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Assessment Of Alternative Fuels For Deep Sea Vessels

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Abstract

During the 21st Climate Change Summit in Paris in 2015, the International Maritime Organization (IMO) pledged to adopt necessary measures to reduce Green House Gas (GHG) emissions from shipping. Several research studies and maritime classification society outlooks argue that the true path to effective decarbonization of the shipping industry could only be achieved by adopting low-carbon or zero-carbon alternative fuel sources. This research was aimed to systematically analyze the three main deep-sea alternate fuel options: Hydrogen, Ammonia & Methanol, which can potentially achieve IMO's 2050 ambitions. Each of these fuel alternatives was assessed against Technical, Environmental, Economic and Social attributes. The systematic assessment was carried out through a hybrid Multi-Criteria Decision Making (MCDM) method, which combines Analytical Hierarchy Process (AHP). Primary data was collected through an online survey involving 57 experts in the maritime industry to compute criteria weights. The results from the AHP pairwise comparison indicated that Environmental attributes were the most preferred criterion for the assessment of alternate marine fuels, followed by Technical, Economic and Social Attributes. The findings of this research can assist the maritime sector's decision-makers in making an informed decision on selecting the most suitable alternate fuel option for their deep-sea fleet, capable of achieving global GHG emission targets of 2050 and beyond.

Keywords: alternative fuels, MCDM, AHP, hydrogen, ammonia, methanol, maritime sustainability

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1. Introduction

During the United Nations Climate Change Conference (COP 21) on the 12th of December 2015, 196 members of the concerned parties made a collective pledge to legally bind their commitment to an international treaty on mitigating global climate change. During this landmark event, the International Maritime Organization (IMO) recognized the emissions of Green House Gasses (GHG) from the maritime sector and pledged to adopt necessary measures to reduce the GHG emissions from shipping (IMO, 2019a). Accordingly, at the 70th Session of the Marine Environmental Protection Committee (MEPC), the IMO devised a roadmap to develop a strategy to reduce GHG. Subsequently, the Initial IMO Strategy for the reduction of GHG emissions from ships was adopted at the 72nd session of MEPC (IMO, 2018a; IMO, 2019b). This strategy included IMO's GHG reduction ambitions for 2030 and for 2050. Research conducted by UMAS, Frontier Economics and CE Delft (2019) forecasted that a switch to alternate fuels across the shipping industry would be needed to achieve IMO's targets beyond 2030 (DNV, 2021). The maritime forecast report states that 80% of the world fleet's CO2 emissions are produced from deep-sea vessels. The importance of zero-carbon fuels to reach the 2050 GHG emissions were further reinforced by research performed by Bouman et al., 2017 cited in Psaraftis (2021)

As alternate fuels are the key to decarbonization, several fuel options have been considered, and pilot projects have been launched to determine their feasibility. Only limited fuel options are available for deep-sea vessel applications when production, storage, and bunkering infrastructure requirements are considered. However, there has not been a systematic assessment of these fuel options to enable the stakeholders to make an informed decision regarding their decarbonization strategies. According to an outlook published by the American Bureau of Shipping (2019a), achieving the IMO's long-term and short-term emission goals will require the development of low and zero-carbon fuels. It also emphasizes that the availability of these fuels and related infrastructure development will be vital to the shipping industry in meeting IMO's emission reduction targets. Several other research (Bouman et al., 2017; UMAS, Frontier Economics and CE Delft, 2019; Psaraftis, 2021) have reinforced the claim of ABS pertaining to the importance of zero-carbon alternative fuel's role in IMO's 2050 GHG emissions ambitions.

However, maritime sector stakeholders exhibit a reactive nature to decarbonization compared to a proactive approach. The Shipping industry is anticipating a demand for a given alternate fuel to develop a supply chain and infrastructure. On the contrary, the ship owners, shipbuilders and engine manufacturers are awaiting progress on infrastructure and re-fueling options to determine their future vessels and engine designs. Foretich et al. (2021) exemplify this situation as a ‘chicken and egg dilemma’ in their publication, Challenges, and opportunities for alternative fuels in the maritime sector. Thus, for effective decarbonization of the shipping industry, the scaling up of alternative fuel infrastructure and the demand for a particular alternate fuel needs to grow simultaneously. The American Bureau of Shipping (2019b) convincingly argues that LNG indicates the inherent challenges in the global adoption of any alternate fuel. The report states that 10 years had elapsed in developing LNG bunkering infrastructure, which could only supply 1% of LNG bunkers to the global fleet. Hence it could be anticipated that all other alternative fuel options will face similar developmental, regulatory and supply change challenges in the future.

