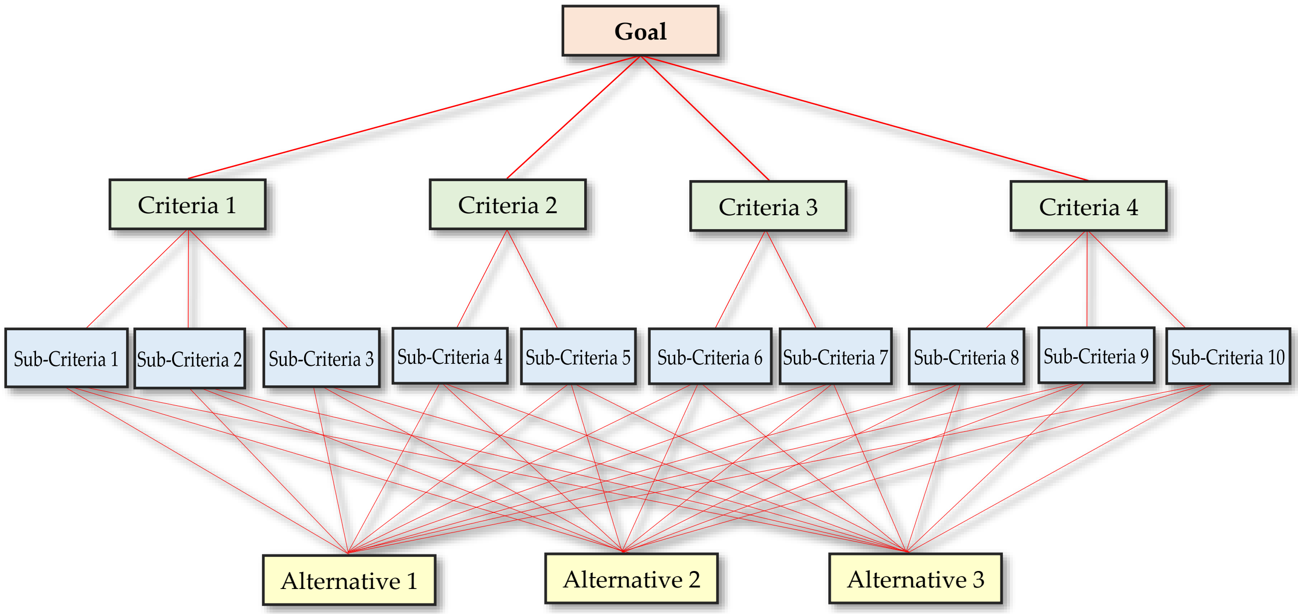

Figure 3. Analytical hierarchy structure. Adapted from: Saaty (1990) [84].

Each of the criteria (or sub-criteria) is arranged in a pairwise configuration, as shown in Equation (1). If n number of criteria is being considered, n number of criteria is placed in the column and row of a n × n matrix. The expert judgements for criteria A_i and A_j are then represented within the matrix, where i,j = 1.2.3. . . . . .n and each a_{ij} is the relative importance of criteria A_i and A_j. When n number of attributes are considered, $[n \times ((n-1))/2]$ number of comparisons will be required [88].

$$A = (a_{ij}) = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ {}^{a}/a_{12} & 1 & \dots & a_{2n} \\ . & . & \dots & . \\ {}^{1}/a_{1n} & {}^{1}/a_{2n} & \dots & 1 \end{bmatrix} \quad (1)$$

Expert judgement is used to make a pairwise comparison of criteria. The aggregation of the comparison is performed against a fundamental weighing scale. Table 2 depicts Saaty's fundamental scale [86,89]. This scale can capture quantitative and qualitative attributes of individual preferences [84,90].

If both comparisons are of equal importance, a score of 1 is given. If a particular criterion is slightly more important than the other, a score of 3 is awarded. Scores 5 and 7 are given when the compared criteria have strong and very strong importance over the other. Extreme impotence is awarded a score of 9. Intensities 2,4,6 and 8 are presented for intermediate values between the two adjacent judgements [86].

Table 2. Fundamental scale for pairwise comparison. Source [86].

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement strongly favour one activity over another
5	Essential or strong importance	Experience and judgement strongly favour one activity over another
7	Very strong importance	An activity is strongly favoured, and its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgements	A compromise is required
Reciprocals	If activity *i* has one of the above numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	
Rational	Ratios arising from the scale	If consistency were to be forced by obtaining *n* numerical values to span the matrix

To obtain relative weights for respective criteria, a pairwise comparison matrix AHP Equation (1) is used in conjunction with Equation (2) [88].

$$w_k = \frac{1}{n}\sum_{j=1}^{n}\left(\frac{a_{kj}}{\sum_{i=1}^{n} a_{ij}}\right)\ (k = 1,\ 2,\ 3, \ldots,\ n) \tag{2}$$

where a_{ij} stands for the value of row i and column j in the pairwise comparison matrix of order n, and the relative criteria weights are denoted by w_k. According to [83], the consistency of a pairwise decision matrix is defined and evaluated by an expression involving a non-principal eigenvalue, known as λ_{max}. It is computed using Equation (3) as shown below:

$$\lambda_{max} = \frac{\sum_{j=1}^{n} \frac{\sum_{k=1}^{n} w_k a_{jk}}{w_j}}{n} \tag{3}$$

where n is the number of criteria being compared, and λ_{max} is the average sum-weight value of the $n \times n$ pairwise comparison matrix. The consistency index is then calculated using Equation (4).

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4}$$

where CI is the consistency index, and n is the number of criteria being compared. If the matrix is perfectly consistent, $CI = 0$ [83,89,91], proving that when the number of pairwise comparisons is increased, the possibility of the consistency index would also proportionately increase. Thus, the author proposed a solution to this problem by introducing a consistency ratio (CR), calculated through Equation (5).

$$CR = CI/RI \tag{5}$$

where CR is the consistency ratio, CI is the consistency index, and RI is Saaty's random index. The value of RI is obtained from Table 3. Ref. [89] proposes that if the calculated value of the consistency ratio $CR \leq 0.10$, the consistency of the pairwise comparison is considered to be reasonable. Alternatively, if $CR \geq 0.10$, the pairwise comparison is deemed inconsistent.

Table 3. Saaty's random index (RI) values.

Order of Matrix	2	3	4	5	6	7	8	9	10
Saaty's RI	0	0.58	0.9	1.12	1.24	1.32	1	1.45	1.49

3.3. Decision-Making Formulation Through TOPSIS

TOPSIS stand for Technique of Order Preference Similarity to the Ideal Solution and was presented in [92]. Due to its simplicity, it is considered one of the classical MCDA methods and has been a popular choice among researchers [93].

It is based on determining the positive ideal solution and the negative ideal solution and comparing the Euclidean distance to each alternative [48,93].Ref [49] state that the best alternative should have the shortest Euclidean distance from the positive ideal, while the longest distance will denote the negative ideal.

According to [94], TOPSIS consists of the following six steps:

1. Construction of the normalized decision matrix
2. Transformation of the normalized decision matrix to a weighted normalised decision matrix
3. Determination of the positive ideal solution and the negative ideal solution for each attribute
4. Calculation of the separation measures between each alternative using an n-dimensional Euclidean distance
5. Computing the relative closeness to the ideal solution
6. Ranking of the preference order.

3.3.1. Vector Normalization of Decision Matrix

Firstly, the performance values X_{ij} of the MCDA matrix of Figure 2 has to be normalised using vector normalisation [81]. If r_{ij} is the weighted-vector normalised value of X_{ij}, then this can be expressed by Equation (6).

$$r_{\mathrm{ij}} = \mathrm{X}_{\mathrm{ij}} = \left(\frac{x_{\mathrm{ij}}}{\sqrt{\sum_{j=1}^{n} x_{ij}^2}} \right) \textit{where } i = 1, 2, \ldots m;\ j = 1, 2 \ldots n \tag{6}$$

where x_{ij} is considered as the 'performance value' of the j-th criteria of the i-th alternative of the $m \times n$ decision matrix.

3.3.2. Weighted Normalisation of Decision Matrix

Each of the normalised performance values are then multiplied by criteria weights derived using the AHP.

$$\mathrm{V}_{\mathrm{ij}} = r_{\mathrm{ij}} \times \mathrm{w}_j \ \textit{ where } i = 1, 2, \ldots m;\ j = 1, 2 \ldots n \tag{7}$$

V_{ij} would be the weighted-vector normalised performance value, whereas w_j would be the criteria weights.

3.3.3. Ideal Positive and Ideal Negative Solutions

The positive ideal is denoted by A^+, whilst the negative ideal is denoted by A^-. Beneficial criteria are where the highest performance value is preferred, while non-beneficial criteria are where the least performance value is preferred. A^+ indicates the most preferred alternative, the ideal solution. Alternatively, A^- denotes the least preferred alternative or the negative ideal solution [93].

$$A^+ = \{(maxV_{ij}|j\epsilon J), (minV_{ij}|j\epsilon I)|i = 1,2\ldots.m\} = \left\{V_1^+, V_2^+, \ldots V_j^+ \ldots.V_n^+\right\} \quad (8)$$

$$A^- = \{(minV_{ij}|j\epsilon J), (maxV_{ij}|j\epsilon I')|i = 1,2\ldots.m\} = \left\{V_1^-, V_2^-, \ldots V_j^- \ldots.V_n^+\right\} \quad (9)$$

where $I = \{j = 1,2,\ldots\ldots,n|$j associated with beneficial criteria$\}$ where $I' = \{j = 1,2,\ldots\ldots,n|$j associated with non-beneficial criteria$\}$

3.3.4. Calculation of the Separation Measures

The positive Euclidean distance, S_i^+, between alternative A_j and the ideal solution A^+ is calculated as follows:

$$S_i^+ = \sqrt{\sum_{j=1}^{n}\left(V_{ij} - V_j^+\right)^2} \quad (10)$$

where V_j^+ is the j-th criteria's performance of the ideal solution A^+. Similarly, the negative Euclidean distance, S_i^-, is calculated using Equation (11).

$$S_i^- = \sqrt{\sum_{j=1}^{n}\left(V_{ij} - V_j^-\right)^2} \quad (11)$$

where V_j^- is the j-th criteria's performance of the negative ideal solution A^-.

3.3.5. Relative Closeness and Preference Order

Subsequently, the relative closeness degree of alternative A_j with respect to the ideal solution A^+ is calculated by Equation (12):

$$P_i = \frac{S_i^-}{S_i^- + S_i^+} \quad (12)$$

where P_i denotes the closeness degree. Finally, the preference order or the optimal alternative is determined by identifying the maximum closeness degree and the shortest Euclidean distance to the ideal solution and the furthest distance from the negative ideal solution. Accordingly, the alternative having the maximum P_i value would represent the best alternative [82].

