applied sciences

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Comparative Analysis of Marine Alternative Fuels for Offshore Supply Vessels

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Abstract: This paper provides an in-depth analysis of alternative fuels, including liquefied natural gas (LNG), hydrogen, ammonia, and biofuels, assessing their feasibility based on operational requirements, availability, safety concerns, and the infrastructure needed for large-scale adoption. Moreover, it examines hybrid and fully electric propulsion systems, considering advancements in battery technology and the integration of renewable energy sources, such as wind and solar power, to further reduce SOV emissions. Key findings from this research indicate that LNG serves as a viable short- to medium-term solution for reducing GHG emissions in the SOV sector, due to its relatively lower carbon content compared to MDO and HFO. This paper finally insists that while LNG presents an immediate opportunity for emission reduction in the SOV sector, a combination of hydrogen, ammonia, and hybrid propulsion systems will be necessary to meet long-term decarbonisation goals. The findings underscore the importance of coordinated industry efforts, technological innovation, and supportive regulatory frameworks to overcome the technical, economic, and infrastructural challenges associated with decarbonising the maritime industry.

Keywords: maritime decarbonisation; alternative marine fuels; GHG emission; SOVs

Citation: Park, C.; Hwang, I.; Jang, H.; Jeong, B.; Ha, S.; Kim, J.; Jee, J. Comparative Analysis of Marine Alternative Fuels for Offshore Supply Vessels. *Appl. Sci.* **2024**, *14*, 11196. https://doi.org/10.3390/app142311196

Academic Editor: José A. Orosa

Received: 20 September 2024
Revised: 5 November 2024
Accepted: 19 November 2024
Published: 30 November 2024

1. Introduction

Offshore supply ships (SOVs) play a crucial role in supporting offshore industries, particularly the oil, gas, and renewable energy sectors, by transporting essential supplies, equipment, and personnel to offshore platforms and installations. These vessels often operate in dynamic environments, requiring high operational flexibility, fuel efficiency, and compliance with increasingly stringent environmental regulations. As the offshore energy sector transitions towards greener energy sources, the need for decarbonising SOVs has become a priority. Transitioning to alternative fuels presents an opportunity to significantly reduce the environmental impact of these vessels while meeting the operational demands of the industry.

Various alternative fuels, including ammonia, hydrogen, liquefied natural gas (LNG), methanol, biodiesel, and electricity, have been proposed as potential solutions to decarbonise the maritime sector. Each of these fuels offers distinct advantages and challenges in terms of energy density, fuel storage, engine compatibility, environmental impact, and cost. Despite these developments, there is no universally applicable solution due to the vast diversity in ship types, sizes, operational profiles, and routes.

Given the critical nature of fuel choice in achieving both economic and environmental objectives, a thorough comparative analysis of alternative fuels is essential. This analysis is necessary to evaluate the technical feasibility of each fuel, assess the environmental and regulatory impacts, and understand the economic implications for ship operators. Additionally, it is important to consider the broader infrastructure requirements, such as fuel production, supply chains, and bunkering facilities, which will play a major role in the adoption of alternative fuels.

Conducting a comparative analysis allows stakeholders to make informed decisions about which fuels are best suited for different vessel types and operational contexts. This is particularly important as the maritime industry faces increasing pressure to make strategic decisions about fuel transitions, given the rapid development of fuel technologies and evolving international regulations. The purpose of this paper, therefore, is to provide an in-depth comparative analysis of the most promising alternative fuels, exploring their technological readiness, environmental benefits, and economic considerations to support the maritime sector in its journey towards decarbonisation.

A voluminous body of research on marine alternative fuels and decision-making processes highlights the growing need for decarbonising the maritime sector in light of increasing environmental regulations and international climate targets. Various alternative fuels—such as liquefied natural gas (LNG), hydrogen, ammonia, methanol, and biodiesel—are being investigated for their potential to reduce greenhouse gas (GHG) emissions, sulphur oxides (SOx), nitrogen oxides (NOx), and particulate matter (PM) compared to traditional fossil fuels.

Several studies emphasise LNG as a key transitional fuel due to its relative maturity and immediate availability [1]. It is noted for its lower CO_2 emissions and better performance in reducing SOx and PM. However, the issue of methane slip, which releases methane into the atmosphere during incomplete combustion, poses a challenge as methane is a potent greenhouse gas [2]. Studies that compare GHG emissions across various fuels, such as LNG, hydrogen, and ammonia, conclude that while LNG offers near-term benefits, it is not a long-term solution for achieving zero-carbon operations [3].

Hydrogen and ammonia are considered more promising for long-term decarbonisation due to their potential to operate as zero-carbon fuels. Hydrogen, in particular, is discussed in terms of its ability to fuel both internal combustion engines and fuel cells, the latter of which can significantly reduce emissions if used in maritime applications [4]. However, hydrogen faces significant challenges in storage and transportation due to its low energy density and need for cryogenic or high-pressure storage [5]. Ammonia, while offering the potential for zero-carbon emissions at the point of use, poses safety concerns due to its toxicity, as well as technical challenges related to combustion and storage [6].

Methanol is gaining attention as a cleaner alternative fuel, particularly because of its simpler storage and handling compared to LNG and hydrogen [7]. It is highlighted in studies for its ability to reduce SOx and NOx emissions and its adaptability to existing engine designs with minor modifications. However, methanol's lower energy density compared to conventional fuels means larger fuel tanks are required, which poses logistical challenges, particularly for space-constrained vessels.

Biodiesel, derived from renewable sources such as vegetable oils and animal fats, is considered a near-term alternative that can be used with minimal engine modifications [8]. On the other hand, biodiesel's scalability and its potential to increase NOx emissions are critical concerns, which limit its long-term viability for widespread adoption in the shipping sector [9].

Foretich, Zaimes [10] (p. 100033) points to the crucial role of regulatory frameworks in driving the adoption of alternative fuels. Studies on policy impacts indicate that strong international regulations, such as the International Maritime Organization's (IMO) 2030 and 2050 emissions targets, are key drivers for fuel transition. The adoption of market-based measures such as carbon pricing is identified as an essential tool to incentivise the shift to alternative fuels [11].

In conclusion, while significant research has been conducted on alternative marine fuels, it is clear that each fuel option presents its own set of advantages and limitations. Fuels like LNG reduce emissions short-term but face challenges like methane slip, while hydrogen and ammonia offer long-term potential with technical barriers. Methanol and biodiesel also have trade-offs. A multi-criteria decision-making approach is crucial to evaluate environmental, technical, and economic factors for optimal fuel selection in maritime decarbonisation.

In terms of decision-making processes, multi-criteria decision-making (MCDM) approaches are frequently mentioned. These frameworks allow for the evaluation of multiple factors, including cost, environmental impact, fuel availability, and regulatory compliance, to support strategic decision making in the selection of marine fuels [12]. Several studies consistently highlight the importance of integrating sustainability criteria alongside economic and operational considerations to ensure the most effective fuel transition for various vessel types and operational profiles [13].

Several studies have applied MCDM approaches to assess the viability of various alternative fuels in the maritime sector. For example, Mandić, Ukić Boljat [14] (p. 2600) utilised the AHP method to rank alternative fuels based on environmental, economic, and technical criteria.

Similarly, Mandić, Ukić Boljat [14] (p. 2600) applied the TOPSIS method to evaluate the most sustainable fuels by considering emissions reduction, cost, infrastructure requirements, and safety. Their findings emphasised the difficulty in balancing environmental performance with economic and technical feasibility. For instance, although hydrogen emerged as an ideal candidate for zero-emission shipping, the costs associated with its production, storage, and transportation were prohibitive when considering current technological capabilities.

Strantzali, Livanos [12] (p. 7498) applies the TOPSIS and AHP methods to assess LNG and hydrogen for maritime use, incorporating uncertainty into the evaluation process. This highlights the difficulty of weighing short-term benefits (like LNG’s maturity) against long-term environmental impacts (hydrogen’s zero-emission potential).

One of the previous studies applying MCDM to alternative marine fuels, this paper compares LNG and biodiesel, focusing on emissions, cost, and availability [15]. This study identifies key limitations in data availability and subjectivity in criteria weighting, which are still relevant today.

The use of multi-criteria decision-making (MCDM) methods has proven to be a valuable tool in assessing the feasibility of alternative marine fuels. MCDM allows for the systematic evaluation of various fuel options by considering a wide range of factors, including environmental performance, economic viability, technical feasibility, and regulatory compliance. This method enables stakeholders to make informed decisions by balancing the trade-offs between different fuel types, making it especially useful in navigating the complexities of maritime fuel transition under the stringent decarbonisation targets.

Many MCDM studies are limited by theoretical models and lack real-world data on fuel performance, operational costs, and safety. These evaluations often rely on projected data, expert judgment, and simplified assumptions, reducing their accuracy and applicability to actual ships and the evolving maritime industry.

To overcome these limitations, more practical, field-based studies are necessary. Such studies would integrate real-world data from case ships and operating conditions, providing a more comprehensive and accurate assessment of alternative fuels. Practical trials and pilot projects could offer valuable insights into the long-term viability, economic feasibility, and environmental performance of different fuel options, thereby supporting the industry in identifying the most suitable marine fuels for the future. This shift from theoretical to more practicable studies is essential to provide the maritime sector with clear, actionable recommendations for transitioning to sustainable fuel alternatives.

2. Methodology

The purpose of this paper was to seek to determine the viability of green technologies for the SOV by carrying out a high-level screening of the case ship and potential technical solutions to achieve low- or zero-carbon operation.

To achieve this goal, all credible technical solutions for the SOV were investigated through a feasibility study on using various low- or zero-carbon fuels—ammonia, hydrogen, and inland electricity, biodiesel, LNG, methanol, and hybrids—as marine fuels. Credible business scenarios in consideration of the operational profile were provided by the ship consultant. Then, a series of comparative analyses were conducted across the proposed alternative fuel sources and technologies. The technical aspects of these fuels for maritime application were also evaluated in consideration of safety, regulation, costs, infrastructural availability, supply chain constraints, barriers, and the downstream emission pathways to their uptake onboard.

This comparative analysis deals with technology assessment using a matrix analysis for each fuel type and technology as well as propulsion technologies including battery powertrains, ICEs, fuel cells, and others as required. The matrix employs scoring methods for each fuel and technology from technical, environmental, economic, and safety perspectives.

Firstly, it involves identification of all credible design scenarios with alternative fuels and propulsion systems. Then, a comparative analysis is conducted to investigate the proposed design scenarios both qualitatively and quantitatively in consideration of technical maturity, fuel availability, potential risks, safety regulations, capital expenditures, operating expenditures, fuel costs, and space required. Lastly, a decision matrix suggests the most viable fuel and propulsion system solutions.

Figure 1 shows the overall process of the preliminary assessment to confirm the most viable design solutions. This process was designed to identify the optimal design solution, including fuel selection, for the case ship, which remains relatively unexplored. This approach provides new insights into the performance of alternative fuels under conditions unique to Service Operation Vessels (SOVs).

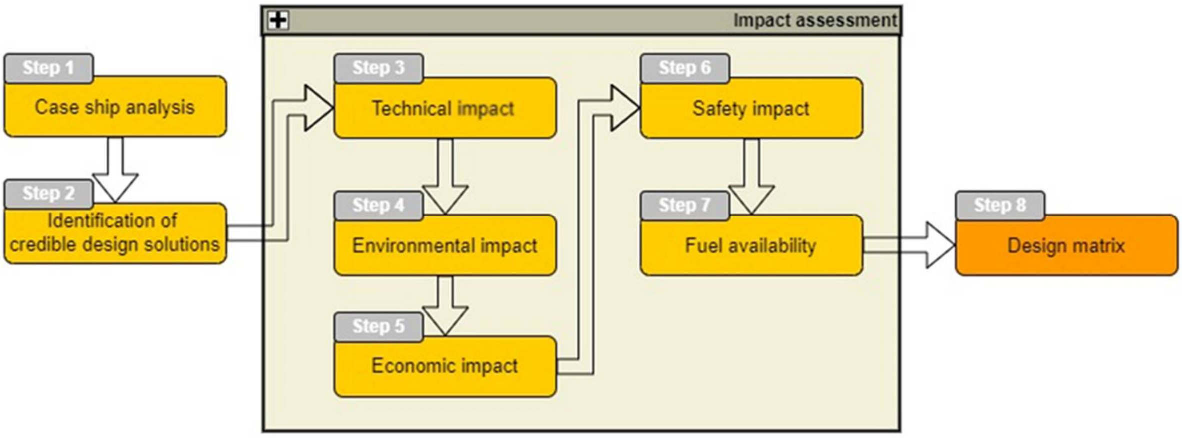


Figure 1. Overview of assessment.