Much of the recent research published (Kolwzan and Narewski, 2012; Månsson, 2017; DNV-GL, 2019a; Hansson et al., 2019; Thepsithar, 2020; Al-Enazi et al., 2021; Chiong et al., 2021b; Gray et al., 2021; Prussi et al., 2021; Ashrafi, Lister and Gillen, 2022) on alternate marine fuels have considered holistic approach all of the alternative energy options available for shipping. These studies consider low/zero alternate carbon fuels for deep-sea, near coastal and inland-water applications. However, to effectively access the most feasible alternate fuel option for a particular maritime industry sector, it would be prudent to consider deep-sea, near coastal and inland-water applications individually. For instance, although a rechargeable battery-powered application would be most suited to inland or near coastal vessels, it would be impractical to consider the same for large deep-sea vessels. Similarly, in large storage quantities, fuels such as LH2, ammonia or methanol would be more suited for deep-sea vessels but would cause storage and bunkering availability for near coastal and inland-water applications.

Additionally, large deep-sea vessels sail long ocean passages to different ports and irregular schedules. Thus, they require an alternate fuel that is globally available and can abide by global and regional regulations related to exhaust emissions (ABS, 2019b; DNV-GL, 2019b). A study conducted by DNV-GL on Maritime Forecast to 2050 (DNV-GL, 2019c) states that the technical applicability and commercial viability vary according to ship types. The study further elaborates that deep-sea vessels, which account for over 80% of the world fleet's CO2 emission, have limited alternate fuel options compared to short-sea vessels.

This research aims to determine the most feasible alternate fuel option capable of meeting the IMO’s 2050 emission targets and subsequent deep decarbonization towards the end of this century. Although many studies have analyzed alternate fuel options, none of these studies has specifically targeted deep-sea vessel applications, even though these vessels are responsible for over 80% of global GHG emissions from the maritime sector. Limited studies with a narrow scope of deep-sea applications (McKinlay, Turnock and Hudson, 2020; McKinlay, Turnock and Hudson, 2021; Ashrafi, Lister and Gillen, 2022) have been researched, but none of these studies has considered the technical, environmental, economic and social considerations of alternate deep-sea fuels. Moreover, these studies are based on appeasing literature and study market trends. They have not systematically analyzed the key attributes of deep-sea alternate fuel options, nor have they convincingly concluded the most feasible option. Thus, the aim of this research is justified by the dire need for a systematic analysis of technical, environmental, economic, and social attributes of deep-sea alternate fuel options in the maritime industry.

2. State-of-the-Art

2.1. The 2050 Future Fuel Mix

There are a wide array of low-carbon fuel choices, where studies have been conducted, and pilot projects have been launched to test these fuels on vessels to determine their technical and economic viability (Psaraftis, 2021). However, each alternative fuel and energy source has drawbacks in global availability, onboard storage, energy density, and support infrastructure (ABS, 2019a). Foretich et al. (2021) elaborate on economic, environmental, infrastructural, safety, and technical challenges by comparing 12 different types of alternate fuels. The study mainly focuses on the financial considerations of the fuels and does not consider the ‘hidden cost’ of fossil fuels. Foretich et al. (2021) conclude 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. Chiong et al. (2021a) have conducted a similar study comparing the challenges of alternate 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-cell, which could be viable propulsion options for 2050 and beyond.

Many of the research suggests that LNG would act as a bridge fuel, while Methanol, Ammonia and Hydrogen are likely to be adopted as the fuel of the future (McKinlay, Turnock and Hudson, 2020; Al-Enazi et al., 2021; Mallouppas and Yfantis, 2021; McKinlay, Turnock and Hudson, 2021; Romano and Yang, 2021). Clarkson’s research on ‘Potential Net Zero’ scenarios predicts that Hydrogen, Ammonia and Methanol will be the dominant alternate fuel options for deep-sea applications by 2050 (Clarksons Research, 2021). As an alternate fuel, LNG is incapable of attaining 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, bio-diesel 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 alternate fuel options for 2050 and beyond.