4. AHP and TOPSIS Analysis

The data collection phase involved four segments. The first phase involved the identification of alternative fuel options capable of meeting the IMO's 2050 emission targets. Upon identifying appropriate alternatives, the evaluation criteria and performance values were determined to evaluate the identified alternatives. Subsequently, a survey was carried out to compile data for the calculation of criteria weights. An academic literature search for the relevant data collection phases was done, while the technical literature was compiled through technical reports published by the Lloyds Registry, DNV-GL and ABS classification societies. Moreover, data were acquired from research carried out by UMAS, Frontier Economics and E4Tech on behalf of the Department for Transport, United Kingdom.

4.1. Selection of Alternatives

A systematic literature review was carried out on academic journals and industrial technical reports pertaining to marine alternative fuel options for deep-sea applications. Subsequently, fuel alternatives hydrogen, ammonia and methanol were identified as the fuel options capable of meeting the IMO's 2050 emission targets. The selection of alternatives was obtained through secondary data sources as many research studies had identified potential alternatives able to attain the IMO's 2050 emission ambitions.

4.2. Selection of Evaluation Criteria

The selection of evaluation criteria for the analysis of alternatives was performed through a literature review. Much research [21,26,48] has identified the most suitable evaluation criteria for alternative marine fuels and sustainable energy sources. Studies [43,78,95] have employed similar evaluation criteria to analyse different disciplines of sustainable energy sources with MCDA methods. Hence, it was prudent to utilize secondary data derived from these sources.

4.3. Pairwise Comparison for the Assessment of Criteria Weights

The collection of primary data through an online survey was performed to generate criteria and sub-criteria weights through AHP. The use of primary data was essential as the criteria weights for the chosen group of evaluation criteria were not available as secondary data.

A web-based online survey was created through Google© Forms and was distributed via email and LinkedIn©. The aim of the survey was to compile pairwise comparison data to develop criteria weights through AHP. Survey responses were collected for a period of 4 weeks. The anonymity of the survey participants was maintained and strictly adhered to during the data collection and analysis stages.

The survey contained seven sections. The first section of the survey provided an overview of the research and information to the participants and participant consent. Sections 2–6 consisted of 27 questions containing a pairwise comparison of assessment criteria. Each section was dedicated to main/sub-criteria, and participants were provided with guidance on Saaty's Fundamental Scale for Pairwise Comparison [86].

4.4. Survey Demographics

The online survey link was distributed to 84 prospective candidates chosen from various disciplines of the maritime industry and the alternative energy sector. They represented various global geological locations consisting of Asia, Europe, Australia, the United States and Africa. A total of 57 positive responses were received by the termination of the survey, corresponding to a 67.5% response rate. The number of 57 respondents can be considered a sufficient sample size given the time for which the survey was open and considering that most of these participants are currently working onboard ships handling and maintaining the engines and propulsion systems that may potentially be retrofitted to run on these alternative fuels. Similarly, given the expertise required to run these systems, as well as the need to have knowledge and experience with these alternative fuels, the available sample pool is limited.

The survey participants represented a vast range of professional roles, academic achievements and professional experiences. The demographics are listed below.

- Professional roles of participants:
    - Academia—8.8%
    - Marine Surveyor—15.9%
    - Technical Superintendent—7%
    - Marine Engineers—71.9%
    - Other technological roles—15.8%
- Education and Qualifications:
    - Diploma—17%
    - Bachelor's Degree—17%

- ◦ Master's Degree—18%
- ◦ PhD—6%
- ◦ STCW (International Convention on Standards of Training, Certification and Watchkeeping for Seafarers) (Professional Qualification)—42%
- Professional Experience:
  - ◦ 0 to 5 years—12.3%
  - ◦ 5 to 10 years—15.8%
  - ◦ 10 to 15 years—10.5%
  - ◦ Over 15 years—61.4%

Experts were selected based on their roles within shipping and expertise in the operation of marine engines on oceangoing vessels as well as experience with either one or more of the outlined alternative fuels. It was noted that many of the survey partakers, representing 42%, held STCW professional qualifications with a Chief Engineer's Certificate of Competency. Equal percentages of participants with diplomas, bachelor's, and master's degrees participated in the survey. Over 61% of the participant demography had extensive professional experience of over 15 years. The remaining professional experience segments represented a relatively equal proportion of responders to the survey.

4.5. Analytical Hierarchy Process for Calculation of Criteria Weights

The research hierarchy was constructed as depicted in Figure 4 by placing the goal on the top level, followed by the decision criteria and sub-criteria at the intermediate levels and the alternative at the lowest level.

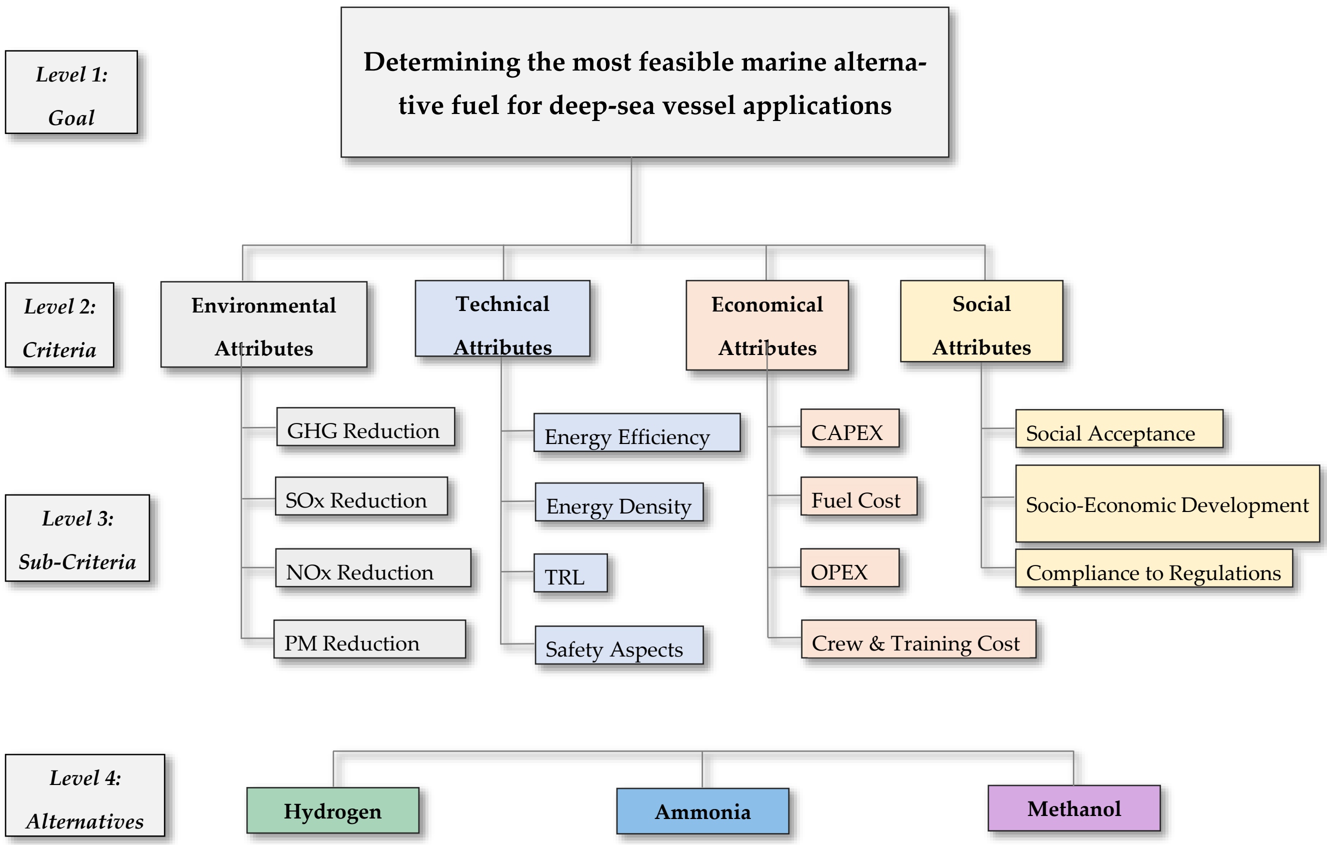

Figure 4. Hierarchical structure of research.

The main criteria and sub-criteria were determined based on existing literature studies (academic, industrial and regulatory). There are additional factors that can be considered such as the economic ranking as well as the availability of these alternative fuels. An economic assessment would be highly comprehensive and is thus not part of this analysis. This analysis serves to compare the suitability of hydrogen, ammonia and methanol in terms of their environmental, technical, social and economic attributes. Further work regarding a more comprehensive economic assessment has been completed [15] and presents an analysis of achieving a transition to near-zero-emissions shipping powered by alternative fuels under uncertainty. In terms of the availability of the fuels, there are several processes that produce these fuels in various volumes; however, for these to be completely viable as alternative fuels they should be produced through "green" processes, such as green water electrolysis for hydrogen. As it stands, the volumes of these fuels created from green sources is not currently sufficient. Furthermore, this analysis assesses the suitability of the alternative fuels for the IMO's 2050 targets. In the time remaining to 2050, the technologies that produce these alternative fuels through green technology will no doubt advance. This can be considered, in this analysis, as a limitation but also as a strong area for future research [43,62,64].

4.5.1. Pairwise Comparison Matrix of Criteria

The relative importance of pairwise comparison data obtained through the online survey was subsequently condensed to a single pairwise comparison matrix by calculating the geometric mean of the consistent individual response. Tables 4 and 5 demonstrate the pairwise comparison for the main criteria and the technical sub-criteria respectively.

Table 4. Pairwise comparison of main criteria.

Comparison Criteria	W	X	Y	Z
Technical (W)	1	0.654	1.562	2.611
Environmental (X)	1.528	1	2.582	3.544
Economic (Y)	0.640	0.387	1	1.607
Social (Z)	0.383	0.282	0.622	1

Table 5. Pairwise comparison of technical sub-criteria.

Comparison Criteria	C1	C2	C3	C4
C1	1	0.6542	1.5622	2.6105
C2	1.5285	1	2.5816	3.5436
C3	0.6401	0.3874	1	1.6072
C4	0.3831	0.2822	0.6222	1

4.5.2. Calculation of Criteria Weights and Consistency Analysis

The results of the AHP pairwise comparison are in each of the tables below and are colour coded for convenience of identification. The colour code red indicates a higher value, followed by orange, yellow and green in descending order of value. Table 6 represents the calculation of main criteria weights and the constancy analysis of the AHP pairwise comparison. The consistency index indicated 0.0051, while the consistency ratio was calculated to be 0.0057. As the calculated CR = 0.0057 < 0.1, the responses can be deemed consistent according to [83] consistency analysis. The results of the main criteria weights indicate that experts concluded that the environmental criterion is of the most importance, while the social attributes were of least significance.

Table 6. Main criteria weights and consistency analysis.