2.1. Case Ship Analysis (Step 1)

The case ship, an offshore supply vessel (SOV), is specifically designed to transport supplies, equipment, and personnel to and from offshore wind power platforms and other offshore installation/maintenance platforms. The vessel is generally equipped with a cargo crane, deck space, and other specialised equipment to handle and transport the supplies needed for offshore operations. The SOV also provides accommodation and other support services to the offshore workforce. It is also equipped with dynamic positioning systems, which allow it to remain in a fixed position in the sea, and others are equipped with an A-frame or a moonpool to perform heavy lifting operations, such as the installation of subsea structures.

2.1.1. Ship Specifications

The case ship is an 85 m SOV proposed to be built in 2026, and its service area consists of, in general, windfarms in Northeast Scotland. Table 1 describes the prospective specifications of the case ship with which the technical assessment was implemented.

Table 1. Case ship specifications.

Items	**Specifications**
Flag	British
Class	IACS
Notations (DNV used as example)	A1A, Offshore Service Vessel (Windfarm Maint), WALK2WORK, CRANE, DYNPOS (AUTR), NAUT (AW), E0, BIS, CLEAN (DESIGN), BWM(T), Strengthened (DK), COMF-V(2)C(2), SPS, RECYCLABLE.
POB	90 persons maximum
Length overall (LOA)	85.0 m
Length (LBP)	84.0 m
Breadth moulded	19 m
Depth moulded	7.5 m
Summer draught	5.0 m
Displacement @ Ts	5525 t
Power source	Diesel–electric
Baseline fuel	MGO
4 Qty main generators	2000 kW
Emergency generator	200 kW
Transit Performance	
Max speed at a design draught of 5.0 metres, not exceeding Beaufort scale 2, 100% power (2 x 1850kw)	14 knots
Service speed (Same environmental conditions)	10–11 knots

2.1.2. Service Route Analysis (Operating Profile)

The case ship was considered to be engaged in service for the Scottish windfarm Morven, which is 37.2 miles off the coast of Aberdeen, the mother port of the case ship. The case ship was assumed to have a 14-day operation for each voyage. Given this, the bunkering interval would be considered as every voyage (14 days) so that the capacity of the fuel storage tanks for each design scenario was assessed. Table 2 illustrates the daily operation pattern while discretising daily hours into different operational phases: port call; transit (10 kts); DP operations; interfiled transits; standby; and at anchor or moored.

Table 2. SOV operation time sheet.

Projected 14-Day SOV Operational Profile															
	Total	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**	**Day 8**	**Day 9**	**Day 10**	**Day 11**	**Day 12**	**Day 13**	**Day 14**
Port call	15	12	-	-	-	-	-	-	-	-	-	-	-	-	3
Transit (10 kts)	12	6	-	-	-	-	-	-	-	-	-	-	-	-	6
W2W DP operations	51.5	-	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.5
Interfield transits	51.5	-	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.5
Standby (non-DP)	76	-	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	4.0
At anchor or moored	130	6	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	4.0
Total hours	336	24	24	24	24	24	24	24	24	24	24	24	24	24	24

Notes: (1) W2W DP operations based on 8 W2W DP interventions per 24 h, each lasting 30 min each. (2) Interfield transits based on 8 transits per 24 h period between turbines, each lasting 30 min each. (3) Total of 6 h per day of standby (non-DP) time allowed for vessel waiting/lunch break with vessel standing by on location using only aft azimuth thrusters. (4) Time at anchor or moored is without DP and/or vessel operations and shall also be considered available charging time offshore. Port call duration shall additionally be available for shore power supply and charging.

2.1.3. Electric Load Analysis

Due to the lack of data availability, the power requirements of the case ship across different operating modes was assumed based on the data from a very similar ship, as described in Table 3. On the other hand, the electric load varies depending on service speeds and sea states. To investigate those impacts on the electric loads as well as ship designs, the project team proposed four different operating scenarios, as given in Table 4.

Table 3. Electric load analysis for the case ship.

	Unit	**Sailing at Eco Speed (10~11 Knots)**	**Sailing at Max Speed (14 Knots)**	**Manoeuvring**	**DPS Operation (Sea State 3, Tide 1 Knot)**	**DPS Operation (Sea State 4, Tide 2 Knot)**	**At Harbour (with Eco Sailing)**	**At Harbour (with Max Sailing)**
Propulsion	kW	1665	3515	925	0	0	0	0
Auxiliary system	kW	280	280	1180.0	1480	2892.5	50	50
Hotel load	kW	150	150	150	200	200	200	200
Margin (10~20%)	kW	209.5	394.5	338.3	336	618.5	25	25
Total load (/h)	kW	2304.5	4339.5	2593.3	2016.0	3711.0	275.0	275.0
Total power consumption (daily)	kWh	14,220.9	20,084.1	1556.0	12,096.0	22,266.0	3088.0	3512.2
Case of ME + GE/mechanical propulsion (GE capacity 1480 kW)								
Number of working generators	Set	1	1	2	2	3	1	1
Generator load factor	%	43%	56%	56%	68%	84%	19%	19%
Case of GE/electrical propulsion (GE capacity 1960 kW)								
Number of working generators	Set	2	3	2	2	3	1	1

Generator load factor	%	59%	74%	66%	51%	63%	14%	14%

Table 4. Forecast of operating scenarios.

4 Different Operating Scenarios			
1	**2**	**3**	**4**
Eco speed sailing + DPS at sea state 3	Max speed sailing + DPS at sea state 3	Eco speed sailing + DPS at sea state 4	Max speed sailing + DPS at sea state 4

2.2. Credible Design Solutions (Step 2)

2.2.1. Market Availability for Fuels and Propulsion Systems by 2026

A realistic roadmap for deploying carbon-neutral propulsion systems requires a corresponding technological maturity. This includes non-fossil fuels such as ammonia, hydrogen, biodiesel, LNG, methanol, and electricity, and also a carbon capture system. To identify all credible fuels and technologies available in 2026, the market availability was explored.

A DNV report [16] provides a timeline for the implementation of alternative fuels and CCS technologies in maritime applications. Methanol and ammonia are the closest to regulatory and technological readiness, particularly for engines, while hydrogen and CCS are expected to take longer to reach high regulatory maturity and full onboard deployment. The graph underscores the gradual transition in maritime energy sources, indicating which technologies will likely become viable and safe for onboard application first, with methanol leading, followed by ammonia, hydrogen, and CCS. The following is a summary of the current status/projection of each fuel technology projected by the report.

- Methanol: Methanol is expected to reach high regulatory maturity for onboard use before 2026. Both 2-stroke and 4-stroke engines for methanol are projected to be available around 2024, while other applications, such as in boilers and fuel cells, are anticipated to become available by approximately 2028.
- Ammonia: The 2-stroke engine technology is anticipated to be available around 2025, with regulatory maturity still in progress. Full maturity for regulations is expected by 2030. Other applications for ammonia, such as in fuel cells and boilers, are projected to reach availability in later years, with some potentially extending into the early 2030s.
- Hydrogen: The 4-stroke engine and fuel cell technologies are anticipated to become available around 2026–2028. Regulatory maturity for hydrogen technologies is forecasted for around 2030.
- CCS (Carbon Capture and Storage): CCS technology is in the early stages of regulatory maturity. Full maturity is expected to be achieved around 2030, with onboard technology potentially available around the same timeframe.

2.2.2. Identification of Credible Solutions: 15 Design Scenarios

Through the technical review on the current statuses of fuels and systems, 15 credible design scenarios were identified, as given in Table 5.

Table 5. Propulsion system scenarios.

Design Scenario	Technology	Fuel Types
1	ICE with mechanical propulsion	LNG + HFO/MGO
2		Biodiesel
3		Methanol
4		Ammonia
5	Generator with electric propulsion	LNG

6		Biodiesel
7		Methanol
8		Ammonia
9	Generator with electric propulsion and battery	LNG + electricity
10		Biodiesel + electricity
11		Methanol + electricity
12		Ammonia + electricity
13	Full battery	Electricity
14	Fuel cell with battery	Hydrogen
15	Fuel cell with cracking system and battery	Ammonia

2.3. Technical Impact (Step 3)

The fuel storage capacity is greatly affected by the fuel consumption and bunkering cycle. In addition, based on the characteristics of the fuel itself, the energy density of the fuel is a key feature that determines the amount of fuel to be stored. Therefore, the technical impact score was justified based on Table 6.

Table 6. Characteristics regarding fuel storage capacity and rating number details.

Fuel	Energy Density (MJ/L)	Tank Size Ratio to HFO/MGO Tank (Times)	Weight Unit (kg/m^3)	Tank Type
Ammonia	12.7	3–4	683	Type C
Hydrogen (LH_2)	8.5	7	71	Type C
Hydrogen (CGH_2)	8.5	13–15	42	Type C
Biodiesel	35.7	1	880	Integral tank
Methanol	15.7	2.5	791	Integral tank
LNG	21.2	2–3	450	Type C
Electricity (battery)	2.1	-	-	Battery

Scoring justification: 5: energy density (MJ/L) 31–50; 4: energy density (MJ/L) 15–30; 3: energy density (MJ/L) 10–14; 2: energy density (MJ/L) 5–9; 1: energy density (MJ/L) 0–4.

The potential fuel types and propulsion systems available by 2026 are listed in Table 7, and their technical maturity levels were assessed based on the data/information (DNV, MARITIME FORECAST TO 2050. 2022).

Table 7. Technical maturity per fuel and rating number details for maturity.

Fuel	Propulsion System	Maturity
Ammonia	ICE	4
	Fuel cell	2
Hydrogen	Fuel cell	4
Biodiesel	ICE	4
Methanol	ICE	4
	Fuel cell	3
LNG	ICE	5
	Fuel cell	3
Electricity	Battery	5

Note: ICE: the internal combustion engine (ICE) composed of an engine, fuel tank, and process system. The fuel cell comprises a fuel cell, fuel tank, electric motor, converter, and battery. The battery system has an electric motor, battery, and battery management system (BMS) as components. Scoring justification: 5: equipment that is off the shelf and commonly used on new ships; 4: equipment that is commercially available, but not fully mature, 3: equipment that is under pilot testing, and/or with only a few commercial applications; 2: equipment that has not been tested at full scale and has no piloting or full-scale testing underway; 1: equipment that has been under development or is expected to be present on the market soon.

Fuel storage capacity and technological maturity can be summarised as shown in the following table, Table 8, based on the energy density, applied fuel, and power source types of the fuel.

Table 8. Rating numbers for technical impact assessment.

Fuel	Case	Fuel Type	Technical Impact		
			Fuel Storage Capacity	Technological Maturity	Total
Ammonia	Mechanical propulsion	Grey	3	4	7
		Blue	3	4	7
		Green	3	4	7
	Electric propulsion	Grey	3	4	7
		Blue	3	4	7
		Green	3	4	7
	Electric propulsion + battery	Grey	3	4	7
		Blue	3	4	7
		Green	3	4	7
	Fuel cell (PEMFC) + battery	Grey	3	2	5
		Blue	3	2	5
		Green	3	2	5
Hydrogen	Fuel cell (PEMFC) + battery	Grey	2	4	6
		Blue	2	4	6
		Green	2	4	6
Biodiesel	Mechanical propulsion	1st gen.	5	4	9
		2nd gen.	5	4	9
		Green	5	4	9
	Electric propulsion	1st gen.	5	4	9
		2nd gen.	5	4	9
		Green	5	4	9
	Electric propulsion + battery	1st gen.	4	4	8
		2nd gen.	4	4	8
		Green	4	4	8
Methanol	Mechanical propulsion	Grey	4	4	8
		Bio	4	4	8
		E	4	4	8
	Electric propulsion	Grey	4	4	8
		Bio	4	4	8
		E	4	4	8
	Electric propulsion + battery	Grey	3	4	7
		Bio	3	4	7
		E	3	4	7
LNG	Mechanical propulsion	Grey	4	5	9
		Bio	4	5	9
		E	4	5	9
	Electric propulsion	Grey	4	5	9
		Bio	4	5	9

		E	4	5	9
	Electric propulsion + battery	Grey	4	5	9
		Bio	4	5	9
		E	4	5	9
Electricity	Battery	Grey	1	5	6
		Blue	1	5	6
		Green	1	5	6

2.4. *Environmental Impacts (Step 4)*

The LCA study examined fuel production and usage in ship propulsion systems through WTT and TTW aspects. Fuels were categorised as grey, blue, or green based on production methods. Propulsion systems were classified as mechanical, electric, fuel cell, or battery-powered. Mechanical systems mainly use diesel, emitting various pollutants. Electric propulsion is less harmful but still contributes to climate change. Fuel cells primarily use hydrogen, emitting only water and heat, but their impact depends on fuel production. Battery-powered systems do not emit pollutants, but their environmental impact depends on the electricity source used for charging.