2.2. Hydrogen

Hydrogen offers the ship owners a low-carbon, low-emission fuel, which could be used in either internal combustion engines or fuel cells (ABS, 2021a). 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 (ABS, 2021a). Among the potential alternative energy options, Hydrogen is a much-preferred fuel because of its environmental impact (Atilhan et al., 2021). It is the cleanest marine fuel in combustion emissions, as it does not produce any NOx, SOx or PM (ABS, 2019b).

Unlike fossil fuels, hydrogen is deemed an energy carrier (DNV-GL, 2019b; Hasan et al., 2021; Wan et al., 2021) 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 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 (ABS, 2019b)

According to DNV-GL (2019b), the current global production of H2 amounts to about 55 million tonnes per year. At present, around 95% of this H2 is produced from fossil fuels, while the remaining 5% is generated through electrolysis. Hydrogen production from a replenishable feedstock and renewable energy is considered 'green hydrogen' (Al-Enazi et al., 2021; Atilhan et al., 2021). Hydrogen production through electrolysis using solar or wind turbines has been analysed using sustainable energy (DNV-GL, 2019b; Wang et al., 2019; ABS, 2021b). The world's largest green hydrogen production plant is proposed to be built by 2025 and is designed to produce 650 tons of hydron daily, utilising 4GW of renewable energy (Chemical Engineering, 2020). The EU aims to install a 6GW renewable energy electrolyser by 2024, producing one million tons of green hydrogen annually. The EU strategy plans to increase electrolyser capacity to 40GW by 2030 to produce 10 million tons of green hydrogen (European Commission, 2020). The global hydrogen market is projected to grow from 70 million tons in 2019 to 120 million tonnes in 2024 (Focus on Catalysts, 2020). Australia is anticipating exporting one million tons of Hydrogen by 2030, projecting a GDP growth of AUD 11 billion by 2050 (American Bureau of Shipping, 2021a)

As a marine fuel, hydrogen can generate power by combustion in IC engines or gas turbines (Jain, 2009). Alternatively, it can be used directly in fuel cells like the PEM (Wang et al., 2011; Vogler and Sattler, 2016; Thomas et al., 2020; ABS, 2021b). Hydrogen is easily ignitable, but IC engines require special modification due to the low heat capacity and density (Al-Enazi et al., 2021). Conventional IC engines will be required to be retrofitted to enable LH2 operation by injection of a pilot fuel such as MDO (Atilhan et al., 2021). Fuel-cell is expected to develop an electrical efficiency of about 50%~60%, which is considerably higher than utilising hydrogen in an IC engine between 40%~50% (ABS, 2019b; DNV-GL, 2019b; UMAS et al., 2019).

The major challenge for hydrogen fuel would be the high production cost and the lack of bunkering infrastructure (DNV-GL, 2019b). On the other hand, the ABS (2021a) also identify 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^{O}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 by McKinlay, Turnock and Hudson (2020) 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 lesser, but the tank needs to withstand cryogenic temperatures.

With the current technological advancements, hydrogen as a marine fuel is limited to short-sea voyages due to constraints in storage volume on board (ABS, 2019b; DNV-GL, 2019b).

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 (Zhou et al., 2019; Wan et al., 2021). Chehade and Dincer (2021) claim that Ammonia has a 3-times higher energy density than Hydrogen. However, a report compiled by Al-Aboosi et al. (2021) indicates that Ammonia has a comparable energy density of 22.5MJ/Kg when compared to Methanol (22.7 MJ/Kg), but a lower value than LNG (55 MJ/Kg and MDO (45MJ/Kg). By weight, 18% of Ammonia consists of Hydrogen; thus, Ammonia contains 50% more Hydrogen than LH2 (Chehade and Dincer, 2021; Kurien and Mittal, 2022). Hence Ammonia is an effective hydrogen carrier, containing 107kg of Hydrogen in 1m3 of Ammonia.