Comparison Criteria	W	X	Y	Z	Weights
Technical (W)	0.282	0.282	0.271	0.298	**0.283**
Environmental (X)	0.430	0.430	0.448	0.404	**0.428**
Economic (Y)	0.180	0.167	0.173	0.183	**0.176**
Social (Z)	0.108	0.121	0.108	0.114	**0.113**
$\lambda_{MAX} = 4.0029$ $CI = 0.0051$ $CR = 0.0057 < 0.1$					

The results of technical sub-criteria weights are shown in Table 7. The consistency analysis of the technical sub-criteria pairwise comparison indicates that the responses for the pairwise comparison for this section are consistent. The CI value was found to be 0.0051, corresponding to CR = 0.0057 < 0.1. The findings of environmental sub-criteria local weights are presented in Table 8. Consistency analysis performed on the survey response for this section was found to be consistent as the consistency index had a value of 0.0017, while CR = 0.0019 < 0.1. Table 9 depicts the AHP pairwise comparison analysis findings for the economic sub-criteria local weights calculation. Saaty's consistency analysis was applied to the survey participants' responses. The collective responses were deemed consistent as CI = 0.0050 followed by a consistency ratio, CR = 0.0055 < 0.1.

Table 7. Technical sub-criteria weights and consistency analysis. Source: Author.

Comparison Criteria	C1	C2	C3	C4	Weights
C1	0.211	0.238	0.253	0.187	**0.222**
C2	0.119	0.134	0.132	0.142	**0.132**
C3	0.185	0.225	0.222	0.242	**0.218**
C4	0.484	0.404	0.393	0.429	**0.428**
$\lambda_{MAX} = 4.0054$ $CI = 0.0051$ $CR = 0.0057 < 0.1$					

Table 8. Environmental sub-criteria weights and consistency analysis.

Comparison Criteria	C5	C6	C7	C8	Weights
C5	0.315	0.324	0.316	0.303	**0.314**
C6	0.242	0.249	0.268	0.236	**0.249**
C7	0.244	0.227	0.244	0.271	**0.247**
C8	0.198	0.200	0.172	0.190	**0.190**
$\lambda_{MAX} = 4.0052$ $CI = 0.0017$ $CR = 0.0019 < 0.1$					

Table 9. Economic sub-criteria weights and consistency analysis.

Comparison Criteria	C9	C10	C11	C12	Weights
C9	0.226	0.210	0.224	0.258	**0.229**
C10	0.328	0.305	0.279	0.321	**0.309**
C11	0.296	0.321	0.294	0.248	**0.290**
C12	0.150	0.164	0.203	0.172	**0.172**
$\lambda_{MAX} = 4.015$ $CI = 0.0050$ $CR = 0.0055 < 0.1$					

Finally, Table 10 denotes the pairwise comparison of the social sub-criteria results. Evaluation of the geometric means of the participants' responses revealed that they were consistent as the CR = 0.0510, corresponding to a CR = 0.0880 < 0.1.

Table 10. Social sub-criteria weights and consistency analysis.

Comparison Criteria	C13	C14	C15	Weights
C13	0.365	0.271	0.491	**0.376**
C14	0.416	0.308	0.215	**0.313**
C15	0.219	0.421	0.294	**0.311**
$\lambda_{MAX} = 3.1020$ $CI = 0.0510$ $CR = 0.0880 < 0.1$				

Table 11 presents a collective summary of the assessment criteria weights calculated with AHP by utilizing primary data from expert survey responses. The global weights were calculated based on the AHP hierarchy structure represented in Figure 4. The highest value of global weights is represented by the environmental sub-criteria, while the lower range of global criteria weights is recorded by the social sub-criteria.

Table 11. Local weights of assessment criteria.

Main Criteria			**Sub-Criteria**			
Assessment Criteria	**Notation**	**Weights**	**Assessment Criteria**	**Notation**	**Local Weight**	**Global Weight**
Technical Criteria	W	0.283	Energy Efficiency	C1	0.222	0.063
			Energy Density	C2	0.132	0.037
			TRL	C3	0.218	0.062
			Safety	C4	0.428	0.121
Environmental Criteria	X	0.428	GHG Reduction	C5	0.314	0.134
			SOX Reduction	C6	0.249	0.108
			NOX Reduction	C7	0.248	0.106
			PM Reduction	C8	0.190	0.081
Economic Criteria	Y	0.176	CAPEX	C9	0.229	0.040
			Fuel Cost	C10	0.308	0.054
			OPEX	C11	0.291	0.051
			Crew and Training Cost	C12	0.172	0.030
Social Criteria	Z	0.113	Social Acceptance	C13	0.376	0.042
			Socio-Econ Development	C14	0.313	0.036
			Compliance to Regulation	C15	0.311	0.035

Consistency analysis was performed on each survey participant's responses by calculating the consistency index. Responses of participants 2, 6, 7, 11, 17, 38, 39, 46 and 56 were disregarded as all their responses presented a CR > 0.1, indicating a high level of inconsistency. A total of 9 out of 57 responses were discarded due to inconsistency, corresponding to 15.7% of the entire survey.

4.6. TOPSIS Analysis

The TOPSIS analysis was performed individually on the technical, environmental, economic and social sub-criteria, and to overall attributes. While carrying out TOPSIS for individual sub-criteria, local weights were utilized while global weights were applied for the TOPSIS calculation on overall attributes. Similarly, the performance values for each alternative were derived from secondary data. These data and their sources are listed in Table A1 in the Appendix A.

TOPSIS Decision Matrix

The performance values of each alternative corresponding to the respective assessment criteria were obtained through a literature review as secondary data. These data sources ranged from academic literature to technical publications. The decision to utilize secondary data was primarily due to the higher accuracy of the existing data available. Table 12 shows the scale and the linguistic term. The rating for each criterion using this scale was determined through assessment of secondary data pertaining to these criteria and combining the results to produce a ranking list per alternative fuel. This data has been utilized for various studies, and their validity has been demonstrated. The scaling for C4, C12, C13, C14 and C15 had been determined as an interval scale between 1 and 5, based on the secondary data in the sources of information listed in Table 13. Table 13 presents the TOPSIS decision matrix containing local and global criteria weights and performance values of individual alternatives corresponding to their respective criteria.

Table 12. Conversion scaling for criteria scaling for C4, C12, C13, C14 and C15.

Performance Score	**1**	**2**	**3**	**4**	**5**
Linguistic Term	Very Low	Low	Moderate	High	Very High

The local weights have been transformed into global weights in Table 14. Table 15 depicts the weighted normalized decision matrix utilizing global weights. Subsequently, the positive ideal and negative ideal were identified. It should be noted that criteria C1, C2, C3, C4, C6, C7, C8, C13, C14 and C15 were considered beneficial criteria, while C5, C9, C10, C11 and C12 were deemed non-beneficial or cost criteria. The notation A^+ denotes the ideal positive, and A^- represent the ideal negative.

Calculation of positive and negative Euclidean distances followed by computation of relative closeness to the ideal solution resulting in the aggregation of preference order was calculated using Equation (12) and is shown in Table 16.

4.7. Sensitivity Analysis

A sensitivity analysis was conducted on the AHP analysis to determine how changes in input judgments affect the criteria weights, alternative performance and the final decision, revealing the model's robustness and identifying critical factors. The recalculated weights from the AHP sensitivity analysis were fed into the TOPSIS analysis to determine the magnitude of change on the final performance scores for hydrogen, ammonia and methanol. Initially the geometric mean of the pairwise comparison survey results (Figure A1 in Appendix A) were altered from −15% to +15% in increments of 5%.

4.7.1. AHP Sensitivity Analysis

Figure 5 shows the change in magnitude of the weights of the main criteria in the AHP analysis when the input data from the participant survey is altered. The order of the relative weights does not alter despite a moderate positive change for the technical criterion and a moderate negative change for economic and social criteria. This demonstrates robustness in the input data and analysis as the relative importance of the main criteria weights remain unchanged. However, should the sensitivity analysis extend to a variation of −20% in input data, then a change of ranking may be seen between technical and economic criteria.

The sensitivity analysis was also applied to the sub-criteria. Figures 6–9 show the magnitude of change within each of the sub-criteria. İt can be seen that the ranking order of each of the relative weights does not vary greatly. For technical criteria (Figure 6), the energy efficiency and TRL swap rankings between the second and third most important criteria. The ranking changes mainly show a slightly greater sensitivity to change for energy efficiency, from negative to positive. The weight of TRL remains largely unchanged.

Table 13. TOPSIS decision matrix with performance values and criteria weights.

Criteria		Technical Attributes				Environmental Attributes				Economic Attributes				Social Attributes		
		C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**	**C15**
Local Weights		0.283				0.428				0.176				0.113		
		0.222	0.132	0.218	0.428	0.314	0.249	0.247	0.19	0.229	0.308	0.291	0.172	0.376	0.313	0.311
Global Weights		0.063	0.037	0.062	0.121	0.134	0.108	0.106	0.081	0.040	0.054	0.051	0.030	0.042	0.036	0.035
Alternatives	Hydrogen	57	9.2	4	5	0	100	100	100	1.5	315	0.06	5	2	5	5
	Ammonia	381	12.7	6	3	102	100	96	100	0.94	260	0.047	3	4	3	3
	Methanol	381	15.8	9	1	533	92	45	56	0.16	105	0.0064	2	4	2	3
$\sqrt{\sum_{j=1}^{n} x_{ij}^2}$		542.82	22.26	11.53	5.92	543.67	168.71	145.74	152.11	1.777	421.72	0.0765	6.16	6	6.16	6.56

Table 14. Vector normalized decision matrix.

Criteria		Technical Attributes				Environmental Attributes				Economic Attributes				Social Attributes		
		C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**	**C15**
Local Weights		0.283				0.428				0.176				0.113		
		0.222	0.132	0.218	0.428	0.314	0.249	0.247	0.190	0.229	0.308	0.291	0.172	0.376	0.313	0.311
Global Weights		0.063	0.037	0.062	0.121	0.134	0.108	0.106	0.081	0.040	0.054	0.051	0.030	0.042	0.036	0.035
Alternatives	Hydrogen	0.105	0.413	0.347	0.845	0.000	0.593	0.686	0.657	0.844	0.747	0.784	0.811	0.333	0.811	0.762
	Ammonia	0.703	0.570	0.520	0.507	0.188	0.593	0.659	0.657	0.529	0.617	0.614	0.487	0.667	0.487	0.457
	Methanol	0.703	0.710	0.780	0.169	0.982	0.545	0.309	0.368	0.090	0.249	0.084	0.324	0.667	0.324	0.457

Table 15. Weighted normalized decision matrix with positive and negative ideals.