2.4.1. Environmental Data Collection

Considering the fuel production stage (WTT stage) and fuel consumption stage (TTW stage), the results of the comprehensive environmental impact on various alternative fuels were estimated, as shown in Table 9 and Figure 2. This study estimated comprehensive environmental impacts of various alternative fuels, considering both the WTT and TTW stages, based on several research works [17–19]. The results were indexed relative to HFO (set at 100). The findings show that all alternative fuels have a significant impact when produced as grey fuels, emphasising the importance of using blue or green fuels. Biodiesel shows decreasing climate change impact with each generation. Alternative fuels vary in local air pollutant emissions; ammonia and methanol emit less SOx and PM but still produce NOx, while hydrogen and electricity are cleanest. Fuel cells represent the most environmentally friendly propulsion system. However, these relative values are not absolute, as actual impact depends on factors like production method and region. A comprehensive evaluation should consider the physical characteristics of each fuel and the situation of the specific ship.

Table 9. Estimations for emissions of each fuel [18].

		(%/Emissions of HFO)			
		Relative GHG	**Relative SOx**	**Relative NOx**	**Relative PM**
Ammonia	Grey [19]	139	0	100	0
	Blue	34	0	100	0
	Green	0	0	0	0
Hydrogen	Grey [19]	166	0	0	0
	Blue	14	0	0	0
	Green	0	0	0	0
Biodiesel	1st gen. [17]	90	11	70	26
	2nd gen. [17]	50	11	70	26
	Green	1	11	108	26
Methanol	Grey	129	0	19	0
	Blue	51	0	19	0
	Green	15	0	19	0
LNG	Grey	92	0	7	4
	Blue	24	0	7	4

	Green	2	0	0	0
Electricity	Grey	6	0	0	0
	Blue	0	0	0	0
	Green	0	0	0	0
HFO	Grey	100	100	100	100

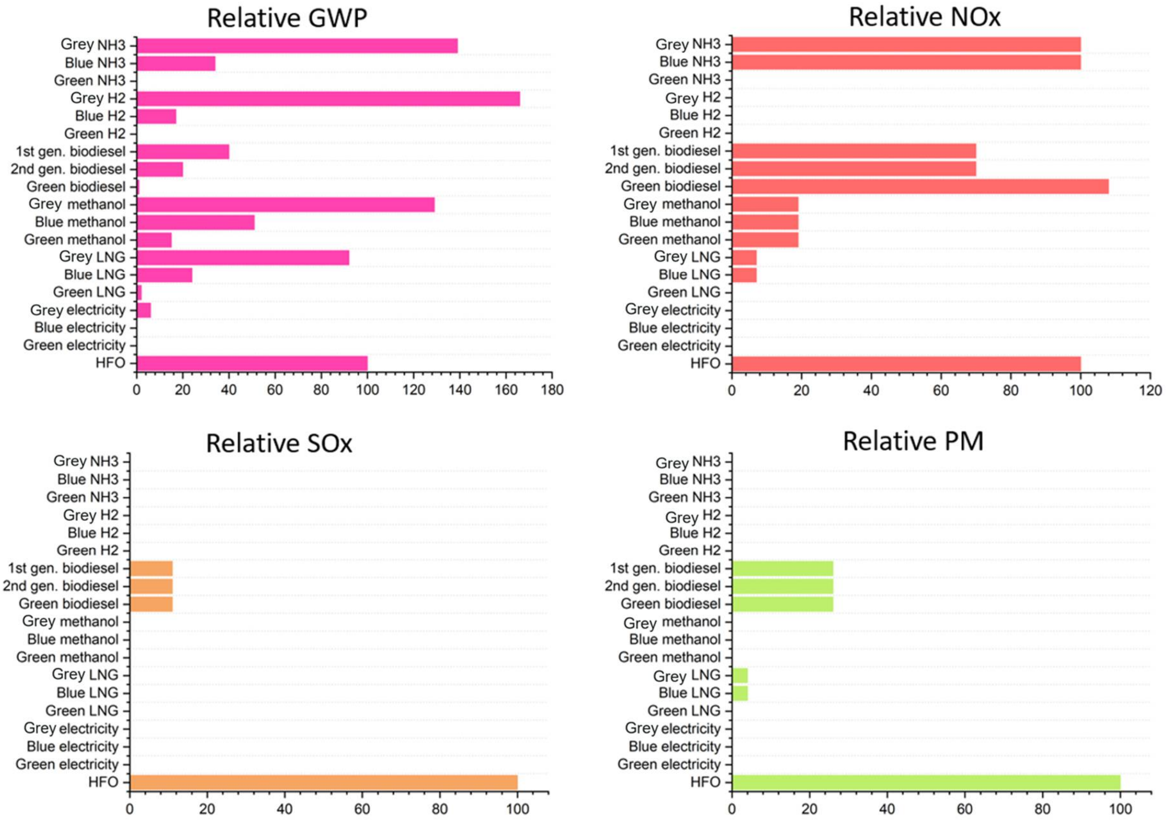


Figure 2. Emission estimation per fuel.

(a) Ammonia

Ammonia is emerging as a promising hydrogen storage and distribution solution for marine fuel, largely due to its higher energy density compared to liquid hydrogen [20]. Specifically, ammonia has a volumetric energy density of 12.7 MJ/L, which is greater than that of liquid hydrogen at 8.5 MJ/L, making it particularly suitable for long-distance shipping applications [21].

However, traditional ammonia production through the Haber–Bosch process is associated with significant CO_2 emissions. In contrast, green ammonia produced through electrolysis using renewable energy is a more environmentally friendly alternative, offering a path towards reduced carbon footprints in shipping [22]. Quantitative assessments indicate that green ammonia derived from renewable sources is the most promising carbon-free fuel for maritime use, whereas grey ammonia produced from fossil fuels actually generates higher greenhouse gas (GHG) emissions compared to heavy fuel oil (HFO) [23].

Despite its potential, a major challenge in utilising ammonia as a green fuel is the emission of nitrogen oxides (NOx) during combustion. Nitrous oxide (N_2O), in particular, has a global warming potential (GWP) roughly 270 times that of CO_2, which underscores the need for advanced combustion technologies and effective emissions control systems when considering ammonia as a marine fuel [23].

(b) Hydrogen

Hydrogen is emerging as a promising marine fuel due to its potential to significantly reduce greenhouse gas emissions, as its only combustion byproduct is water vapor. This makes it an attractive alternative for decarbonising the maritime sector, although several challenges need to be addressed to facilitate its adoption [24].

The environmental impact of hydrogen depends heavily on the production method. Steam Methane Reforming (SMR), a common production method, is cost-effective but emits high levels of carbon—around 11 kg of CO_2 per kg of hydrogen produced [25]. Electrolysis offers lower emissions—about 2.02 kg CO_2 per kg—when powered by renewable energy. However, using grid electricity increases emissions to 17.2 kg CO_2 per kg [25]. Biomass gasification is another alternative that can lower greenhouse gas emissions but is associated with significant aquatic ecotoxicity and human toxicity impacts [26].

In addition to environmental concerns, there are technological and economic barriers. Many advanced production methods, like thermochemical processes, require further development to enhance efficiency. Additionally, high capital and operational costs hinder the competitiveness of hydrogen compared to traditional fuels [27].

Despite these challenges, hydrogen remains a key component in the shift towards cleaner marine fuel systems. Continued research into production efficiency, cost reduction, and sustainability is crucial for hydrogen to fulfil its potential as a viable solution for maritime decarbonisation.

(c) Biodiesel

Biodiesel, derived from renewable sources such as vegetable oil, animal fat, and recycled cooking oil, offers a cleaner alternative to conventional marine fuels. It significantly reduces emissions of sulphur oxides (SOx), nitrogen oxides (NOx), and particulate matter, contributing to improved air quality and environmental sustainability. The production process, primarily through transesterification, allows for the conversion of waste oils into biodiesel, which can displace fossil fuels and mitigate greenhouse gas emissions by up to 86% compared to petroleum diesel [28].

The environmental impact of biofuels largely depends on the feedstock and production methods used. Second-generation biofuels, derived from lignocellulosic materials like agricultural residues, can reduce greenhouse gas (GHG) emissions by 70–90% compared to heavy fuel oil (HFO). Advanced methods, such as biological pretreatment, significantly improve the yields of these biofuels [29,30].

In contrast, first-generation biofuels produced from food crops like soybean and palm oil often result in indirect land use changes that negate GHG savings. When these changes are taken into account, GHG emissions from these biofuels can be similar to those from fossil fuels [31,32].

This highlights the promise of second-generation biofuels for sustainability, while underscoring the need for better feedstock selection and production practices to ensure environmental benefits in biofuel development.

(d) Methanol

Methanol can be combined with marine gas oil to create a low-emission fuel with virtually no sulphur content, making it well suited for maritime engines that have lower energy demands compared to traditional fuels [33]. Renewable production methods, such as carbon dioxide capture powered by renewable energy, enhance the sustainability of methanol [34]. However, conventional methods using fossil fuels like coal and natural gas are carbon-intensive and detrimental to the environment [35,36]. In contrast, methanol produced from biomass has the potential to be carbon-neutral or even carbon-negative, representing a more sustainable pathway for the energy transition.

(e) LNG

Liquefied natural gas (LNG), primarily composed of methane, has a lower carbon content compared to conventional marine fuels. Utilising LNG in marine engines can result in a reduction in CO_2 emissions by approximately 20–25% [37]. Additionally, LNG provides significant environmental benefits by emitting considerably lower levels of sulphur oxides (SOx), nitrogen oxides (NOx), and particulate matter compared to traditional marine fuels [38].

However, the climate benefits of LNG are complicated by methane slip—a phenomenon where unburned methane escapes either during combustion or through the supply chain [39]. This is of particular concern because methane is a highly potent greenhouse gas, with a global warming potential 28–36 times greater than that of CO_2 over a 100-year horizon [40].

The overall climate impact of LNG as a marine fuel depends on several critical factors. Methane slip rates vary significantly across different engine types [39], and this slip tends to increase during operation at low engine loads, underscoring the necessity for optimal engine performance [37]. As a result, although LNG provides immediate greenhouse gas reductions, it is not seen as a comprehensive long-term solution for achieving climate neutrality in the maritime sector. Both the International Maritime Organization (IMO) and the European Union are advocating for more ambitious decarbonisation pathways that extend beyond LNG [41].

To fully leverage the benefits of LNG while mitigating its climate challenges, ongoing research and technological innovation remain crucial. Key focus areas include enhancing engine technology to reduce methane slip and improving monitoring systems throughout the supply chain.

(f) Electricity

Electricity produced from fossil fuels can lead to emissions comparable to those from traditional marine fuels, contributing significantly to greenhouse gases, SOx, NOx, and particulate matter. The maritime sector, being a major emitter, faces considerable challenges in adopting low-carbon alternatives due to its high energy requirements and current dependence on fossil fuels [42].

Conversely, renewable energy sources like solar, wind, and hydropower present a much cleaner alternative by generating electricity without direct emissions. Moving towards renewable energy is crucial for achieving zero-emission shipping, and solutions like lithium-ion batteries have proven effective for ships with short-to-medium-range operations [42].

Although the transition to renewable energy for shipping is a promising strategy to mitigate environmental impacts, there is a need to balance the advantages of emission reduction with the environmental cost of renewable infrastructure [43]. As a result, the overall environmental benefit depends on the electricity source used.

2.4.2. Environmental Impact Analysis

Based on Table 10, the final rating numbers are indicated in Table 11.

Table 10. Rating number capacity (environmental assessment).

Rating Number	Relative Life-Cycle GHG	Relative Life-Cycle SOx	Relative Life-Cycle NOx	Relative Life-Cycle PM2.5
5	0	0	0	0
4	1–20	1–20	1–20	1–20
3	21–59	21–59	21–59	21–59
2	60–89	60–89	60–89	60–89
1	90–	90–	90–	90–

Table 11. Rating numbers for environmental assessment.