Ammonia has a reliable production, storage and distribution infrastructure due to industrial applications and fertiliser production for agriculture (Hasan et al., 2021). In 2019, 150 million tons of ammonia were produced globally (Al-Aboosi et al., 2021). Bulk quantities of ammonia are usually stored at -330C and atmospheric pressure (Bartels, 2008; ABS, 2019b). Pressurised liquid ammonia (10bar) can be stored at ambient temperature in thermal stress relief vessels (McKinlay, Turnock and Hudson, 2020; Chehade and Dincer, 2021). Thus, the storage of ammonia is more convenient than the storage of hydrogen. Presently, nearly 90% of ammonia is produced by synthesizing hydrogen and nitrogen in a process known as the Haber-Bosch method (Al-Enazi et al., 2021). When the hydrogen and the nitrogen for the Haber-Bosch are acquired from renewable energy sources, the ammonia generated is termed 'green ammonia' (Valera-Medina et al., 2018; Al-Aboosi et al., 2021; Kurien and Mittal, 2022). However, this is an energy-intensive process (McKinlay, Turnock and Hudson, 2020). Ammonia can also be generated using carbon-free routes such as cryogenic distillation column, pressure swing adsorption, and membrane separation (Gomez, Baca and Garzon, 2020). Kurien and Mittal (2022) convincingly argue that the 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 (Dimitriou and Javaid, 2020). It was noted that the potential of green ammonia emitted a third less GHG in an IC engine than in an MDO-operated IC engine (Kurien and Mittal, 2022). However, the low flame speed (7cm/s at atmospheric conditions) and high auto-ignition temperature (6300C) makes ammonia impossible to be used as single fuel and would require a pilot fuel with a dual-fuel injection configuration in IC engines (Kurien and Mittal, 2022). Detailed studies by Dimitriou and Javaid (2020) have explored how advanced injection can improve the overall efficiency of an ammonia dual-fuel engine. Moreover, the combustion of ammonia will generate high levels of NOx, which can be mitigated by employing selective catalytic reduction systems (ABS, 2019b; McKinlay, Turnock and Hudson, 2020)

Ammonia is a corrosive and toxic substance in a concentrated form. The toxicity of ammonia mainly depends on its concentration, duration of exposure and physical form (Chehade and Dincer, 2021). 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, rapid corrosive burning of the respiratory and may lead to death (ABS, 2019b; Chehade and Dincer, 2021). A sustainability white paper published by the American Bureau of Shipping (2020b) states that the odour threshold of ammonia could be as low as 0.037ppm to 1.0ppm; 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 TLV of 50ppm in 8 hours. Ammonia has a relatively lower flammable range of about 15%~33% in dry air and an auto-ignition temperature of 6300C. Thus, the risk of an ammonia-rated fire is much lower than other marine alternate fuels (ABS, 2020b). Since ammonia is much lighter than air and highly soluble in water, hence it makes it easy to control in case of a fire or explosion (Hales and Drewes, 1979, cited in Kurien and Mittal, 2022).

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 (Al-Enazi et al., 2021). 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 (Al-Enazi et al., 2021). According to the ABS (2021c), methanol draws interest in oceangoing, short-sea and inland waterway vessel shipowners due to its CO2 reduction potential. According to Ming and Chen (2021), the popularity of methanol is drawn due to its ease of handling, operation safety, and engine compatibility.

Methanol (CH3OH) is considered the simplest form of alcohol. It is a volatile, colourless, and flammable liquid which emits a distinct odour at ambient temperature (Olah, Goeppert and Prakash, 2018 cited in Ming and Chen, 2021). A report on methanol by FCBI Energy (2015) 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 (Ming and Chen, 2021). Methanol production from fossil feedstock, such as natural gas and coal, has a well-established global infrastructure (Ming and Chen, 2021). According to the Methanol Institute (2017) statistic, over 90 methanol plants have a combined annual capacity of about 110 million metric tons. The industry generates nearly $55 billion in economic activity each year. Alternatively, methanol could also be produced utilising renewable feedstocks or as an electro-fuel. (FCBI Energy, 2015; ABS, 2021c) . Ming and Chen (2021) state 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 CO2 from the atmosphere (Ming and Chen, 2021).

FCBI Energy (2015) claims that methanol is often overlooked as an alternate fuel despite having many advantages, such as global availability and the ability to be produced with various fossil and renewable feed socks. 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 (ABS, 2020b). 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 (FCBI Energy, 2015).

2.5. Research Gap

Only a limited number of studies have been carried out to compare alternate marine fuels. The most recent study was carried out by Ashrafi, Lister and Gillen (2022), 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 alternate 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 have not emphasized 2050 emission targets. McKinlay, Turnock and Hudson (2021) performed a case study using an LNG tanker, using secondary data from literature and MySQL simulations. The study identifies key engineering challenges anticipated with the integration of Hydrogen, Ammonia & LNG. The findings state that hydrogen was the favored option among the other fuel options. It was also proposed that Ammonia and hydrogen have a promising potential for decarbonization in the future.