Criteria		Technical Attributes				Environmental Attributes				Economic Attributes				Social Attributes		
		C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**	**C15**
Alternatives	**Hydrogen**	**0.007**	**0.015**	**0.021**	**0.102**	**0.000**	0.063	**0.072**	0.053	**0.034**	**0.041**	**0.040**	**0.025**	**0.014**	**0.029**	**0.027**
	Ammonia	0.044	0.021	0.032	0.061	0.025	**0.063**	0.070	**0.053**	0.021	0.033	0.031	0.015	**0.028**	0.017	**0.016**
	Methanol	**0.044**	**0.027**	**0.048**	**0.020**	**0.132**	**0.058**	**0.033**	**0.030**	**0.004**	**0.014**	**0.004**	**0.010**	0.028	**0.011**	0.016
A+		0.007	0.027	0.048	0.020	0.000	0.063	0.072	0.053	0.004	0.014	0.004	0.010	0.028	0.029	0.027
A−		0.044	0.015	0.021	0.102	0.132	0.058	0.033	0.030	0.034	0.041	0.040	0.025	0.014	0.011	0.016

Blue denotes the Ideal Positive solution. Red Denotes the Ideal Negative solution.

Table 16. Euclidean distance from ideal and performance score—Overall.

		S_j^+	S_j^-	P_i	**Rank**
Alternatives	Hydrogen	0.1043	0.1465	0.5840	**2**
	Ammonia	0.0757	0.1257	0.6241	**1**
	Methanol	0.1465	0.1043	0.4160	**3**

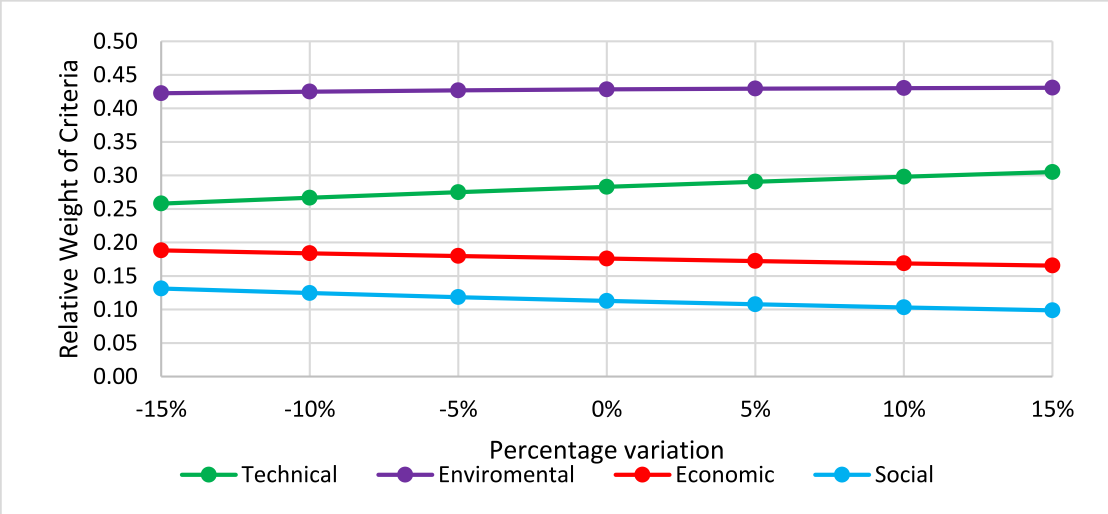

Figure 5. Sensitivity analysis of main criteria in the AHP assessment.

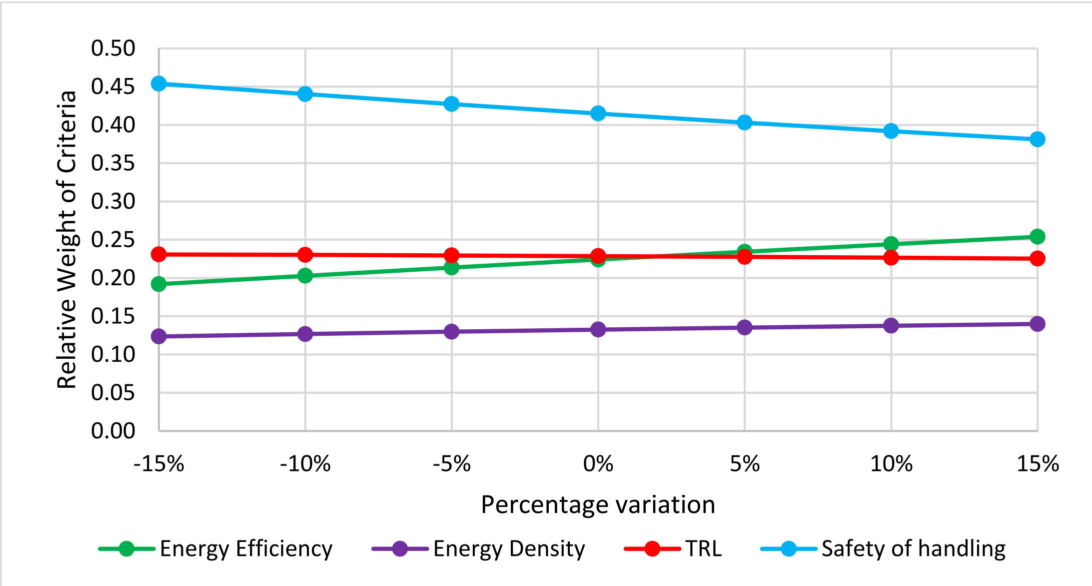

Figure 6. Sensitivity analysis of technical criteria.

Figure 7 shows a more drastic change in the values of the relative weights of the environmental sub-criteria. However, as with the technical criteria, the ranking order only changes with the second- and third-ranked criteria. SOx reduction and NOx reduction show a change in their ranking from positive to negative, mainly for NOx reduction. The relative weight for SOx reduction is minimally altered. This shows a level of consistency in the responses by participants in terms of what reduction in emissions is most important.

Figure 8 shows the change in relative wights of the economic criteria. There is a small change in the relative weights with a negative variation of the input data—so much so that at a variation of −15% operational expenditure becomes the most important criteria, by a very small magnitude. Similarly, training costs and capital expenditure demonstrate a smaller interval between weights as the variation increases in the negative direction. The greatest change occurs with a positive variation with fuel cost increasing in importance and operational expenditure reducing. Similarly, training cost importance reduces greatly with the positive change, but capital expenditure increases in importance. This increase also most allows for the ranking order to change with the reduction in operational expenditure and increase in capital expenditure. These changes demonstrate that the weights of the economic sub-criteria are susceptible to variation, which indicates a level of uncertainty among the participant responses for economic criteria. This is not unusual as economic assessment tends to consider objective quantitative data; however, the pairwise is based on the opinions of experts. This subjectivity regarding economic questions could be the cause of the greater variations in the sensitivity analysis.

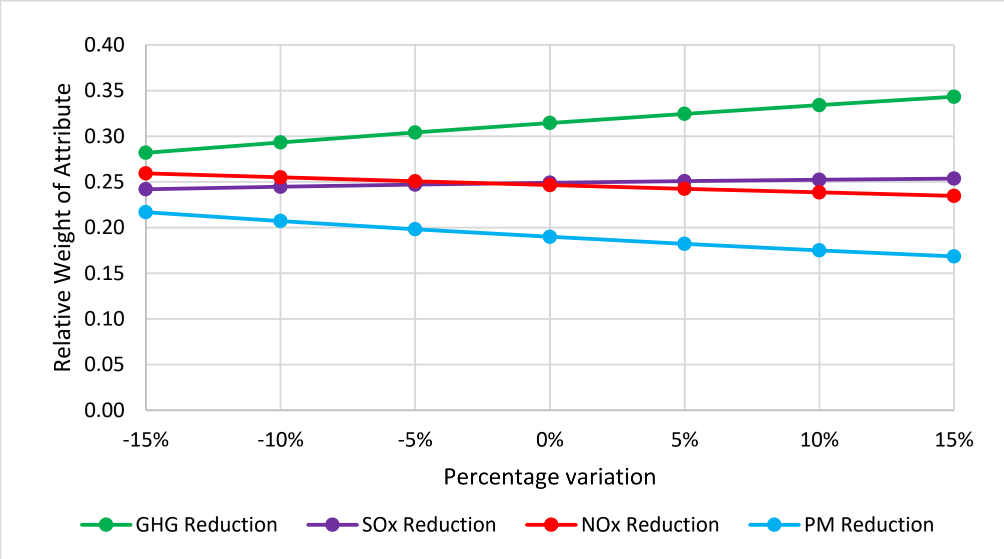

Figure 7. Sensitivity analysis of environmental criteria.

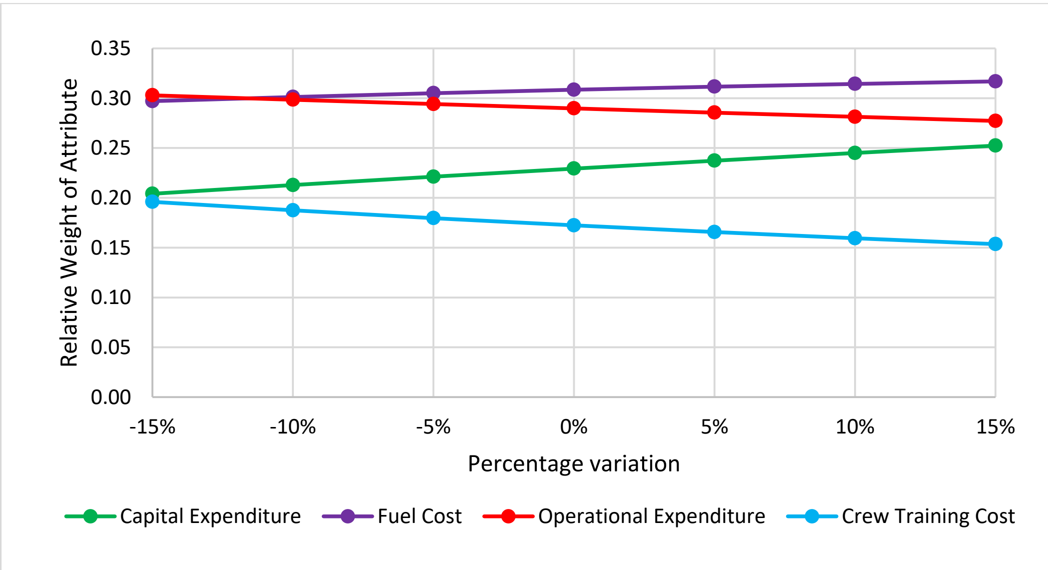

Figure 8. Sensitivity analysis of economic criteria.

Figure 9 shows the variation of the social sub-criteria. Throughout the variation in input data the relative weights are altered enough to change the ranking order multiple times. The main reason for this is that socio-economic development shows very little change; however, compliance to regulations and social acceptance vary greatly from positive to negative and negative to positive respectively. That said, the actual values change moderately, but relative to each other the change appears drastic. This could be explained by a level of uncertainty from participant to participant on the social aspects of the application of these alternative fuels.