Fuel	**Case**	**Fuel Type**	**Environment Impact**				**Total**
			Relative Life-Cycle GHG	**Relative Life-Cycle SOx**	**Relative Life-Cycle NOx**	**Relative Life-Cycle PM2.5**	
Ammonia	Mechanical propulsion	Grey	1	5	1	5	12
		Blue	3	5	1	5	14
		Green	5	5	5	5	20
	Electric propulsion	Grey	1	5	5	5	16
		Blue	3	5	5	5	18
		Green	5	5	5	5	20
	Electric propulsion + battery	Grey	1	5	5	5	16
		Blue	3	5	5	5	18
		Green	5	5	5	5	20
	Fuel cell (PEMFC) + battery	Grey	1	5	5	5	16
		Blue	4	5	5	5	19
		Green	5	5	5	5	20
Hydrogen	Fuel cell (PEMFC) + battery	Grey	1	5	5	5	16
		Blue	4	5	5	5	19
		Green	5	5	5	5	20
Biodiesel	Mechanical propulsion	1st gen.	1	4	2	3	10
		2nd gen.	3	4	2	3	12
		Green	4	4	1	3	12
	Electric propulsion	1st gen.	1	4	2	3	10
		2nd gen.	3	4	2	3	12
		Green	4	4	1	3	12
	Electric propulsion + battery	1st gen.	1	4	2	3	10
		2nd gen.	3	4	2	3	12
		Green	4	4	1	3	12
Methanol	Mechanical propulsion	Grey	1	5	4	5	15
		Bio	3	5	4	5	17
		E	4	5	4	5	18
	Electric propulsion	Grey	1	5	4	5	15
		Bio	3	5	4	5	17
		E	4	5	4	5	18
	Electric propulsion + battery	Grey	1	5	4	5	15
		Bio	3	5	4	5	17
		E	4	5	4	5	18
LNG	Mechanical propulsion	Grey	1	5	4	4	14
		Bio	3	5	4	4	16
		E	4	5	5	5	19
	Electric propulsion	Grey	1	5	4	4	14
		Bio	3	5	4	4	16
		E	4	5	5	5	19
	Electric propulsion + battery	Grey	1	5	4	4	14
		Bio	3	5	4	4	16
		E	4	5	5	5	19
Electricity	Battery	Grey	4	5	5	5	19
		Blue	5	5	5	5	20

	Green	5	5	5	5	20

2.5. Economic Impact

The preliminary economic assessment aims to identify the financial benefit for each case. The results of the cost analysis rely heavily on the reference data, which are based on commercial prices, market-based research, and academic studies. The most reliable data are selected from the various data collected from numerous studies and research works. Since this study is based on a realistic scenario in the UK, the USD ($) and EUR (€) cost from research are converted into GBP (£) using an exchange rate of GBP 1 = USD 1.21, and GBP 1 = EUR 1.14, which were exchange rates in early January 2023 [8,9]. The lifetime of the case ship is set to 20 years with 8736 h per annum based on a 14-day voyage.

CapEx includes the installation cost of machinery and equipment, with costs varying for fuel tanks (GBP/kg) and machinery (GBP/kW), as shown in Figure 3. Less mature technologies like hydrogen tanks and fuel cells have significant cost variations, while ICE is stable with diesel but differs for alternative fuels. Batteries require replacement every 35,000 h, and fuel cells every six years, leading to four and two replacements, respectively, over the vessel’s lifespan. Mechanical propulsion connects the propeller directly to the engine, while electric propulsion uses an electric motor and gearbox. Figure 3 represents the variation in CapEx based on various data.

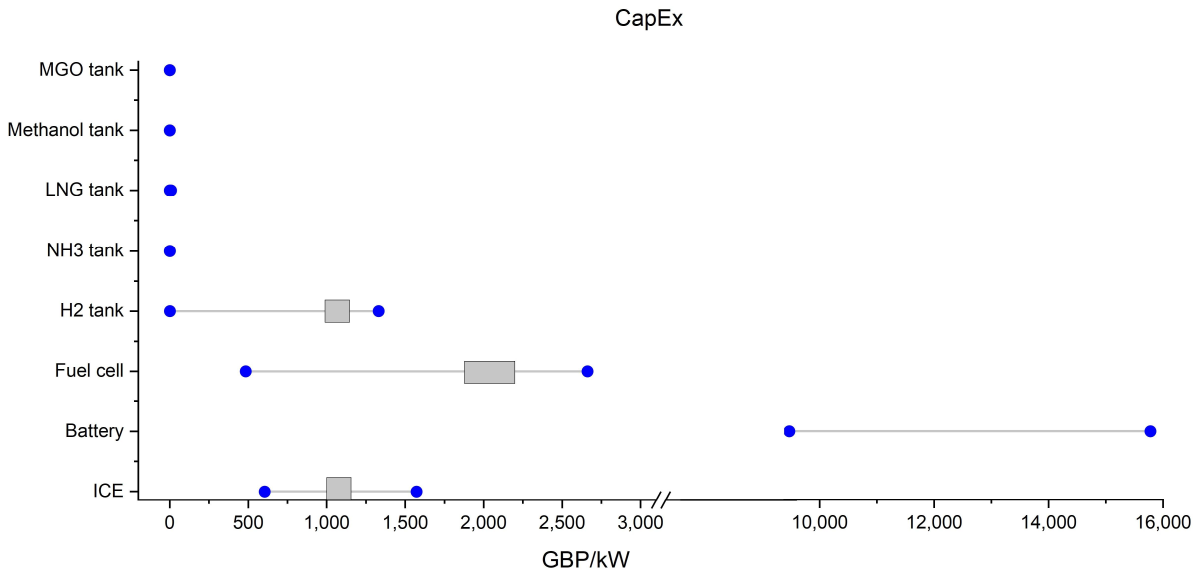


Figure 3. The variation in CapEx data [44–56].

Figure 4 shows the OpEx factors, which include operation and maintenance costs. While some studies include fuel price in OpEx, this study treats it separately due to its high variability and influence on life-cycle cost. Marine fuel options are diversifying due to emissions regulations. Although OpEx is lower than CapEx, it incurs yearly costs until a ship’s retirement. Most equipment requires maintenance, except for diesel and methanol storage systems, which need no special treatment.

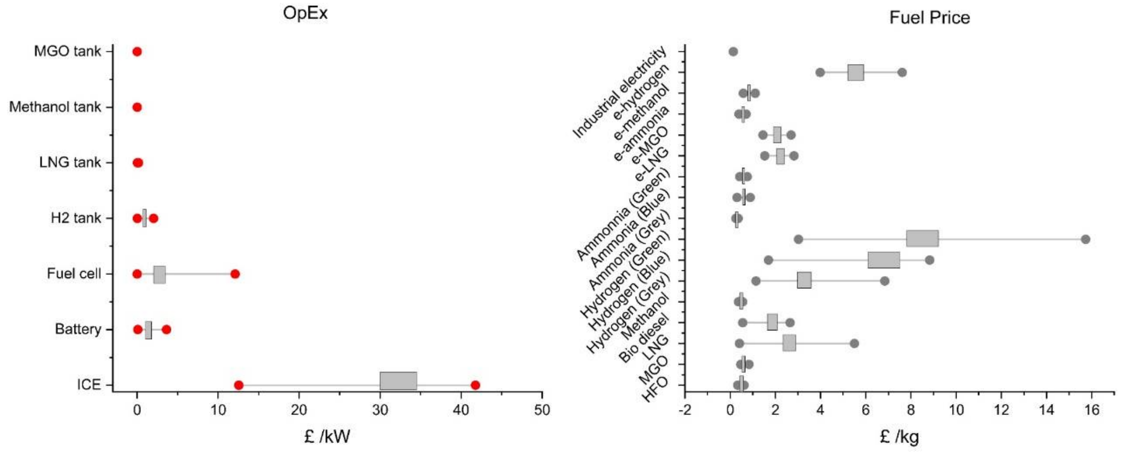


Figure 4. The variation in OpEx data and fuel costs [44–68].

Based on the operation scenario and collected data matrix, the cost analysis is calculated. The major goal of this cost assessment is to identify the cost capacity of each case in CapEx, OpEx, and fuel cost from a general economic perspective. Individual figures are rated from 5 (favourable performance) to 1 (unfavourable performance) for each CapEx, OpEx, and fuel cost. The rating capacity depends on the distribution of figures.

Table 12 shows the distribution of CapEx, OpEx, and fuel cost, as well as the range of rating figures. In the preliminary stage, the rating numbers indicate quantitative analysis for each factor per system and fuel. To organise this information, Table 13 was created, as shown below.

Table 12. Rating number capacity (economic assessment).

Rating Number	CapEx Capacity (k£)	OpEx Capacity (k£)	Fuel Cost Capacity (k£)
5	~15,000	~3000	~20,000
4	15,000~30,000	3000~4000	20,000~30,000
3	30,000~60,000	4000~5000	30,000~40,000
2	60,000~120,000	5000~6000	40,000~50,000
1	120,000~	6000~	50,000~

Table 13. Rating numbers for economic assessment.

Fuel	Case	Fuel Type	Cost Rating			
			CapEx	OpEx	Fuel Cost	Sum
Ammonia	Mechanical propulsion	Grey	5	5	5	15
		Blue	5	5	3	13
		Green	5	5	2	12
	Electric propulsion	Grey	5	4	5	14
		Blue	5	4	3	12
		Green	5	4	2	11
	Electric propulsion + battery	Grey	3	2	5	10
		Blue	3	2	3	8
		Green	3	2	3	8
	Fuel cell (PEMFC) + battery	Grey	2	1	5	8
		Blue	2	1	3	6
		Green	2	1	4	7
Hydrogen	Fuel cell (PEMFC) + battery	Grey	2	1	5	8
		Blue	2	1	2	5

		Green	2	1	2	5
Biodiesel	Mechanical propulsion	1st gen.	5	5	2	12
		2nd gen.	5	5	1	11
		Green	5	5	1	11
	Electric propulsion	1st gen.	5	5	2	12
		2nd gen.	5	5	1	11
		Green	5	5	1	11
	Electric propulsion + battery	1st gen.	4	3	3	10
		2nd gen.	4	3	2	9
		Green	4	3	2	9
Methanol	Mechanical propulsion	Grey	5	5	4	14
		Blue ¹⁾	5	5	2	12
		Green ²⁾	5	5	2	12
	Electric propulsion	Grey	5	5	4	14
		Blue	5	5	2	12
		Green	5	5	2	12
	Electric propulsion + battery	Grey	4	3	4	11
		Blue	4	3	3	10
		Green	4	3	3	10
LNG	Mechanical propulsion	Grey	5	4	1	10
		Blue ³⁾	5	4	3	12
		Green ⁴⁾	5	4	2	11
	Electric propulsion	Grey	5	3	1	9
		Blue	5	3	3	11
		Green	5	3	2	10
	Electric propulsion + battery	Grey	3	1	1	5
		Blue	3	1	4	8
		Green	3	1	3	7
Electricity	Battery	Grey	1	5	5	11
		Blue	1	5	5	11
		Green	1	5	5	11

Note: 1) Bio-methanol fuel cost is considered as blue methanol fuel cost; 2) E-methanol fuel cost is considered as green methanol fuel cost; 3) bio-LNG fuel cost is considered as blue LNG fuel cost; 4) E-methanol fuel cost is considered as green LNG fuel cost.

Table 13 presents a quantitative analysis of the economic benefit, where higher values indicate better economic performance. Fuel cell systems using hydrogen and ammonia rank lowest in both CapEx and OpEx. ICE remains economically viable for both mechanical and electric propulsion. However, the ICE–battery hybrid ranks lower than single-use ICE or battery systems. Alternative fuels like ammonia and methanol show strong economic value across most systems.

2.6. Safety Impact

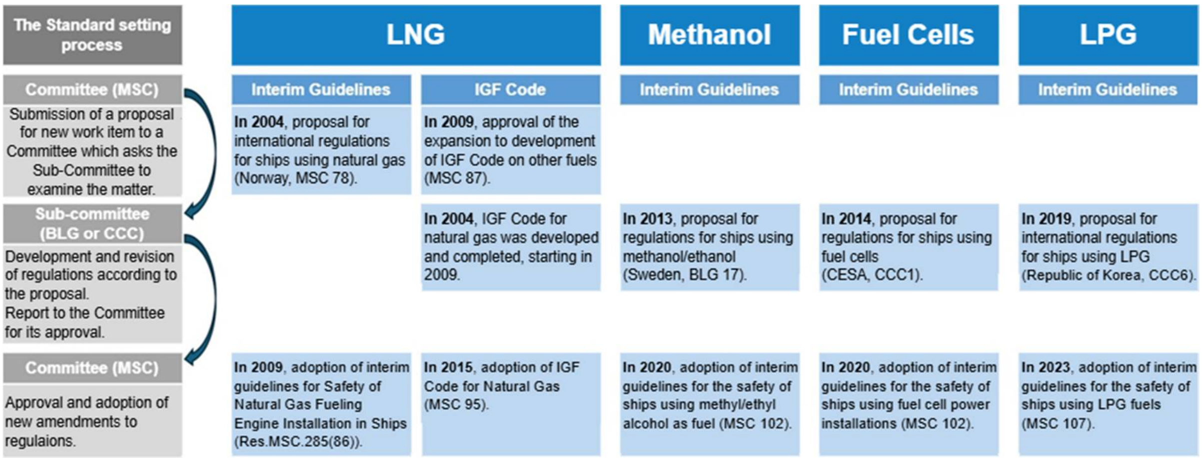
In this section, an analysis of fuel characteristics, which serve as a critical parameter in terms of safety, and a review of the safety regulations and guidelines for potential alternative fuels are conducted to impart a comprehensive understanding of the safety assessment of various fuel options. A number of crucial inherent characteristics of alternative fuels, including electricity, have a direct impact on the safe application of these fuels onboard. The analysis of these aspects is critical in understanding the safe utilisation of alternative fuels in the maritime environment.