All the recent studies identified above on alternate marine fuels have not considered IMO’s 2050 ambitions and focused 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. Methodology

This research aims to determine the most suited fuel options in the maritime sector that would enable IMO’s 2050 GHG emission targets. The research framework is depicted in Figure 1.This research has employed a AHP to assess the criteria for three main marine alternate 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. Subsequently, NVivo Version 12 software package was to systematically organise data obtained from the literature review. Technical, environmental, economic, and social attributes of alternate fuels; Hydrogen, Ammonia and Methanol were compered. A number of 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 was 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.

3.1. Analytical Hierarchy Process for Assigning the Relative Weights

Saaty (2008) and Vaidya and Kumar (2006) state that in order to make an informed decision, the decision problem needs to be decomposed into the following steps:

1) The problem needs to be defined, and background knowledge is to be researched.
2) The objectives of the problem or decision need to be identified.
3) 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.
4) Evaluate the relative importance of each decision criteria by constructing a pairwise comparison matrix.
5) Perform normalisation for comparison matrix and subsequently calculate the weights for each of the criteria and priorities.
6) Calculate the maximum eigenvalue, Consistency Index (CI), and Consistency Ratio (CR) and analyse the consistency.

Each of the criteria (or sub-criteria) is arranged in a pairwise configuration, as shown in Equations 1. If n number of criteria is being considered, n number of criteria is placed in the column and row of a n x n matrix. The expert judgements for criteria A_i and A_j are then represented within the matrix. Where $i,j=1.2.3 \ldots\ldots n$ 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 (Tan and Promentilla, 2013).

$$A = \left(a_{ij}\right) = \begin{bmatrix} 1 & a_{12} & \ldots & a_{1n} \\ {}^{a}/_{a_{12}} & 1 & \ldots & a_{2n} \\ . & . & \ldots & . \\ {}^{1}/_{a_{1n}} & {}^{1}/_{a_{2n}} & \ldots & 1 \end{bmatrix} \tag{1}$$

The weight vector indicates the priority of each element in the pair-wise comparison matrix in terms of its overall contribution to the decision-making process (Tan & Promentilla, 2013). Such a weight value can be calculated using Equation 2.

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

where a_{ij} stands for the entry of row ***i*** and column ***j*** in a comparison matrix of order ***n***. The weight values obtained in the pair-wise comparison matrix are checked for consistency purpose using a Consistency Ratio (*CR*). The *CR* value is computed using the following equations (Saaty, 1990):

$$CR = CI/RI \tag{3}$$

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

$$\lambda_{max} = \frac{\sum_{j=1}^{n} \frac{\sum_{k=1}^{n} w_k a_{jk}}{w_j}}{n} \tag{5}$$

where ***n*** equals the number of items being compared, λ_{max} stands for maximum weight value of the $n \times n$ comparison matrix, ***RI*** stands for average random index (Table 2) and ***CI*** stands for consistency index.

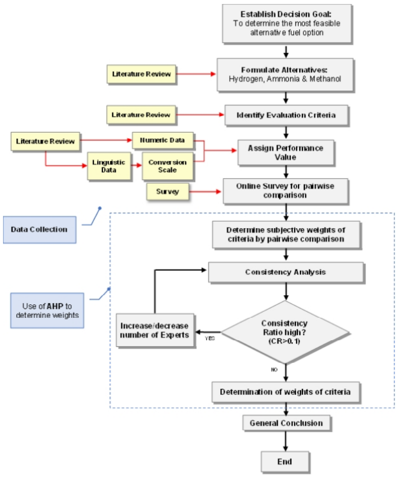

Fig. 1. Research framework.

Table 1. 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

CR is designed in such a way that a value greater than 0.10 indicates an inconsistency in pair-wise comparison. If *CR* is 0.10 or less, the consistency of the pair-wise comparisons is considered reasonable (Saaty, 1990).

4. Results and analysis

The online survey link was distributed to about 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.

Table 2. Participant demographics.