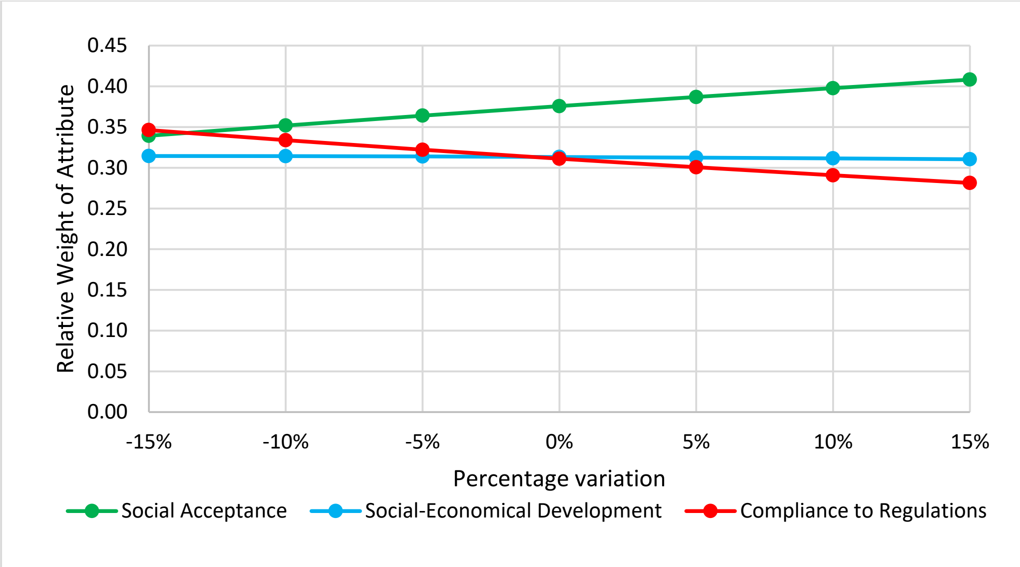

Figure 9. Sensitivity analysis of social criteria.

4.7.2. Consistency Ratio Sensitivity Analysis

The consistency ratios were also assessed as part of the sensitivity analysis. Figure 10 demonstrates the variations in consistency ratios along with the 0.1 threshold value. The consistency of all but one of the pairwise comparisons is excellent. Social sub-criteria show a vast change in the magnitude of the consistency ratios. This again potentially shows uncertainty across the participant responses for social acceptance, regulatory compliance and socio-economic development. This makes sense as the importance of specific social criteria for alternative fuel application will vary depending on the role, location and experience of the expert. Similarly, social criteria are difficult to assess without some objective data, and the exposure of this data to different participants will influence their subjective opinions. Part of our future work would be to review the social sub-criteria and potentially conduct further surveys to gather more responses from a more diverse sample pool. Nevertheless, the sensitivity analysis shows a good level of consistency in the analysis across the applied percentage variations.

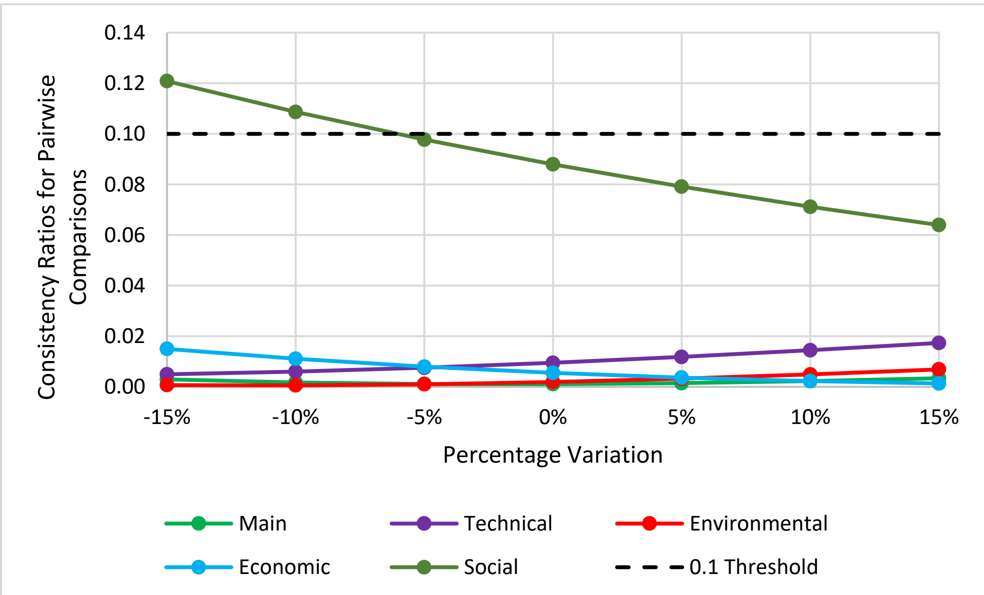

Figure 10. Sensitivity analysis of the consistency ratios.

4.7.3. TOPSIS Sensitivity

The updated relative weights from the AHP sensitivity analysis were applied to the TOPSIS assessment. The data for the TOPSIS performance values in Table 12 are not subject to variation from a sensitivity analysis as these are objective data that can be considered to remain constant in this analysis. Figure 11 shows the results of the TOPSIS analysis based on the variations in the calculated relative weights, from −5% to +15%. Even with the variation in relative weights of all the criteria and sub-criteria, the ranking order of ammonia, hydrogen and methanol does not change. Methanol is still very much the least preferable alternative fuel to tackle the IMO's 2050 goals, with ammonia still ranking first. However, the graph in Figure 11 does show that with a positive variation, the interval between ammonia and hydrogen does reduce. However, it appears that a greater positive variation would be required for hydrogen to overtake ammonia as the most suitable alternative fuel. This further demonstrates the robustness of the analysis as the results and ranking order are not affected by the ±15% range of variations in input data.

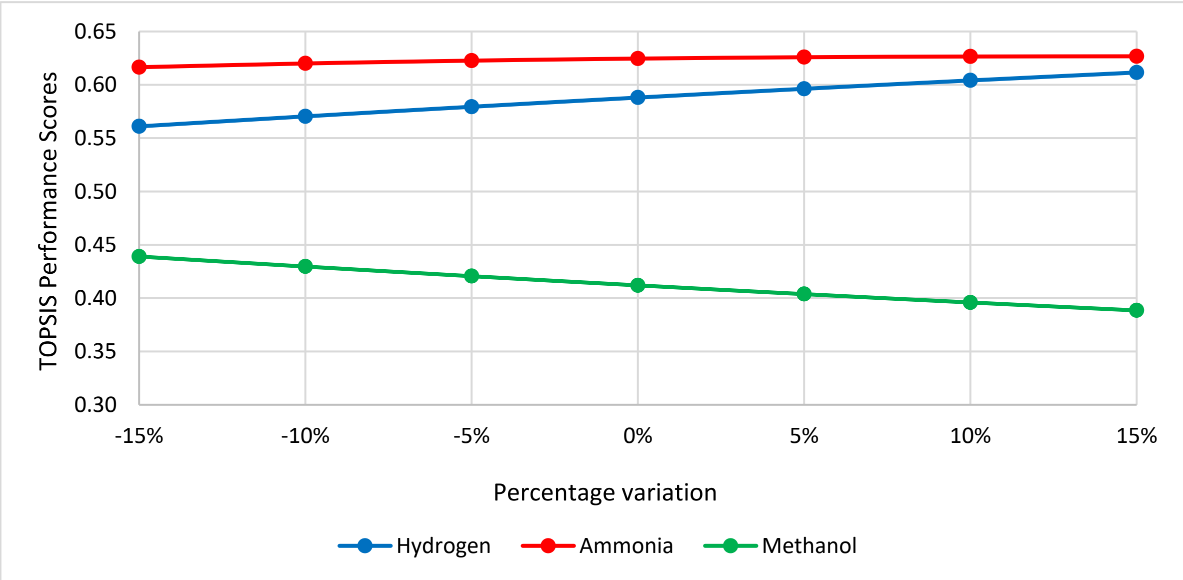

Figure 11. Sensitivity analysis of final TOPSIS performance scores.

5. Discussion

Our detailed literature search identified that hydrogen, ammonia and methanol are potential alternative fuels for deep-sea vessels capable of meeting the IMO's long-term decarbonization ambitions (2050). Furthermore, these fuels could be effectively assessed by utilizing technical, environmental, economic and social attributes. The AHP analysis suggests that environmental attributes carry the highest weightage among the selected assessment criteria. The TOPSIS analysis concluded that ammonia could possibly be the most feasible alternative fuel option for deep-sea vessels in the future.

The secondary data extracted from the literature review suggest that hydrogen, ammonia and methanol were the most suited fuel options for future deep-sea vessel applications. They are all capable of meeting the IMO's 2050 GHG emission targets according to reports published by classification societies and other industrial research, as indicated in Section 2. The findings pertaining to the alternatives in this report—hydrogen, ammonia and methanol—as potential future fuel sources align with the findings in [20,32,45]. Technical, environmental, economic and social attributes relate to the core sustainability assessment criteria of any energy source. Moreover, they provide a broader perspective of all influences of a novel or age-old technology on mankind and the planet. Studies related to alternative marine fuels, such as [19,21,43,95], which were quoted in the literature review, employed technical, environmental, economic and social attributes for their analyses.

The consistency ratio for the AHP pairwise comparison presented a value of CR = 0.0057, suggesting that the data utilized to generate these weights were consistent and reliable. It is evident that environmental criteria have the highest weightage, corresponding to 42.8% of the total weight. This is then followed by technical attributes, with a weightage of one-third of the environmental attributes. Economic and social attributes account for 17.6% and 11.3% of weightage, respectively. Thus, the findings suggest that environmental attributes are the most important assessment criteria for any alternative marine fuel. The findings of this research deviate from the historical patterns, where economic attributes were the driving factors of fuels, as stated in the literature review of [74]. The transition from coal to heavy fuel oil in the past was mainly driven by economic factors. However, the findings of this research suggest that the industry prioritises the environment above other attributes, which could be viewed as a positive notion. It could be suggested that obstacles such as technical challenges and economically unfavourable fuel options might still be given priority as long as they positively influence the environment. Moreover, the findings of this research, where the considerable degree of prioritisation of environmental attributes over other criteria highlights and complements the IMO's past efforts and future ambitions in pollution abatement measures.

However, recent research performed by the authors of [21] indicates a slight deviation from the findings of this study. Ref. [21] reports an analysis of identical assessment criteria to this study, recruiting a diverse demography in Sweden for their survey. The results indicate that authorities prioritized environmental attributes over the other criteria 41% of the time, while ship owners, fuel manufacturers and engine makers considered environmental aspects as their lowest priority (7%) and economic attributes as their highest preference (47%). The findings of [21] pertaining to the preferences of authorities reinforce the findings of this research, indicating a near exact weight preference for environmental attributes. A study of the selection of sustainable energy sources for shipping [95] carried out an analysis combining Dempster–Shafer theory and trapezoidal fuzzy AHP employing identical assessment criteria. Results of the study indicated 0.4673, 0.2772, 0.1601, and 0.0954 criteria weights for technical, environmental, economic and social attributes, with a consistency ratio of CR = 0.0115. The literature pertaining to the study did not provide information on the survey demography. Thus, the probable causes for the deviation of the findings cannot be clearly identified.