Table 14 presents an overview of the fuel characteristics of relevant fuels.

Table 14. Fuel characteristics regarding safety [19,69].

Property	**Ammonia**	**Hydrogen**	**Biodiesel**	**Methanol**	**LNG (Methane)**
Chemical formula	NH_3	H_2	$RCOOCH_3$	CH_3OH	CH_4
Toxicity	Highly toxic	Not toxic	Not toxic	Low acute toxicity	Not toxic
TWA [ppm]	25	-	-	200	-
STEL [ppm]	35	-	-	250	-
Flammability limits (% by volume)	15–28	4.1–74	0.6–7.5	7.3–36	5.3–15
Flashpoint (°C)	132	Not defined	>61	12	−188
Autoignition temperature (°C)	630	500	204	470	537
Physical properties for storage	Liquid at −33 °C	Compressed gas at >250 bar or liquid at −253 °C	Liquid	Liquid (up to 65 °C)	Liquid at −162 °C
Lower heating value (MJ/kg)	18.6	119.93	42.7	19.93	50.02

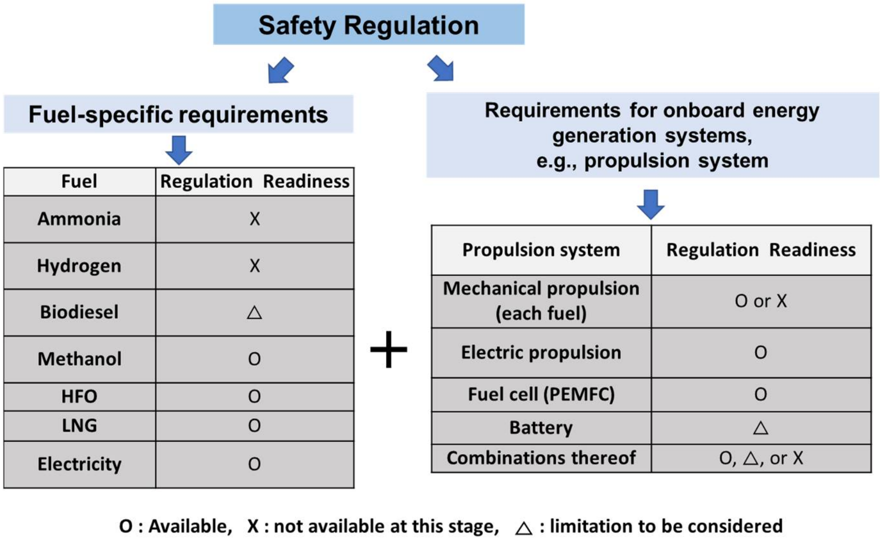
Safety regulations for alternative fuels are developed after the technology reaches technical maturity. Over the past decade, the IMO has established regulations to mitigate risks for marine fuels. Interim guidelines for methanol, ethanol, fuel cells, and LPG have been introduced based on limited operational experience, as seen in Figure 5. These guidelines are expected to be integrated into the IGF Code soon, with additional regulations applied for fuel cells depending on the fuel used.



The Standard setting process	LNG		Methanol	Fuel Cells	LPG
	Interim Guidelines	IGF Code	Interim Guidelines	Interim Guidelines	Interim Guidelines
Committee (MSC) Submission of a proposal for new work item to a Committee which asks the Sub-Committee to examine the matter.	**In 2004**, proposal for international regulations for ships using natural gas (Norway, MSC 78).	**In 2009**, approval of the expansion to development of IGF Code on other fuels (MSC 87).			
Sub-committee (BLG or CCC) Development and revision of regulations according to the proposal. Report to the Committee for its approval.		**In 2004**, IGF Code for natural gas was developed and completed, starting in 2009.	**In 2013**, proposal for regulations for ships using methanol/ethanol (Sweden, BLG 17).	**In 2014**, proposal for regulations for ships using fuel cells (CESA, CCC1).	**In 2019**, proposal for international regulations for ships using LPG (Republic of Korea, CCC6).
Committee (MSC) Approval and adoption of new amendments to regulaions.	**In 2009**, adoption of interim guidelines for Safety of Natural Gas Fueling Engine Installation in Ships (Res.MSC.285(86)).	**In 2015**, adoption of IGF Code for Natural Gas (MSC 95).	**In 2020**, adoption of interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel (MSC 102).	**In 2020**, adoption of interim guidelines for the safety of ships using fuel cell power installations (MSC 102).	**In 2023**, adoption of interim guidelines for the safety of ships using LPG fuels (MSC 107).

Figure 5. A brief overview of the formulation process in the IMO for IGF Code and interim guidelines.

The IMO has not yet focused on ship battery use, though this may change with new GHG targets. Development is mostly led by Flag States, such as through the UK's guidelines for lithium-ion batteries. Safety standards for ammonia, hydrogen, and batteries follow MSC.1/Circ.1455, which outlines alternative fuel approvals. The IGF Code requires a HAZID study during design to assess risks. Safety readiness for alternative fuels is evaluated based on two criteria: (a) fuel-specific requirements for handling and storage, and (b) onboard energy systems like propulsion, fuel cells, and batteries. Ships must comply with both, as shown in Figure 6.



Fuel	Regulation Readiness
Ammonia	X
Hydrogen	X
Biodiesel	△
Methanol	O
HFO	O
LNG	O
Electricity	O

Propulsion system	Regulation Readiness
Mechanical propulsion (each fuel)	O or X
Electric propulsion	O
Fuel cell (PEMFC)	O
Battery	△
Combinations thereof	O, △, or X

O : Available, X : not available at this stage, △ : limitation to be considered

Figure 6. Flow chart for evaluation of safety regulation readiness.

Safety regulations for mechanical and electrical propulsion systems for LNG, methanol, and HFO are available, but regulations for ammonia and hydrogen are still under development. Once fuel-specific requirements are established, mechanical propulsion regulations will apply through the IGF Code or interim guidelines. Electric propulsion systems are governed by SOLAS Chapter II-1, which covers electrical power generation. For lithium-ion batteries, this analysis assumes limited application based on UK regulations. Some biofuels have flashpoints between 52 °C and 60 °C, with IMO guidelines still in development, meaning full regulatory readiness is not yet achieved.

The evaluation of the potential risk posed by ship fuel necessitates a thorough examination of its physical properties and characteristics, including toxicity, corrosiveness, and flammability. Based on Table 15, the final rating numbers are indicated in Table 16.

Table 15. Rating numbers for fuel characteristics.

Rating Number	Toxicity (TWA ppm)	Corrosiveness	Flammability (Range of Flammability, ULF-LFL)
5	0–200	Too low	0–4
4	201–400	Low	5–8
3	400–600	Moderate	9–20
2	600–800	High	21–30
1	800–1000	Too high	30-

Table 16. Rating numbers for safety assessment.

Fuel	Case	Fuel Type	Safety Impact				
			Toxicity	Corrosiveness	Flammability	Rules and Regulations	Total
Ammonia	Mechanical propulsion	Grey	1	1	3	1	6
		Blue	1	1	3	1	6
		Green	1	1	3	1	6
	Electric propulsion	Grey	1	1	3	1	6
		Blue	1	1	3	1	6
		Green	1	1	3	1	6
	Electric propulsion + battery	Grey	1	1	3	1	6
		Blue	1	1	3	1	6

		Green	1	1	3	1	6
	Fuel cell (PEMFC) + battery	Grey	1	1	3	2	7
		Blue	1	1	3	2	7
		Green	1	1	3	2	7
Hydrogen	Fuel cell (PEMFC) + battery	Grey	5	4	1	2	12
		Blue	5	4	1	2	12
		Green	5	4	1	2	12
Biodiesel	Mechanical propulsion	1st gen.	5	1	4	4	14
		2nd gen.	5	1	4	4	14
		Green	5	1	4	4	14
	Electric propulsion	1st gen.	5	1	4	4	14
		2nd gen.	5	1	4	4	14
		Green	5	1	4	4	14
	Electric propulsion + battery	1st gen.	5	1	4	3	13
		2nd gen.	5	1	4	3	13
		Green	5	1	4	3	13
Methanol	Mechanical propulsion	Grey	1	1	2	4	8
		Bio	1	1	2	4	8
		E	1	1	2	4	8
	Electric propulsion	Grey	1	1	2	4	8
		Bio	1	1	2	4	8
		E	1	1	2	4	8
	Electric propulsion + battery	Grey	1	1	2	4	8
		Bio	1	1	2	4	8
		E	1	1	2	4	8
LNG	Mechanical propulsion	Grey	5	5	3	5	18
		Bio	5	5	3	5	18
		E	5	5	3	5	18
	Electric propulsion	Grey	5	5	3	5	18
		Bio	5	5	3	5	18
		E	5	5	3	5	18
	Electric propulsion + battery	Grey	5	5	3	4	17
		Bio	5	5	3	4	17
		E	5	5	3	4	17
Electricity	Battery	Grey	5	5	3	4	17
		Blue	5	5	3	4	17
		Green	5	5	3	4	17

2.7. Fuel Availability

Figure 7 illustrates the fuel production sites that are available in Scotland, but only inland locations are included. The availability of fuels based in Scotland is taken into account when scoring the matrix.

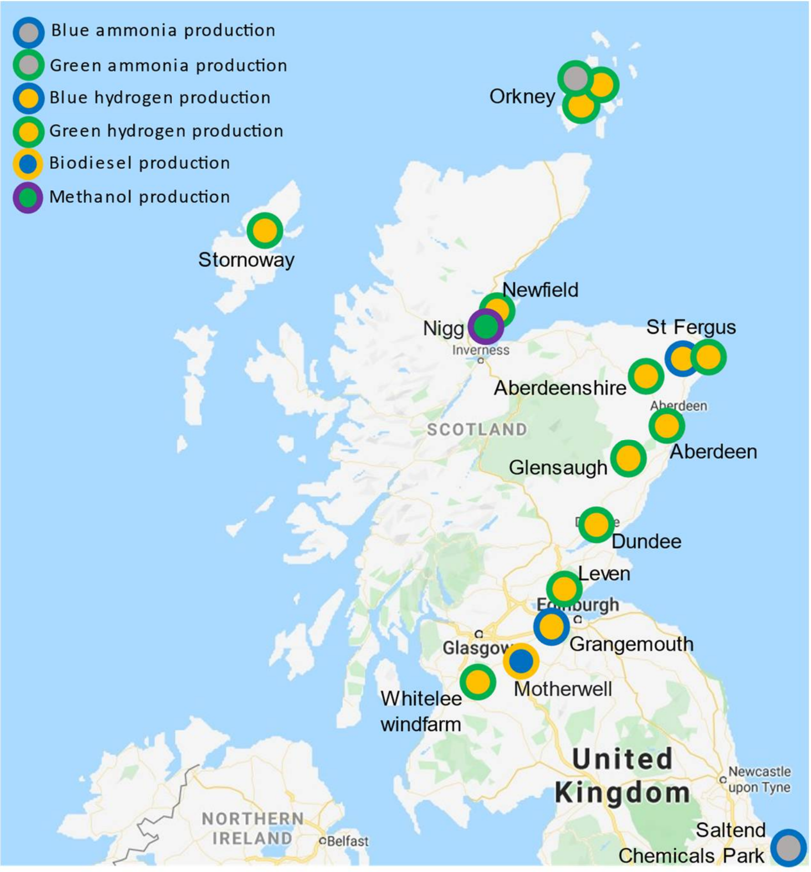


Figure 7. Fuel production sites in Scotland.