Role	Academic	Surveyor	Technical Superintendent	Marine Eng.	Other	**Total**
	5	5	3	41	3	57
Qualification	Diploma	BSc	MSc	PhD	STCW	
	10	10	10	3	24	**57**
Experience (Years)	0-5	5-10	10-15	15+		
	8	8	6	35		**57**

The research hierarchy was constructed as depicted in Figure 2 by placing the goal on the top level, followed by the decision criteria, sub-criteria in the intermediate levels and the alternative at the lowest level. First, normalization was performed on each pairwise comparison matrices, and the calculation of local and global criteria weights. Consistency analysis was executed on each of the normalized-pairwise comparison matrices in accordance with the procedure. Table 3 below represents the global and local weights of assessment criteria. As the calculated CR is $0.0057<0.1$ (for the main criteria), the responses can be deemed consistent according to Saaty's (1977) consistency analysis. Similarly, the CR for each of the assessment levels are 0.0091, 0.0019, 0.0055, 0.088 for Technical, Environmental, Economic and Social respectively, and so can also be assume dot be consistent. The results of the main criteria weights indicate that experts conclude environmental criterion is of the most importance while the social attributes were of least importance.

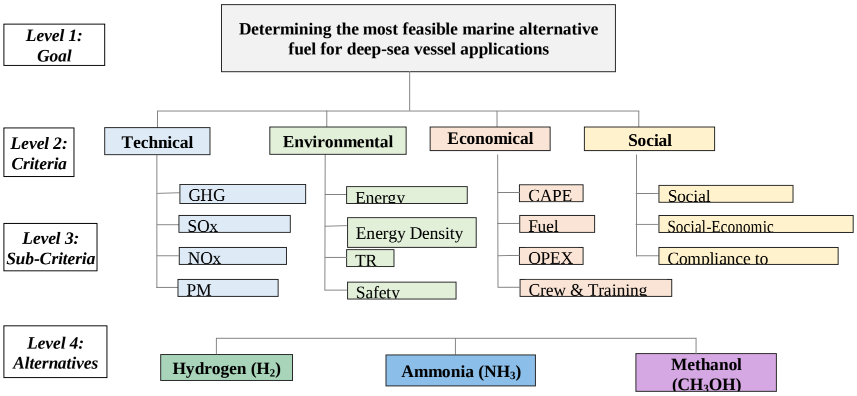

Figure 2. Evaluation hierarchy.

Table 3. Global & Local Weights of Assessment Criteria.

Main Criteria			Sub-Criteria			Overall
Assessment Criteria	Notation	Weights	Assessment Criteria	Notation	Local Weight	Global Weight (Weight × Local 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
			SO_X Reduction	C6	0.249	0.108
			NO_X Reduction	C7	0.248	0.106
			PM Reduction	C8	0.19	0.081
Economic Criteria	Y	0.176	CAPEX	C9	0.229	0.04
			Fuel Cost	C10	0.308	0.054
			OPEX	C11	0.291	0.051
			Crew & Training Cost	C12	0.172	0.03
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 inconsistence responses from the entire survey. Table 5 outlines the normalized performance values associated with each alternative fuel (Hydrogen, Ammonia & Methanol), along with the sources of information for assessment criteria under each alternative. The performance values for each fuel alternative, in Table 5, are then combined with the global weights of each criteria and then normalised to produce an overall score for each of the alternative fuels. Table 6 shows the data sources for the performance values The ranking of each alternative fuel is shown in Table 7.

Table 5. Normalized Performance Values.

		Technical Criteria				Environmental Criteria				Economic Criteria				Social Criteria		
	Assessment Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Normalized performance values	H_2	0.105	0.413	0.347	0.845	0	0.593	0.686	0.657	0.844	0.747	0.784	0.811	0.333	0.811	0.762
	NH_3	0.703	0.57	0.52	0.507	0.188	0.593	0.659	0.657	0.529	0.617	0.614	0.487	0.667	0.487	0.457
	CH_3OH	0.703	0.71	0.78	0.169	0.982	0.545	0.309	0.368	0.09	0.249	0.084	0.324	0.667	0.324	0.457

Table 6. Data sources for Normalized Performance Values in Table 5.