The radar graph represented in Figure 12 shows a comparison of the local weights of all the sub-criteria. By analysing the distribution of the local weights, it could be observed that the sub-criteria weight values related to GHG reduction, SO_x reduction and NO_x reduction are plotted towards the outer periphery of the radar graph, representing a higher weight. The individual sub-criteria pairwise analysis and consistency analysis indicated consistency ratios of 0.0051, 0.0017,0.0050 and 0.0880 for the technical, environmental, economic and social sub-criteria, respectively. Hence, the response for the sub-criteria pairwise comparison could be considered consistent, and the results were reasoned to be reliable. The highest sub-criteria weight correlates to GHG emissions, corresponding to 13.4% of the weightage. This value is followed by safety concerns bearing a percentage of 12.1% of the weight. The combined weights of safety sub-criteria and environmental sub-criteria (GHG, SOx, NOx and PM) amount to 55% of the total local weights of the sub-criteria. All the remaining attributes combined amount to 45% of the criteria weightage.

Upon further analysis of the sub-criteria local weights implies that the safety of the crew and prevention of pollution of the environment are the most important sub-criteria of a potential low-/zero-carbon fuel for the future of the industry. These findings once again align with the IMO's efforts to promote the safety of life at sea through the SOLAS convention and the prevention of environmental pollution governed by the MARPOL convention.

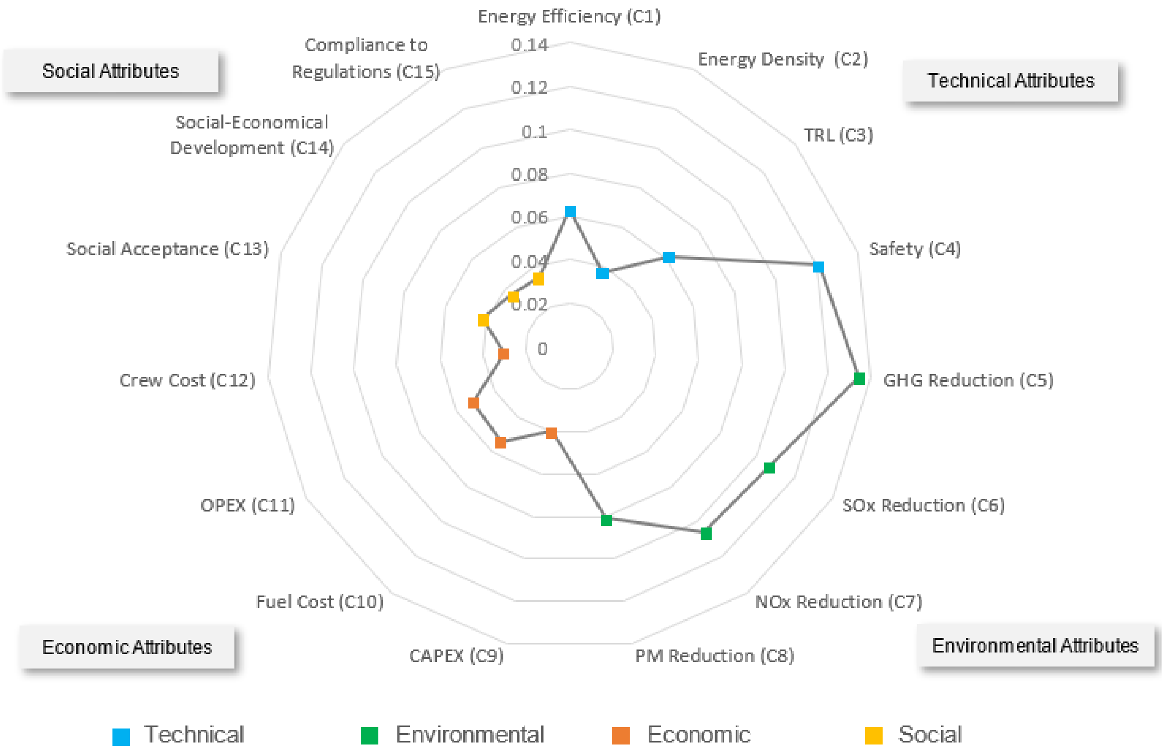

Figure 12. Global weight distribution of sub-criteria.

From a policy perspective, the results of this analysis suggest that the IMO and national regulators should prioritize ammonia and hydrogen in long-term decarbonization frameworks, particularly through targeted investments in fuel production, bunkering infrastructure, and safety regulations addressing toxicity, storage, and onboard handling. The strong performance of ammonia highlights its potential as a zero-carbon fuel at the point of use, warranting accelerated development of international standards and incentive mechanisms such as carbon pricing, fuel mandates, and green corridors. Hydrogen's close ranking underscores the need for continued policy support for scalability, renewable production pathways, and port infrastructure integration. Although methanol ranks third, its relatively lower score still reflects its role as a transitional fuel, benefiting from existing engine compatibility and supply chains; therefore, policies should encourage its short- to medium-term deployment while avoiding lock-in effects. Overall, the ranking supports a phased and differentiated policy approach aligned with the IMO's 2050 targets, balancing immediate feasibility with long-term zero-emission potential [10,17,36].

5.1. Assessment of Sub-Criteria

5.1.1. Technical Criteria

Safety aspects carried the highest weight among the technical sub-criteria, representing 42.3%. The weights assigned to energy efficiency and TRL stood nearly equal at 22.2% and 21.8%. The least importance was given to energy density, relating to 13.2%. In comparison to safety aspects, the local weights of energy efficiency and TRL stood at half, while energy density related to one-third. The findings suggest that a particular energy source with considerably higher energy density and requiring more storage space might be a feasible option, if it is safe to handle during bunkering, storage and operation. However, factors such as TRL and energy density will significantly impact the fuel choice. The findings of [95] suggest that TRL is a more significant factor than energy density, which partially confirms the findings of this study. However, the authors of [21] did not consider safety aspects and energy density as assessment attributes in their study.

5.1.2. Environmental Criteria

The findings related to environmental sub-criteria indicate that each of the sub-criteria carries almost the same weight. The weightage of 34% on GHG reductions could be the result of the recent increase in global awareness of the contribution of GHG emissions to climate change. Moreover, the nearly equal preference for each of the sub-criteria representing MARPOL Annex VI could suggest that the same degree of importance the industry has shown to SOx, NOx and PM could be expected towards GHG. This is again a favourable notion toward the IMO's GHG reduction ambitions. The findings pertaining to environmental attributes in this research are validated by the findings in [19], where GHG emissions were given the highest priority. On the contrary, the findings of [95] indicate that the reduction of NOx emissions was more prominent than GHG emissions. However, the validity of the results reported in [21] pertaining to environmental attributes is questionable as only NOx and GHG emissions were considered. Important attributes such as SOx and PM were omitted from that study.

5.1.3. Economic Criteria

Fuel cost and OPEX have been allocated a similar significance of 30%, while CAPEX gained a weightage of 22.9%. Crewing and training costs exhibited a lower weight relating to 17.2%. The findings imply that fuel cost and operational expenditures would be critical factors among economic criteria. However, the influence of CAPEX also strongly impacts economic attributes. Hence it could be assumed that the findings indicate that a fuel requiring a high CAPEX would be reasonably feasible if the operation cost and fuel cost are relatively low. Research carried out in [21] also concluded similar results for the weightage of economic sub-criteria. Similarly, research reported in [96] indicates that OPEX-related costs, particularly fuel and operational expenses, dominate the economic decision-making framework, outweighing both CAPEX and crewing and training costs. The study ranks OPEX as the most influential, or among the top two, economic sub-criteria across different scenarios and vessel types. Although CAPEX remains a significant factor, it consistently ranks below OPEX and fuel-related operational costs in both this study and [96], highlighting the critical importance of minimizing operating expenditures when evaluating the economic feasibility of alternative fuels and technologies. These findings closely match the results of the research in this paper.

5.1.4. Social Criteria

The findings of the pairwise comparison analysis for social criteria denote a 37.6% weight towards social acceptance, while nearly equal prominence was given to socio-economic development and compliance with regulations. Thus, based on the findings, it is evident that social acceptance plays a vital role in choosing alternative fuels. Moreover, it could be presumed that increasing awareness among the public on a certain fuel option will gain more acceptance.

5.2. Preference Order Ranking of Alternative Fuels—Overall

As shown in Table 15, the findings suggest that ammonia is the most feasible fuel option for deep-sea vessel applications capable of meeting the IMO's 2050 emission targets. Hydrogen was found to be the second preference, while the least preferred fuel option was found to be methanol. The closeness degree value for P_i for ammonia was found to be 0.6241, while the values for hydrogen and methanol were 0.5840 and 0.4160, respectively, according to the findings represented in Table 15. Although ammonia was the most preferred choice, the difference of preference value between ammonia and hydrogen is not a significantly high value. This could imply that improvements in electrolysis technology and novel methods to produce hydrogen economically and efficiently may lead to hydrogen being a potential contender to be a favourable fuel choice in the future.

Contradicting the findings of this study, research reported in [22] pertaining to an assessment of hydrogen and ammonia suggests that hydrogen was favoured above ammonia. As stated in the literature review, the authors of this study recognised the potential of ammonia as a solution to the drawbacks of hydrogen by using ammonia as a hydrogen storage and transportation medium. The literature review of this research identified sources that support the claim that ammonia is a potential hydrogen carrier. Similarly, the findings of [32] also agree with the findings of [22], claiming hydrogen is a favoured option over ammonia. These studies did not use a systematic analysis employing an MCDA method. Moreover, neither of these studies viewed the alternatives from a holistic perspective considering technical, environmental, economic or social attributes. They were merely based on technical characteristics or market trends. Hence, the reliability, accuracy and versatility of the findings of [22,32] are questionable. Furthermore, [62] assessed the roadmap for green ammonia and suggest that the successful implementation of green ammonia is dependent on key success factors including technology, infrastructure and energy investments, propulsion improvements, and maximisation of fuel availability. Some of which have been covered in our study, and the results of [62] reflect the findings here in terms of technology. However, their study covers further factors related to green ammonia implementation. Further analysis could be considered with these success factors for the other alternative fuels of hydrogen and methanol. Thus, as stated previously in this paper, few studies compare the suitability or success factors of all three of these prominent alternative fuels.

On the contrary, [24] concurs with the findings of this research. Most importantly, the findings identify that both hydrogen and ammonia offer the most promising pathways, which further validates the findings of this research concerning the closeness degree of ammonia and hydrogen found in close proximity. The systematic analysis conducted by the authors of [76] using AHP proposed hydrogen as a replacement for LNG in the future. Methanol was not seen as a viable option in [76], and the authors did not consider the potential of ammonia in their analysis. A similar discovery was made in [77], where hydrogen was prioritised above methanol by a fair margin. Ref. [76] reports a systematic analysis through fuzzy TOPSIS and considers a wide array of evaluation criteria, though the authors did not include ammonia in their analysis. Similarly, the authors of [19,21] both performed an AHP analysis employing technical, environmental, economic and social attributes on marine fuel options but omitted ammonia as a potential contender. The result of both these studies suggest that hydrogen is a superior option in relation to methanol.