Ammonia is primarily produced from fossil fuels, but Scotland has green and blue hydrogen production sites, with more expected due to GHG reduction policies. While ammonia production infrastructure is sufficient, the lack of bunkering facilities remains a key barrier to its adoption in shipping.

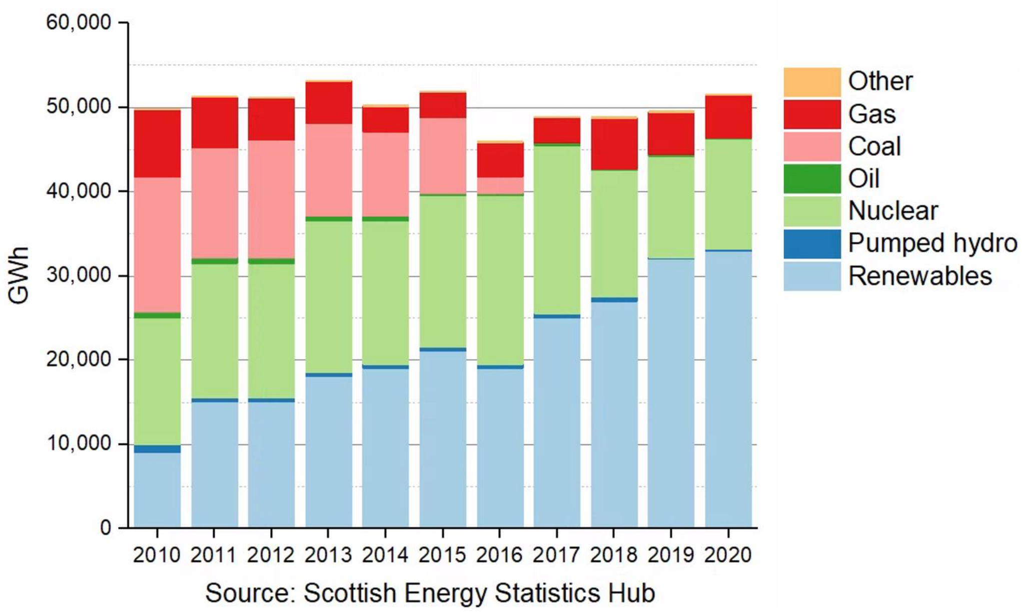
Hydrogen can be produced from various energy sources without major capacity limitations. Green hydrogen is essential to avoid GHG emissions from grey hydrogen production. While 95% of global hydrogen comes from fossil fuels, Scotland has significant green and blue hydrogen production capacity. However, the lack of bunkering infrastructure is a key challenge for using hydrogen as a future marine fuel.

Biodiesel has the advantage of being classified as a drop-in fuel and can be easily applied to ships. However, the current production capacity is very limited, especially rare in green biodiesel. On the other hand, bunkering infrastructure of conventional fuels can be shared considering the characteristics of these fuels.

Methanol is not yet a major marine fuel, so bunkering infrastructure is limited. However, building infrastructure for methanol is expected to be easier than for hydrogen or ammonia. With existing production infrastructure, methanol production can scale up easily as demand increases.

As the number of ships using LNG as fuel increases, LNG bunkering infrastructure is gradually being established around the world. However, the UK currently lacks the infrastructure for LNG bunkering, especially in Scotland, where there are no LNG ports, which poses challenges to fuel applications in terms of infrastructure. In addition, LNG production is not well settled in Scotland.

Onshore power supply infrastructure is well developed, but few ships use batteries as their main propulsion, and the energy density of electric power limits its application to sea-going vessels, resulting in limited charging infrastructure. Scotland, however, has ample green electricity production from renewables, generating more than half of its electricity this way, which also supports the production of green ammonia and hydrogen. As shown in Figure 8, more than half of total electricity is generated by renewable energy. Based on this, green ammonia and hydrogen can be produced in Scotland as well.



Source: Scottish Energy Statistics Hub

Figure 8. Electricity production by sources in Scotland.

Table 17 summarises the results of ratings associated with fuel availability in consideration of fuel types, infrastructure available, and production capacity for various propulsion systems.

Table 17. Rating numbers for fuel availability.

Fuel	Case	Fuel Type	Fuel Availability		
			Infrastructure (Bunkering)	Production Capacity	Total
Ammonia	Mechanical propulsion	Grey	2	4	6
		Blue	2	4	6
		Green	2	4	6
	Electric propulsion	Grey	2	4	6
		Blue	2	4	6
		Green	2	4	6
	Electric propulsion + battery	Grey	2	4	6
		Blue	2	4	6
		Green	2	4	6
	Fuel cell (PEMFC) + battery	Grey	2	4	6
		Blue	2	4	6
		Green	2	4	6
Hydrogen	Fuel cell (PEMFC) + battery	Grey	1	4	5
		Blue	1	4	5
		Green	1	4	5
Biodiesel	Mechanical propulsion	1st gen.	4	3	7
		2nd gen.	4	2	6
		Green	4	1	5
		1st gen.	4	3	7

	Electric propulsion	2nd gen.	4	2	6
		Green	4	1	5
	Electric propulsion + battery	1st gen.	4	3	7
		2nd gen.	4	2	6
		Green	4	1	5
Methanol	Mechanical propulsion	Grey	3	3	6
		Bio	3	3	6
		E	3	2	5
	Electric propulsion	Grey	3	3	6
		Bio	3	3	6
		E	3	2	5
	Electric propulsion + battery	Grey	3	3	6
		Bio	3	3	6
		E	3	2	5
LNG	Mechanical propulsion	Grey	3	3	6
		Bio	3	2	5
		E	3	1	4
	Electric propulsion	Grey	3	3	6
		Bio	3	2	5
		E	3	1	4
	Electric propulsion + battery	Grey	3	3	6
		Bio	3	2	5
		E	3	1	4
Electricity	Battery	Grey	2	4	6
		Blue	2	4	6
		Green	2	4	6

2.8. Matrix Analysis (Step 8)

The initial feasibility study aims to identify the most viable design options for the case ship. To evaluate feasibility, four criteria were examined in relation to ship design, technical assessment, and social assessment. While this is not a comprehensive list of criteria, the purpose of this research is to address the most significant issues that would affect the future development of the SOV.

2.8.1. Matrix Scoring

A decision matrix was developed to determine the best developmental options by gathering all the evaluation criteria and scores into one evaluation. This method has the advantage of being clear and can be easily modified if necessary. Each criterion is given a score from 1 to 5 based on either data or expert opinion. The scoring system for each attribute can be found in Table 18.

Table 18. Technical attributes applied to matrix.

No. of Attributes	Top Level	Second Level	Description	Scoring Justification
1.1	Technical impact	Fuel storage capacity	Size of fuel tank storage required onboard	Section 2.3
1.2		Technical maturity	Availability of the technology for the case ship in 2026	Section 2.3
2.1	Environmental impact	Life-cycle GHG	Well-to-wake greenhouse gas emission from fuels	Section 2.4
2.2		Life-cycle SOx	Well-to-wake SOx emission from fuels	
2.3		Life-cycle NOx	Well-to-wake NOx emission from fuels	
2.4		Life-cycle PM	Well-to-wake PM emission from fuels	
3.1	Economic impact	CAPEX	Capital cost of and initial investment in the technologies	Section 2.5
3.2		Maintenance cost	Lifetime operating/maintenance costs for the technologies	
3.3		Fuel cost	Lifetime fuel costs	
4.1	Safety impact	Toxicity	Risk to humans	Section 2.6
4.2		Corrosiveness	Risk to ship/structures	
4.3		Flammability	Risk of fire/explosion to humans/ship	
4.4		Rules and regulations	Availability of safety requirements from International Maritime Organization (IMO)	
5.1	Fuel availability	Infrastructure	Bunkering infrastructure/supply chain	Section 2.7
5.2		Production capability	Infrastructure of fuel production plant and its capacity for marine usage	

2.8.2. Weighting Factor

Weighting factors were applied in the matrix to prioritise and allocate relative importance to different attributes (both top and second levels). By assigning weights to different attributes, the project team could determine the overall importance of each option and make more informed decisions. This process would help the team to ensure the most viable design solutions for the case ship by taking into account all relevant factors in a way that aligns with their objectives and goals.

The weighting for each attribute was determined based on a professional survey conducted among the project partners. The details of the weighting values were reviewed and agreed on by the consortium based on the results of the survey. The linguistic evaluations were translated into weighting scores, as proposed in Table 19.

Table 19. Weighting scores for five linguistic scales.

Linguistic Scale	Weighting Score
Not important	20
Less important	40
Normal	60
Highly important	80
Extremely important	100

The weighting factors were proposed with the two different stages. The scores were then multiplied by their assigned weighting values to create weighting factors.

$$\text{Weighting factors for each sub-attribute} = \text{Top Score} \times \text{Second Score} \tag{1}$$

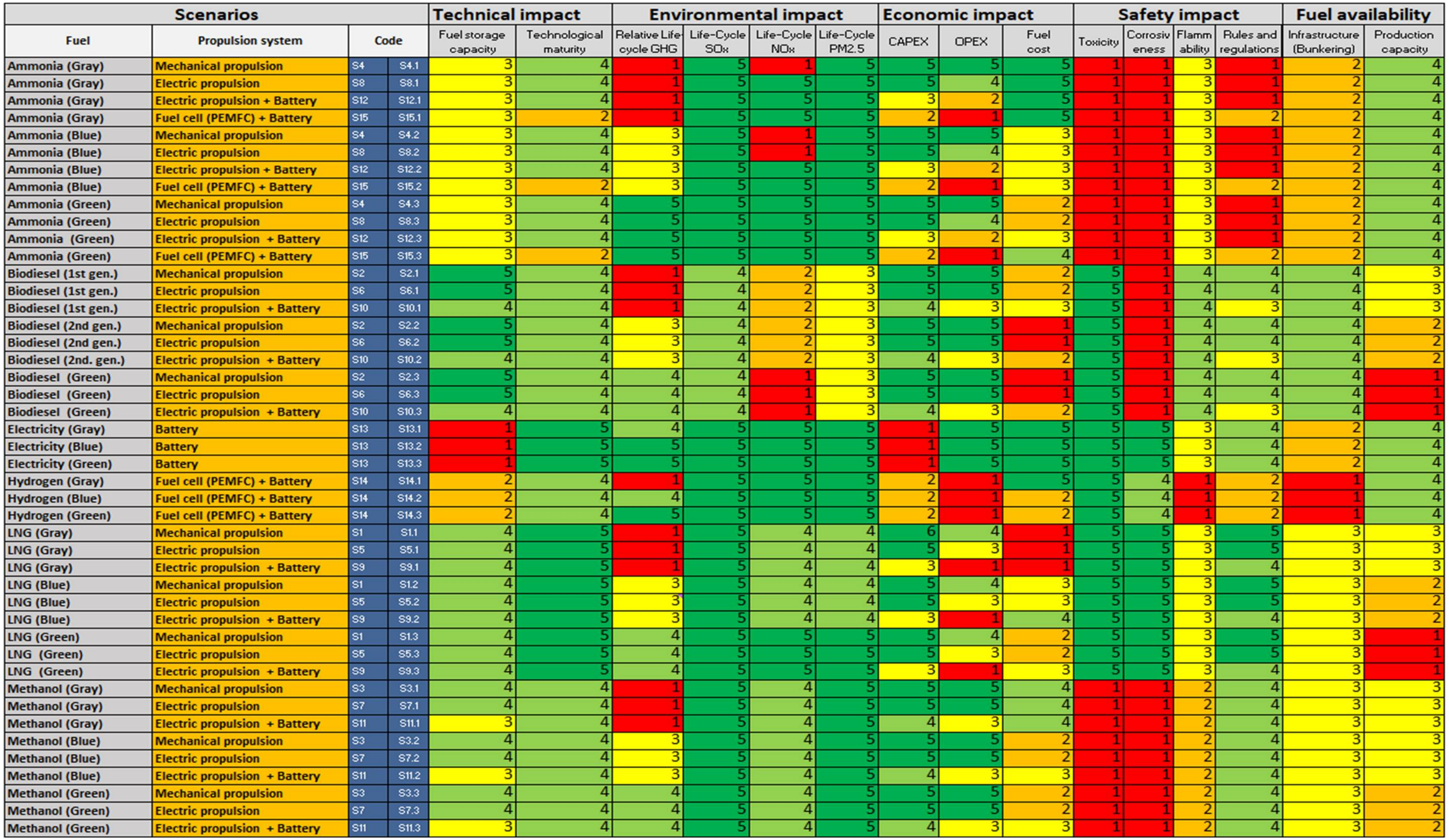
2.8.3. Results of Scoring

The responses were made by eight (8) persons, four from UoS and four from ORE Catapult. Table 20 shows the results of the linguistic assessment for the consortium members, which confirm the weighting factors for top and sub-attributes.