Main Criteria	Sub-Criteria	Units	Performance Values Data Sources
Technical Attributes	Energy Efficiency	g/kW-hr	(ABS, 2020b; ABS, 2021c; ABS, 2021b; Ming and Chen, 2021)
	Energy Density	MJ/L	(DNV-GL, 2019b; ABS, 2020b; ABS, 2021a; DNV, 2021; Ming and Chen, 2021; Wan et al., 2021)
	TRL	TRL Scale Rating	(DNV-GL, 2019b; Lloyd's Register and UMAS, 2020; DNV, 2021; Ming and Chen, 2021; Mäkitie et al., 2022)
	Safety of Bunkering, handling & Storage	Rating Scale	(Valera-Medina et al., 2018; DNV-GL, 2019b; American Bureau of Shipping, 2021a; Wan et al., 2021; American Bureau of Shipping, 2022)
Environmental Attributes	GHG Emission	g/kW-hr	(Gilbert et al., 2018; ABS, 2019b; DNV-GL, 2019b; ABS, 2021a; Ming and Chen, 2021; Xing et al., 2021)
	SOx Reduction Potential	% Compared to HFO	(Gilbert et al., 2018; ABS, 2019a; ABS, 2019b; Maritime, 2019; Ming and Chen, 2021; Xing et al., 2021; Mäkitie et al., 2022)
	NOx Reduction Potential	% Compared to HFO	(Gilbert et al., 2018; ABS, 2019b; DNV-GL, 2019b; ABS, 2020a; Ming and Chen, 2021; Xing et al., 2021; Mäkitie et al., 2022)
	PM Reduction Potential	% Compared to HFO	(Brynolf, Fridell and Andersson, 2014; Gilbert et al., 2018; ABS, 2019b; DNV-GL, 2019b; Ming and Chen, 2021; Xing et al., 2021)
Economic Attributes	CAPEX	USD/Kg of Fuel	(Lloyd's Register and UMAS, 2020; DNV, 2021)
	Fuel Cost	USD/MWh Shaft Output	(DNV-GL, 2019b; Lloyd's Register and UMAS, 2020; Al-Enazi et al., 2021; DNV, 2021)
	OPEX	USD/Kg of Fuel	(Deniz and Zincir, 2016; Lloyd's Register and UMAS, 2020; DNV, 2021)
	Crew & Training Cost	Rating Scale	(Deniz and Zincir, 2016; Al-Enazi et al., 2021)
Social Attributes	Social Acceptance	Rating Scale	(Ren and Liang, 2017; Ren and Lützen, 2017; Wan et al., 2021; Ashrafi, Lister and Gillen, 2022)
	Social-Economic Development	Rating Scale	(Ren and Liang, 2017; Ren and Lützen, 2017; Ashrafi, Lister and Gillen, 2022)
	Compliance to Regulations	Rating Scale	(Ren and Liang, 2017; Ren and Lützen, 2017; DNV-GL, 2019b; DNV, 2021)

Table 7. Main Criteria score and overall ranking of the alternative fuels.

	Technical Criteria	Environmental Criteria	Economic Criteria	Social Criteria	Overall	Overall Normalized	Ranking
Hydrogen	0.146	0.190	0.138	0.070	0.544	0.349	1
Ammonia	0.159	0.212	0.100	0.062	0.533	0.343	2
Methanol	0.139	0.253	0.031	0.056	0.479	0.308	3

The secondary data extracted from the literature review suggest that Hydrogen, Ammonia & Methanol were the most suited fuel options for future deep-sea vessel applications. They are all capable of meeting IMO’s 2050 GHG emission targets according to reports published by classification societies and other industrial research. The findings pertaining to the alternatives in this report: Hydrogen, Ammonia & Methanol as potential future fuel sources, align with the findings of Xing et al. (2021); McKinlay, Turnock and Hudson (2021); DNV-GL (2019).Table 7 depicts the overall ranking of the AHP analysis conducted. The findings suggest that Hydrogen is the most feasible fuel option for deep-sea vessel applications capable of meeting IMO’s 2050 emission targets. Ammonia was found to be the second preference, while the least preferred fuel option was found to be 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 hydrogen storage and transporting medium. The literature review of this research identified sources that support the claim that Ammonia is a potential Hydrogen carrier. Similarly, the findings of McKinlay, Turnock and Hudson (2021) also agree with the findings of Al-Enazi et al. (2021), claiming Hydrogen is a favoured option over Ammonia. These studies had not used a systematic analysis employing an MCDM 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 Al-Enazi et al. (2021) and McKinlay, Turnock and Hudson (2021) are questionable. On the contrary, research carried out by Gray et al. (2021) concurs with the findings of this research. Most importantly, their findings identify that both hydrogen and ammonia o-er are the most promising pathways, which further validates the finding of this research as the closeness degree of Ammonia and Hydrogen found in close proximity. Similarly, Hansson et al. (2019) and Mansson (2017) 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 suggested that hydrogen was a superior option in relation to methanol.

5. Conclusions

The discovery of Hydrogen 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 potential of Hydrogen as an 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 Hydrogen and Ammonia in shipping, aviation and other transport modes intended to operate on alternate 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.

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