6. Conclusions

The aim of this study was to assess the alternative fuel options available for deep-sea shipping applications, which could attain the IMO's 2050 GHG emission targets. In order to achieve this aim, the study evolved around answering the research question: "What would be the most feasible marine alternative fuel option for deep-sea vessel applications that could meet the IMO's 2050 emission targets?". A series of research objectives were established to accomplish the research aim and answer the research question.

The initial research objective was to outline the IMO's 2050 GHG emission targets and to appraise the recent developments in the alternative marine fuel sector. The second objective was to develop suitable assessment criteria to evaluate the identified alternative fuel options. These objectives were accomplished through the detailed literature review presented in Section 2. The third objective was directed toward determining weights for the assessment criteria. This was fulfilled by the implementation of an online survey and AHP computation. The fourth and final research objectives focused on acquiring performance values for each assessment criteria and evaluation of alternative fuel options through TOPSIS analysis. The data required for the performance values were extracted from secondary data through a literature search. Finally, the evaluation of the fuel options was performed employing TOPSIS.

The key findings suggest that ammonia would be the most feasible fuel option for the deep-sea segment to meet the IMO's future goals. The results also indicated that hydrogen could also be a favourable choice if its inherent safety concerns could be effectively mitigated. Further findings show that environmental and safety attributes are the most significant in assessing alternative energy sources. Technical attributes and economic attributes were ranked successively, while social attributes were given the least priority among the assessment criteria.

Recent studies on alternative marine fuels have considered the entire maritime sector as a whole while attempting to provide decarbonization solutions through alternative fuel options. However, when the feasibility of an effective energy source is evaluated, it is prudent to analyse the deep-sea, near-coastal and inland-water marine applications within its individual domain. This would enable mitigating the challenges of alternative energy sources through bespoke solutions for each maritime segment. The aim of this research was to cater to the lack of research related to deep-sea applications, which represent much of the global cargo volume and are responsible for 80% of the global GHG emissions from shipping.

The discovery of ammonia as the most feasible option for a deep-sea vessel can contribute numerous ways to the maritime industry's decarbonization efforts. Firstly, it can assure the shipowners and shipbuilders of the true potential of ammonia as a potential energy source. Engine manufacturers may consider prioritizing the development of ammonia-fuelled propulsion systems. The findings of this research may encourage further research on the applicability of ammonia in other shipping segments, aviation and other transport modes intended to operate on alternative fuels. It directs the focus of academia and the industry towards devising means to mitigate the toxicity of ammonia. Government bodies may consider awarding incentives for ammonia-related pilot projects and the development of ammonia bunkering infrastructure. The findings can be utilized to gain public acceptance of ammonia and encourage investments in ammonia projects.

As further developments in future research, it is suggested that the survey demography should encompass equal representation of maritime stakeholders. The expert survey should be directed toward shipowners, charter parties, engine manufacturers, fuel developers, naval architects, government authorities, and marine engineers. Moreover, safety aspects could be considered a main attribute and sub-criteria such as safety of bunkering, handling, and storage could be analysed separately as each fuel option poses benefits and drawbacks in each of these concerns.

6.1. Limitations

Although the pairwise comparison survey invitations were extended to representatives of all stakeholders of the maritime industry, a majority of 71.9% of partakers in the survey were marine engineers engaged in active sea service. The survey demography lacked the representation of parties directly involved in the economic interests of the industry. These categories include ship owners, ship charterers, fuel suppliers and engine makers. Moreover, the findings of this survey would have been more robust if more participants from academia and authorities had responded to the survey. However, it should also be noted that all participants possessed the required proficiencies and experience to make an informed response. It is strongly believed that, although an improvement in the survey demography as proposed would have further validated the study, it would have had an insignificant influence on the analysis and findings of the research outcome.

6.2. Applicability of the Research

The most significant discovery of this study is the emergence of ammonia as a feasible fuel for the future. None of the past limited systematic analyses of alternative marine fuels had considered ammonia as a viable option. The over-rated misconception of ammonia being highly toxic has hindered the pathway of ammonia as a future fuel. Although ammonia possesses a degree of toxicity, modern technology and novel safety procedures can contain and mitigate the adverse effects of ammonia.

The findings of this study can contribute to the maritime industry in numerous ways. Firstly, it can divert the industry's attention towards the true potential of ammonia and encourage further research on its drawbacks. Studies could be undertaken to devise methods and means to mitigate the toxicity of ammonia and procedures to improve safe handling on board. Secondly, the finding may encourage engine makers and fuel-cell manufacturers to further develop propulsion systems to operate efficiently on ammonia. The preference for ammonia would enable shipowners to diversify new builds to operate on ammonia. Governments and lawmakers may consider making legislative changes and providing economic incentives to pave the path for an ammonia-based economy. The IMO, classification societies and marine consultants may devise protocols to enhance the safe handling of ammonia. The findings can be used to attract regional and governmental stakeholders to further invest in developing bunkering infrastructure for ammonia. Maritime training institutions and STCW certification may consider including academic content on ammonia and related safety concerns. They may also develop specialized training programmes for ammonia-powered vessels. Naval architects and ship builders may benefit from the outcome of this research by improving ammonia vessel designs. Finally, short-sea voyage vessels, near-coastal ships and inland-water vessels could consider the possibility of considering ammonia as a viable fuel source.

Additionally, the weights of the assessment criteria obtained through the AHP analysis of this study can be used to analyse other applications of alternative energy. As safety and environmental compatibility were the key performance attributes discovered in this research, they can be used as data to assess any other alternative fuels for all disciples of maritime applications.

Author Contributions: Conceptualization, R.R. and S.L.; Methodology, R.R. and S.L.; Validation, E.B.-D.; Formal analysis, R.R.; Investigation, R.R. and E.B.-D.; Data curation, R.R.; Writing—original draft, S.L.; Writing—review & editing, R.R. and E.B.-D.; Supervision, S.L. and E.B.-D.; Project administration, S.L.; Funding acquisition, S.L. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The research process was conducted in accordance with Liverpool John Moores University's Code of Practice for Research. LJMU Research Ethics training was completed, and Ethical Approval was submitted to the Faculty Research Ethics Committee. Subsequently, the study was deemed 'Low-Risk', and the Faculty Research Ethics Committee approved the study under reference number PGT/20/615 and date of approval 6 June 2022.

Informed Consent Statement: Informed consent for participation was obtained from all subjects involved in the study.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Author Rushdie Rasheed was employed by the company Brooke's Bell. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The authors declare that this study received funding from UK National Clean Maritime Research Hub.

Appendix A TOPSIS Performance Values and Their Data Sources

Table A1. Performance values for TOPSIS.

Attributes				Alternatives			Performance Values Data Sources
Main Criteria	Sub-Criteria	Criteria Notation	Units	Hydrogen	Ammonia	Methanol	
Technical Attributes	Energy Efficiency	C1	g/kW-hr	57	381	381	[38,39,41,70]
	Energy Density	C2	MJ/L	9.2	12.7	15.8	
	TRL	C3	TRL Scale Rating	4	6	9	[20,29,38–41,46,70]
	Safety of Bunkering, Handling and Storage	C4	Rating Scale	5	3	1	
Environmental Attributes	GHG Emissions	C5	g/kW-hr	0	102	533	[9,20,29,70,97]
	SO_x Reduction Potential	C6	% Compared to HFO	100	100	92	
	NO_x Reduction Potential	C7	% Compared to HFO	100	96	45	[20,29,38,39,46,65,73]
	PM Reduction Potential	C8	% Compared to HFO	100	100	56	
Economic Attributes	CAPEX	C9	USD/Kg of Fuel	1.5	0.94	0.16	[38–41,70,73,98,99]
	Fuel Cost	C10	USD/MWh Shaft Output	315	260	105	
	OPEX	C11	USD/Kg of Fuel	0.0600	0.0470	0.0064	[17,69,70,97–99]
	Crew and Training Cost	C12	Rating Scale	5	3	2	
Economical Attributes	Social Acceptance	C13	Rating Scale	2	4	4	[17,69,70,97–99]
	Socio-Economic Development	C14	Rating Scale	5	3	2	
	Compliance with Regulations	C15	Rating Scale	5	3	3	[17,20,70,74,98,99]

AHP PAIRWISE MATRIX FOR THE CALCULATION OF CRITERIA WEIGHTS

Main Criteria n=4

	W	X	Y	Z
W	1.000	0.654	1.562	2.611
X	1.528	1.000	2.582	3.544
Y	0.640	0.387	1.000	1.607
Y	0.383	0.282	0.622	1.000
Σ	3.552	2.324	5.766	8.761

W Technical Attributes
X Enviromental Attributes
Y Economic Attributes
Z Social Attributes

Technical n=4

	C1	C2	C3	C4
C1	1.000	1.774	1.139	0.436
C2	0.564	1.000	0.597	0.332
C3	0.878	1.675	1.000	0.564
C4	2.294	3.011	1.774	1.000
Σ	4.736	7.460	4.510	2.332

C1 Energy Efficiency
C2 Energy Density
C3 TRL
C4 Safety of handling

Environmental n=4

	C5	C6	C7	C8
C5	1.000	1.301	1.291	1.595
C6	0.769	1.000	1.098	1.244
C7	0.775	0.911	1.000	1.424
C8	0.627	0.804	0.702	1.000
Σ	3.171	4.016	4.090	5.263

C5 GHG Reduction
C6 SOx Reduction
C7 NOx Reduction
C8 PM Reduction

Economical n=4

	C9	C10	C11	C12
C9	1.000	0.688	0.761	1.501
C10	1.454	1.000	0.952	1.866
C11	1.313	1.050	1.000	1.443
C12	0.666	0.536	0.693	1.000
Σ	4.433	3.274	3.407	5.810

C9 Capital Expenditure
C10 Fuel Cost
C11 Operational Expenditu
C12 Crew Training Cost

Social n=3

	C13	C14	C15
C13	1.000	0.878	1.671
C14	1.139	1.000	0.733
C15	0.599	1.365	1.000
Σ	2.737	3.243	3.403

C13 Social Acceptance
C14 Social-Economical Development
C15 Compliance to Regulations

NORMALIZED PAIRWISE MATRIX

	W	X	Y	Z	CW
W	0.282	0.282	0.271	0.298	0.283
X	0.430	0.430	0.448	0.404	0.428
Y	0.180	0.167	0.173	0.183	0.176
Y	0.108	0.121	0.108	0.114	0.113
Σ	1	1	1	1	1