Based on that, the final 'Decision matrix' has been developed and provided in Figure 9.

Table 20. Weighting scores for attributes.

Top Attributes	Weighting	Sub-Attributes	Weighting	Overall Factor
Technical impact	0.70	Fuel storage capacity	0.83	0.58
		Technological maturity (availability)	0.68	0.47
Environmental impact	1.00	Life-cycle GHG	1.00	1.00
		Life-cycle SOx	0.60	0.60
		Life-cycle NOx	0.60	0.60
		Life-cycle PM2.5	0.55	0.55
Economic impact	0.70	CAPEX	0.73	0.51
		OPEX	0.73	0.51
		Fuel cost	0.80	0.56
Safety impact	0.88	Toxicity	0.88	0.77
		Corrosiveness	0.65	0.57
		Flammability	0.75	0.66
		Rules and regulations	0.70	0.61
Fuel availability	0.68	Infrastructure (bunkering)	0.78	0.52
		Production capacity	0.75	0.51



Scenarios				Technical impact		Environmental impact				Economic impact			Safety impact				Fuel availability	
Fuel	Propulsion system	Code		Fuel storage capacity	Technological maturity	Relative Life-cycle GHG	Life-Cycle SOx	Life-Cycle NOx	Life-Cycle PM2.5	CAPEX	OPEX	Fuel cost	Toxicity	Corrosiveness	Flammability	Rules and regulations	Infrastructure (Bunkering)	Production capacity
Ammonia (Gray)	Mechanical propulsion	S4	S4.1	3	4	1	5	1	5	5	5	5	1	1	3	1	2	4
Ammonia (Gray)	Electric propulsion	S8	S8.1	3	4	1	5	5	5	5	4	5	1	1	3	1	2	4
Ammonia (Gray)	Electric propulsion + Battery	S12	S12.1	3	4	1	5	5	5	3	2	5	1	1	3	1	2	4
Ammonia (Gray)	Fuel cell (PEMFC) + Battery	S15	S15.1	3	2	1	5	5	5	2	1	5	1	1	3	2	2	4
Ammonia (Blue)	Mechanical propulsion	S4	S4.2	3	4	3	5	1	5	5	5	3	1	1	3	1	2	4
Ammonia (Blue)	Electric propulsion	S8	S8.2	3	4	3	5	1	5	5	4	3	1	1	3	1	2	4
Ammonia (Blue)	Electric propulsion + Battery	S12	S12.2	3	4	3	5	5	5	3	2	3	1	1	3	1	2	4
Ammonia (Blue)	Fuel cell (PEMFC) + Battery	S15	S15.2	3	2	3	5	5	5	2	1	3	1	1	3	2	2	4
Ammonia (Green)	Mechanical propulsion	S4	S4.3	3	4	5	5	5	5	5	5	2	1	1	3	1	2	4
Ammonia (Green)	Electric propulsion	S8	S8.3	3	4	5	5	5	5	5	4	2	1	1	3	1	2	4
Ammonia (Green)	Electric propulsion + Battery	S12	S12.3	3	4	5	5	5	5	3	2	3	1	1	3	1	2	4
Ammonia (Green)	Fuel cell (PEMFC) + Battery	S15	S15.3	3	2	5	5	5	5	2	1	4	1	1	3	2	2	4
Biodiesel (1st gen.)	Mechanical propulsion	S2	S2.1	5	4	1	4	2	3	5	5	2	5	1	4	4	4	3
Biodiesel (1st gen.)	Electric propulsion	S6	S6.1	5	4	1	4	2	3	5	5	2	5	1	4	4	4	3
Biodiesel (1st gen.)	Electric propulsion + Battery	S10	S10.1	4	4	1	4	2	3	4	3	3	5	1	4	3	4	3
Biodiesel (2nd gen.)	Mechanical propulsion	S2	S2.2	5	4	3	4	2	3	5	5	1	5	1	4	4	4	2
Biodiesel (2nd gen.)	Electric propulsion	S6	S6.2	5	4	3	4	2	3	5	5	1	5	1	4	4	4	2
Biodiesel (2nd. gen.)	Electric propulsion + Battery	S10	S10.2	4	4	3	4	2	3	4	3	2	5	1	4	3	4	2
Biodiesel (Green)	Mechanical propulsion	S2	S2.3	5	4	4	4	1	3	5	5	1	5	1	4	4	4	1
Biodiesel (Green)	Electric propulsion	S6	S6.3	5	4	4	4	1	3	5	5	1	5	1	4	4	4	1
Biodiesel (Green)	Electric propulsion + Battery	S10	S10.3	4	4	4	4	1	3	4	3	2	5	1	4	3	4	1
Electricity (Gray)	Battery	S13	S13.1	1	5	4	5	5	5	1	5	5	5	5	3	4	2	4
Electricity (Blue)	Battery	S13	S13.2	1	5	5	5	5	5	1	5	5	5	5	3	4	2	4
Electricity (Green)	Battery	S13	S13.3	1	5	5	5	5	5	1	5	5	5	5	3	4	2	4
Hydrogen (Gray)	Fuel cell (PEMFC) + Battery	S14	S14.1	2	4	1	5	5	5	2	1	5	5	4	1	2	1	4
Hydrogen (Blue)	Fuel cell (PEMFC) + Battery	S14	S14.2	2	4	4	5	5	5	2	1	2	5	4	1	2	1	4
Hydrogen (Green)	Fuel cell (PEMFC) + Battery	S14	S14.3	2	4	5	5	5	5	2	1	2	5	4	1	2	1	4
LNG (Gray)	Mechanical propulsion	S1	S1.1	4	5	1	5	4	4	6	4	1	5	5	3	5	3	3
LNG (Gray)	Electric propulsion	S5	S5.1	4	5	1	5	4	4	5	3	1	5	5	3	5	3	3
LNG (Gray)	Electric propulsion + Battery	S9	S9.1	4	5	1	5	4	4	3	1	1	5	5	3	4	3	3
LNG (Blue)	Mechanical propulsion	S1	S1.2	4	5	3	5	4	4	5	4	3	5	5	3	5	3	2
LNG (Blue)	Electric propulsion	S5	S5.2	4	5	3	5	4	4	5	3	3	5	5	3	5	3	2
LNG (Blue)	Electric propulsion + Battery	S9	S9.2	4	5	3	5	4	4	3	1	4	5	5	3	4	3	2
LNG (Green)	Mechanical propulsion	S1	S1.3	4	5	4	5	5	5	5	4	2	5	5	3	5	3	1
LNG (Green)	Electric propulsion	S5	S5.3	4	5	4	5	5	5	5	3	2	5	5	3	5	3	1
LNG (Green)	Electric propulsion + Battery	S9	S9.3	4	5	4	5	5	5	3	1	3	5	5	3	4	3	1
Methanol (Gray)	Mechanical propulsion	S3	S3.1	4	4	1	5	4	5	5	5	4	1	1	2	4	3	3
Methanol (Gray)	Electric propulsion	S7	S7.1	4	4	1	5	4	5	5	5	4	1	1	2	4	3	3
Methanol (Gray)	Electric propulsion + Battery	S11	S11.1	3	4	1	5	4	5	4	3	4	1	1	2	4	3	3
Methanol (Blue)	Mechanical propulsion	S3	S3.2	4	4	3	5	4	5	5	5	2	1	1	2	4	3	3
Methanol (Blue)	Electric propulsion	S7	S7.2	4	4	3	5	4	5	5	5	2	1	1	2	4	3	3
Methanol (Blue)	Electric propulsion + Battery	S11	S11.2	3	4	3	5	4	5	4	3	3	1	1	2	4	3	3
Methanol (Green)	Mechanical propulsion	S3	S3.3	4	4	4	5	4	5	5	5	2	1	1	2	4	3	2
Methanol (Green)	Electric propulsion	S7	S7.3	4	4	4	5	4	5	5	5	2	1	1	2	4	3	2
Methanol (Green)	Electric propulsion + Battery	S11	S11.3	3	4	4	5	4	5	4	3	3	1	1	2	4	3	2

Figure 9. Decision matrix

The design scenarios are ranked in order from the highest weighted score to the lowest, as given in Figure 10.

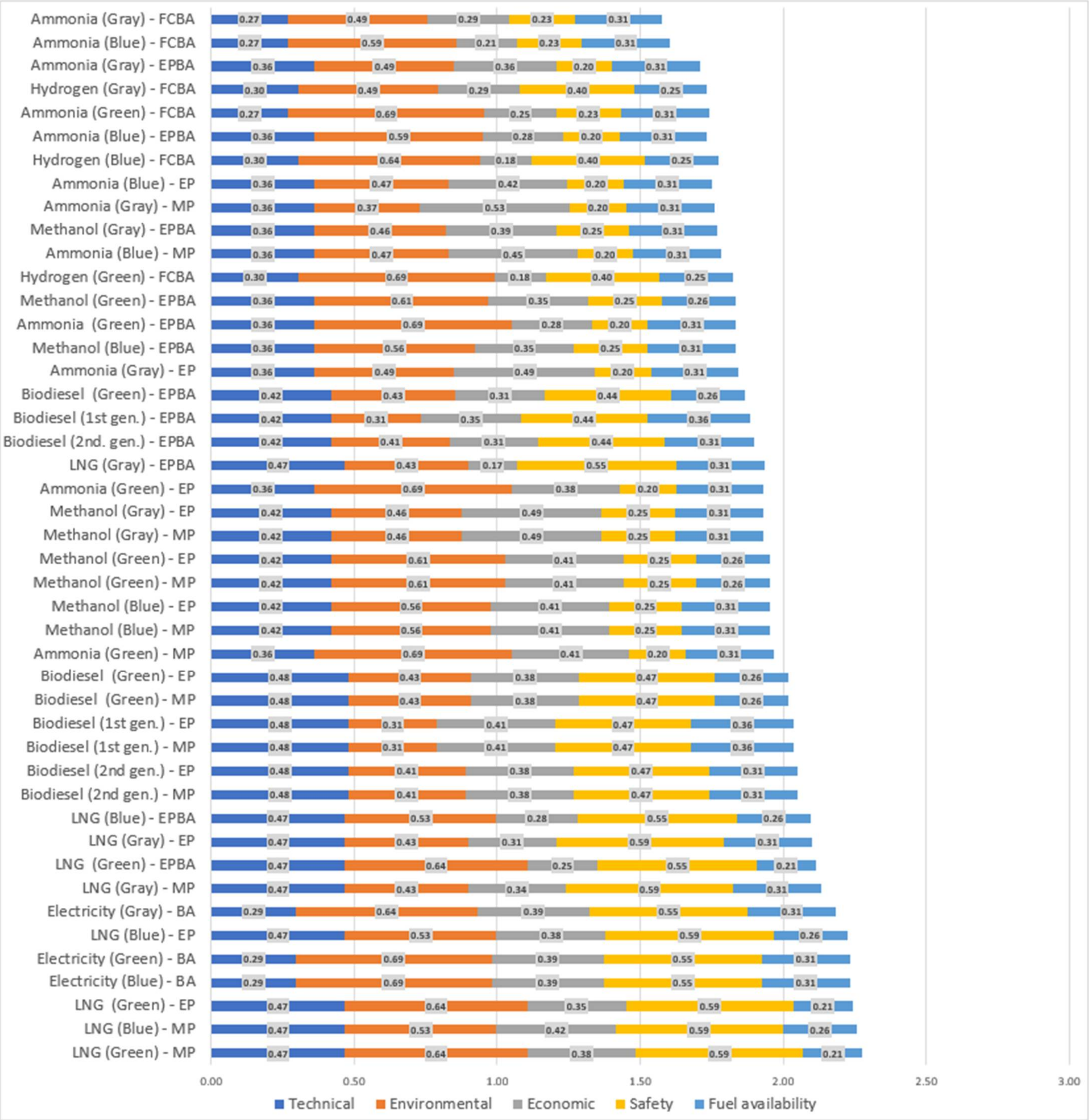


Figure 10. Results with weighting factors (higher is greater). Note: MP—mechanical propulsion; EP—electric propulsion; EPBA—electric propulsion + battery; BA—battery; FCBA—fuel cell + battery.