	C1	C2	C3	C4	CW
C1	0.211	0.238	0.253	0.187	0.222
C2	0.119	0.134	0.132	0.142	0.132
C3	0.185	0.225	0.222	0.242	0.218
C4	0.484	0.404	0.393	0.429	0.428
Σ	1	1	1	1	1

	C5	C6	C7	C8	CW
C5	`	0.324	0.316	0.303	0.314
C6	0.242	0.249	0.268	0.236	0.249
C7	0.244	0.227	0.244	0.271	0.247
C8	0.198	0.200	0.172	0.190	0.190
Σ	0.685	1	1	1	0.99969

	C9	C10	C11	C12	CW
C9	0.226	0.210	0.224	0.258	0.229
C10	0.328	0.305	0.279	0.321	0.308
C11	0.296	0.321	0.294	0.248	0.290
C12	0.150	0.164	0.203	0.172	0.172
Σ	1	1	1	1	1

	C13	C14	C15	CW
C13	0.365	0.271	0.491	0.376
C14	0.416	0.308	0.215	0.313
C15	0.219	0.421	0.294	0.311
Σ	1	1	1	1

CONSISTANCY CHECK

	W	X	Y	Z	WSV	WSV/CW
W	0.283	0.280	0.275	0.295	1.133	4.002
X	0.433	0.428	0.454	0.400	1.715	4.005
Y	0.181	0.166	0.176	0.181	0.704	4.003
Y	0.108	0.121	0.109	0.113	0.452	4.002
					λ_{MAX}	4.0029
					CI	0.0010
					CR	0.0011

Is the response to the section consistant? YES

	C1	C2	C3	C4	WSV	WSV/CW
C1	0.222	0.234	0.249	0.186	0.891	4.013
C2	0.125	0.132	0.130	0.142	0.530	4.012
C3	0.195	0.221	0.218	0.241	0.875	4.009
C4	0.510	0.397	0.387	0.428	1.722	4.027
					λ_{MAX}	4.0154
					CI	0.0051
					CR	0.0057

Is the response to the section consistant? YES

	C5	C6	C7	C8	WSV	WSV/CW
C5	0.314	0.324	0.318	0.303	1.25923	4.00826
C6	0.241	0.249	0.271	0.236	0.9975	4.00506
C7	0.243	0.227	0.247	0.27	0.98735	4.00415
C8	0.197	0.2	0.173	0.19	0.76017	4.00327
					λ_{MAX}	4.0052
					CI	0.0017
					CR	0.0019

Is the response to the section consistant? YES

	C9	C10	C11	C12	WSV	WSV/CW
C9	0.229	0.212	0.221	0.259	0.921	4.01494
C10	0.334	0.308	0.276	0.322	1.23947	4.0178
C11	0.301	0.324	0.29	0.249	1.16374	4.01662
C12	0.153	0.165	0.201	0.172	0.69132	4.01051
					λ_{MAX}	4.0150
					CI	0.0050
					CR	0.0055

Is the response to the sectio YES

	C13	C14	C15	WSV	WSV/CW
C13	0.376	0.275	0.52	1.17058	3.11577
C14	0.428	0.313	0.228	0.96885	3.09353
C15	0.225	0.427	0.311	0.96346	3.09677
				λ_{MAX}	3.1020
				CI	0.0510
				CR	0.0880

Is the response to the section consistant? YES

Figure A1. Calculation of geometric mean values of survey responses and computing criteria weights using AHP. The yellow background in the top row of tables indicated the input data from survey results.

DECISION MATRIX

Criteria	W				X				Y				Z		
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Local Weight	0.283				0.428				0.176				0.113		
	0.222	0.132	0.218	0.428	0.314	0.249	0.247	0.190	0.229	0.308	0.290	0.172	0.376	0.313	0.311
Global Weight	**0.063**	**0.037**	**0.062**	**0.121**	**0.135**	**0.107**	**0.106**	**0.081**	**0.040**	**0.054**	**0.051**	**0.030**	**0.042**	**0.035**	**0.035**
Hydrogen	57	9.2	4	5	0	100	100	100	1.5	315	0.06	5	2	5	5
Ammonia	381	12.7	6	3	102	100	96	100	0.94	260	0.047	3	4	3	3
Methanol	381	15.8	9	1	533	92	45	56	0.16	105	0.006	2	4	2	3
$\sqrt{\sum_{j=1}^{n} x_{ij}^2}$	541.8	22.26	11.53	5.916	542.7	168.7	145.7	152.1	1.777	421.7	0.076	6.164	6	6.164	6.557

NORMALIZED DECISION MATRIX

Criteria	W				X				Y				Z		
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Local Weight	0.283				0.428				0.176				0.113		
	0.222	0.132	0.218	0.428	0.314	0.249	0.247	0.190	0.229	0.308	0.290	0.172	0.376	0.313	0.311
Global Weight	**0.063**	**0.037**	**0.062**	**0.121**	**0.135**	**0.107**	**0.106**	**0.081**	**0.040**	**0.054**	**0.051**	**0.030**	**0.042**	**0.035**	**0.035**
Hydrogen	0.105	0.413	0.347	0.845	0.000	0.593	0.686	0.657	0.844	0.747	0.784	0.811	0.333	0.811	0.762
Ammonia	0.703	0.570	0.520	0.507	0.188	0.593	0.659	0.657	0.529	0.617	0.614	0.487	0.667	0.487	0.457
Methanol	0.703	0.710	0.780	0.169	0.982	0.545	0.309	0.368	0.090	0.249	0.084	0.324	0.667	0.324	0.457

WEIGHTED, NORMALIZED DECISION MATRIX

Criteria		W				X				Y				Z		
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Hydrogen		0.007	0.015	0.021	0.102	0.000	0.063	0.072	0.053	0.034	0.041	0.040	0.025	0.014	0.029	0.027
Ammonia		0.044	0.021	0.032	0.061	0.025	0.063	0.070	0.053	0.021	0.033	0.031	0.015	0.028	0.017	0.016
Methanol		0.044	0.027	0.048	0.020	0.132	0.058	0.033	0.030	0.004	0.014	0.004	0.010	0.028	0.011	0.016
Ideal	A^+	0.007	0.027	0.048	0.020	0.000	0.063	0.072	0.053	0.004	0.014	0.004	0.010	0.028	0.029	0.027
	A^-	0.044	0.015	0.021	0.102	0.132	0.058	0.033	0.030	0.034	0.041	0.040	0.025	0.014	0.011	0.016

CALCULATION OF EUCLIDEAN DISTANCE FROM IDEAL & PERFORMANCE SCORE- OVERALL

Alternative	S_j^+	S_j^-	P_i	Ranking
Hydrogen	0.1043	0.1465	0.5840	2
Ammonia	0.0757	0.1257	0.6241	1
Methanol	0.1465	0.1043	0.4160	3

Figure A2. TOPSIS analysis.

DECISION MATRIX

Criteria	W				X				Y				Z		
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Local Weight	0.283				0.428				0.176				0.113		
	0.222	0.132	0.218	0.428	0.314	0.249	0.247	0.190	0.229	0.308	0.290	0.172	0.376	0.313	0.311
Hydrogen	57	9.2	4	5	0	100	100	100	1.5	315	0.06	5	2	5	5
Ammonia	381	12.7	6	3	102	100	96	100	0.94	260	0.047	3	4	3	3
Methanol	381	15.8	9	1	533	92	45	56	0.16	105	0.006	2	4	2	3
$\sqrt{\sum_{i=1}^{n} x_{ij}^2}$	541.8	22.26	11.53	5.916	542.7	168.7	145.7	152.1	1.777	421.7	0.076	6.164	6	6.164	6.557

NORMALIZED DECISION MATRIX

Criteria	W				X				Y				Z		
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Local Weight	0.283				0.428				0.176				0.113		
	0.222	0.132	0.218	0.428	0.314	0.249	0.247	0.190	0.229	0.308	0.290	0.172	0.376	0.313	0.311
Hydrogen	0.105	0.413	0.347	0.845	0.000	0.593	0.686	0.657	0.844	0.747	0.784	0.811	0.333	0.811	0.762
Ammonia	0.703	0.570	0.520	0.507	0.188	0.593	0.659	0.657	0.529	0.617	0.614	0.487	0.667	0.487	0.457
Methanol	0.703	0.710	0.780	0.169	0.982	0.545	0.309	0.368	0.090	0.249	0.084	0.324	0.667	0.324	0.457

WEIGHTED (LOCAL WEIGHTED) NORMALIZED DECISION MATRIX

Criteria		W				X				Y				Z		
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Hydrogen		0.023	0.055	0.076	0.361	0	0.148	0.169	0.125	0.194	0.23	0.227	0.14	0.125	0.254	0.237
Ammonia		0.156	0.075	0.114	0.217	0.059	0.148	0.162	0.125	0.121	0.19	0.178	0.084	0.25	0.152	0.142
Methanol		0.156	0.094	0.17	0.072	0.309	0.136	0.076	0.07	0.021	0.077	0.024	0.056	0.25	0.102	0.142
Ideal	A^+	0.023	0.094	0.170	0.072	0.000	0.148	0.169	0.125	0.021	0.077	0.024	0.056	0.250	0.254	0.237
	A^-	0.156	0.055	0.076	0.361	0.309	0.136	0.076	0.070	0.194	0.230	0.227	0.140	0.125	0.102	0.142

Figure A3. *Cont.*

CALCULATION OF EUCLIDEAN DISTANCE FROM IDEAL & PERFORMANCE SCORE- TECHNICAL ATTRIBUTES

Alternative	S_j^+	S_j^-	P_i	Ranking
Hydrogen	0.3067	0.1328	0.3022	3
Ammonia	0.2052	0.1509	0.4237	2
Methanol	0.1328	0.3067	0.6978	1

CALCULATION OF EUCLIDEAN DISTANCE FROM IDEAL & PERFORMANCE SCORE- ENVIRONMENTAL ATTRIBUTES

Alternative	S_j^+	S_j^-	P_i	Ranking
Hydrogen	0.0000	0.3271	1.0000	1
Ammonia	0.0594	0.2699	0.8195	2
Methanol	0.3271	0.0000	0.0000	3

CALCULATION OF EUCLIDEAN DISTANCE FROM IDEAL & PERFORMANCE SCORE- ECONOMIC ATTRIBUTES

Alternative	S_j^+	S_j^-	P_i	Ranking
Hydrogen	0.3190	0.0000	0.0000	3
Ammonia	0.2178	0.1113	0.3383	2
Methanol	0.0000	0.3190	1.0000	1

CALCULATION OF EUCLIDEAN DISTANCE FROM IDEAL & PERFORMANCE SCORE- SOCIAL ATTRIBUTES

Alternative	S_j^+	S_j^-	P_i	Ranking
Hydrogen	0.1252	0.1795	0.5891	1
Ammonia	0.1390	0.1351	0.4929	2
Methanol	0.1795	0.1252	0.4109	3

Figure A3. TOPSIS analysis of sub-criteria.

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