The results of the preliminary assessment using the decision matrix show that the use of LNG is the most viable solution overall, having obtained relatively higher scores in environmental and safety impacts. For environmental impact, green LNG is considered as a carbon-neutral fuel, and its life-cycle SOx NOx, and $PM_{2.5}$ emissions are close to zero. In terms of safety impact, safety regulations for using LNG are fully developed, and its safety records with LNG carriers and LNG-fuelled ships have been excellent over several decades.

On the other hand, there are still questions regarding the use of LNG for the case ship, particularly in terms of fuel availability in a green form and bunkering infrastructure. In particular, the Scottish Government has affirmed its strong ambition to reduce GHG emissions from national shipping by 75% by 2030 and 100% by 2045. To meet this target, the use of LNG (especially in a grey or blue form) may not be the ideal option [70].

The second viable option could be battery-powered technology using on/offshore electricity. This has shown excellence in terms of environmental impact as well as safety impact. The technical maturity of batteries for marine usages is still in its early stage, and the economic impact of this option is also relatively higher than that of other options. Therefore, the application of full battery-powered technology for the case ship may not be an ideal option due to its technical immaturity and high costs. During the conceptual design, the technical availability of the full battery power systems will be thoroughly reviewed, and if necessary, hybrid concepts can also be considered to enhance viability more realistically.

The third viable option involves biodiesel (green), which can possibly be a carbon-neutral fuel. A key advantage of using biodiesel can be found in its technical maturity. Diesel technology onboard has proven useful over multiple decades, and biodiesel can be immediately used with existing diesel ICEs. On the other hand, it should be noted that green biofuels are limited in terms of their production, and their use is highly prioritised in other transport sectors: road and aviation. According to the UK Government, biodiesel is not recommended to be utilised in shipping.

Overall, based on the initial assessment results, it is highly recommended that a second-round decision-making process be conducted in the form of a case-specific analysis of the case ship and Scotland’s current and future strategies on shipping decarbonisation. The results of the second-round decision-making process will finally be confirmed for the conceptual design.

3. Discussion

This paper presents a timely and comprehensive analysis of alternative marine fuels with a specific focus on their application to offshore supply vessels (SOVs). While numerous studies have explored decarbonisation pathways for the maritime sector, the novelty of this work lies in its detailed comparative evaluation of four key fuel options: liquefied natural gas (LNG), hydrogen, ammonia, and biofuels. By concentrating on SOVs, a crucial but under-researched segment of the maritime industry, this paper addresses a critical gap in the existing literature, which has predominantly focused on larger vessels such as tankers and container ships.

One of the core contributions of this study is its multi-dimensional approach to fuel feasibility, which incorporates not only the environmental benefits of each fuel but also operational, safety, and infrastructure considerations. While previous studies have tended to focus on either the environmental performance of alternative fuels or their technical viability, this paper integrates these aspects with a pragmatic analysis of the real-world challenges associated with fuel adoption. It evaluates the trade-offs between reducing greenhouse gas emissions, fuel availability, infrastructure readiness, and safety concerns, thus offering a more holistic view of decarbonisation for SOVs.

In particular, this paper’s findings regarding LNG as a short- to medium-term solution are a key original contribution. While LNG is widely discussed as a transitional fuel for the maritime industry, this study provides a focused assessment of its application to SOVs, highlighting not only its benefits in terms of lower carbon content but also the challenges posed by methane slip. By addressing this duality, this paper adds a layer of critical analysis to the debate on LNG’s role in maritime decarbonisation, emphasising the need for more long-term solutions such as hydrogen and ammonia.

Another original aspect of this research is its in-depth evaluation of hydrogen and ammonia as long-term alternative fuels. While hydrogen and ammonia are often mentioned in the context of future zero-carbon shipping, this paper provides a detailed assessment of their specific advantages and limitations when applied to SOVs. The identification of ammonia as a particularly promising fuel, due to its high energy density and zero-carbon emissions at the point of use, offers valuable insights for the industry. However, this paper also acknowledges the significant safety and regulatory hurdles that need to be overcome before ammonia can be widely adopted, contributing a balanced perspective to the ongoing discussion.

Furthermore, this paper introduces an innovative analysis of propulsion systems, including hybrid configurations that combine LNG engines with battery storage. This exploration of hybrid systems, alongside fully electric propulsion and renewable energy integration, is particularly novel in the context of SOVs. While electrification has been extensively studied for other vessel types, its application to SOVs presents unique challenges, especially regarding battery energy density and offshore charging infrastructure. This study's focus on hybrid solutions as a bridge to full electrification provides a fresh perspective on how the SOV sector can gradually transition to zero-carbon operations.

In terms of economic contributions, this paper's analysis of the cost implications of adopting low- and zero-carbon fuels for SOVs is another original element. By considering not only the immediate fuel costs but also the long-term investments required for retrofitting and infrastructure development, this study offers a more realistic outlook on the financial challenges facing the sector. This economic analysis, coupled with discussions on regulatory incentives and carbon pricing, highlights the importance of policy frameworks in enabling the transition to alternative fuels.

The novelty of this research lies in several key findings that contribute new insights to the field of alternative marine fuels, specifically for offshore supply vessels (SOVs). First, this study provides a focused analysis of various alternative fuels—LNG, hydrogen, ammonia, and biofuels—tailored to the operational requirements of SOVs. This vessel-specific approach is relatively unexplored, offering new perspectives on how these fuels perform under conditions unique to SOVs, such as range, refuelling, and safety.

A key result is the identification of LNG as the most viable short- to medium-term solution for reducing GHG emissions in the SOV sector. While green LNG has been discussed in previous research, this study positions it as a practical transitional fuel until more advanced technologies, such as hydrogen and ammonia, can be widely adopted. This strategic framework for managing the fuel transition process provides fresh insight into how the maritime industry can balance immediate emission reductions with long-term decarbonisation goals.

Additionally, this research expands on the integration of hybrid and fully electric propulsion systems, assessing the feasibility of combining these systems with alternative fuels. The consideration of advancements in battery technology and renewable energy sources introduces a more comprehensive approach to decarbonisation, particularly for SOVs.

Finally, this paper emphasises the infrastructural challenges associated with large-scale adoption of alternative fuels, particularly hydrogen and ammonia. By identifying these challenges and advocating for coordinated industry and regulatory efforts, this study contributes valuable knowledge on the practical steps required to achieve long-term decarbonisation.

In conclusion, this paper makes several original contributions to the field of maritime decarbonisation, particularly through its focus on SOVs, its multi-faceted evaluation of alternative fuels, and its novel analysis of hybrid propulsion systems. The findings offer valuable guidance for both industry stakeholders and policymakers as they navigate the complex challenges of transitioning to a low-carbon future in the offshore supply vessel sector.

At a conceptual level, this paper has considered factors such as spatial constraints, refuelling intervals in relation to bunkering infrastructure, and the operational profile.

Nevertheless, it is worth mentioning that further investigation is needed at the detailed design stages to fully consider ship-specific restrictions such as space restrictions for fuel tanks, refuelling periods, and limitations of battery usage such as volume, weight, charging time, etc.

4. Conclusions

This paper conducted a comprehensive analysis of alternative fuels and propulsion technologies for offshore supply vessels (SOVs), focusing on LNG, hydrogen, ammonia, biofuels, and hybrid systems. Based on the findings, several key conclusions can be drawn:

(1) LNG as a Transitional Fuel: The analysis reveals that LNG provides the most feasible short- to medium-term solution for SOVs, with the potential to reduce greenhouse gas (GHG) emissions by approximately 20–25% compared to marine diesel oil (MDO) and heavy fuel oil (HFO). In addition to its lower carbon footprint, LNG infrastructure is relatively well developed, making it a viable near-term option for decarbonisation in the SOV sector.

(2) Hydrogen and Ammonia for Long-term Decarbonisation: Hydrogen and ammonia have been identified as promising long-term alternatives, with the potential for zero-carbon emissions when produced using renewable energy. However, their widespread adoption faces significant challenges, particularly in terms of storage, handling safety, and the need for new infrastructure. For SOVs, hydrogen and ammonia could reduce CO_2 emissions by up to 100%, but only if these challenges are addressed.

(3) Hybrid Propulsion Systems: The integration of hybrid propulsion systems, combining alternative fuels with electric or battery-based propulsion, was found to offer enhanced operational flexibility and fuel efficiency. In particular, hybrid systems could reduce fuel consumption by up to 15%, depending on operational profiles. Battery technology improvements also make full-electric operation increasingly viable for short-distance and low-power applications.

(4) Infrastructure and Regulatory Needs: The adoption of hydrogen and ammonia for SOVs will require substantial investment in bunkering infrastructure and safety regulations. As such, these fuels are recommended as long-term solutions, while LNG and hybrid systems serve as more immediate alternatives for reducing emissions in the near future.

In conclusion, this study underscores the importance of a phased approach to fuel transition in the SOV sector. LNG can offer immediate reductions in GHG emissions, while hydrogen, ammonia, and hybrid systems hold the potential to meet long-term decarbonisation goals, provided that technological and infrastructural barriers are addressed.

Author Contributions: Conceptualization, Park, C. and Jeong, B.; methodology, Park, C. and Jeong, B.; software, Hwang, I. and Jang, H.; validation, Ha, S., Kim, J. and Jee, J.; formal analysis, Hwang, I.; investigation, Park, C., Hwang, I. and Jang, H.; resources, Jeong, B.; data curation, Ha, S. and Jee, J.; writing—original draft preparation, Park, C. and Jang, H.; writing—review and editing, Hwang, I. and Jeong, B.; visualization, Park, C. and Jang, H.; supervision, Hwang, I. and Jeong, B.; project administration, Ha, S. and Kim, J.; funding acquisition, Jee, J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by Korea Institute of Marine Science & Technology Promotion (KIMST) funded by the Ministry of Oceans and Fisheries (RS-2023-00256331).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding authors.

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

References

1. Usiagu, G.S.; Adekoya, O.O.; Okoli, C.E.; Daudu, C.D.; Ekemezie, I.O.; Ayorinde, O.B. LNG as a Bridge Fuel in the Transition to Renewable Energy: A Global Perspective. *World J. Adv. Res. Rev.* **2024**, *21*, 742–749.
2. Zarrinkolah, M.T.; Hosseini, V.J.F. Methane Slip Reduction of Conventional Dual-Fuel Natural Gas Diesel Engine Using Direct Fuel Injection Management and Alternative Combustion Modes. *Fuel* **2023**, *331*, 125775.
3. Xing, H.; Stuart, C.; Spence, S.; Chen, H.J.J. Alternative Fuel Options for Low Carbon Maritime Transportation: Pathways to 2050. *J. Clean. Prod.* **2021**, *297*, 126651.
4. Fu, Z.; Lu, L.; Zhang, C.; Xu, Q.; Zhang, X.; Gao, Z.; Li, J.J.S.E.T. Fuel Cell and Hydrogen in Maritime Application: A Review on Aspects of Technology, Cost, and Regulations. *Sustain. Energy Technol. Assess.* **2023**, *57*, 103181.
5. Van Hoecke, L.; Laffineur, L.; Campe, R.; Perreault, P.; Verbruggen, S.W.; Lenaerts, S.J.E. Challenges in the Use of Hydrogen for Maritime Applications. *Energy Sci.* **2021**, *14*, 815–843.
6. Ishaq, H.; Crawford, C.J.E.C. Review and Evaluation of Sustainable Ammonia Production, Storage, and Utilization. *Energy Convers. Manag.* **2024**, *300*, 117869.
7. Al-Enazi, A.; Okonkwo, E.C.; Bicer, Y.; Al-Ansari, T.J.E.R. A Review of Cleaner Alternative Fuels for Maritime Transportation. *Energies* **2021**, *7*, 1962–1985.
8. Mondal, P.; Basu, M.; Balasubramanian, N.J.B. Direct Use of Vegetable Oil and Animal Fat as Alternative Fuel in Internal Combustion Engine. *Bioprod. Bioprocess.* **2008**, *2*, 155–174.
9. Santos, N.D.S.A.; Roso, V.R.; Malaquias, A.C.T.; Baeta, J.G.C. Internal Combustion Engines and Biofuels: Examining Why This Robust Combination Should Not Be Ignored for Future Sustainable Transportation. *Renew. Sustain. Energy Rev.* **2021**, *148*, 111292.
10. Foretich, A.; Zaimes, G.G.; Hawkins, T.R.; Newes, E.J. Challenges and Opportunities for Alternative Fuels in the Maritime Sector. *Marit. Transp. Res.* **2021**, *2*, 100033.
11. Lagouvardou, S.; Psaraftis, H.N.; Zis, T.J.S. A Literature Survey on Market-Based Measures for the Decarbonization of Shipping. *Sustainability* **2020**, *12*, 3953.
12. Strantzali, E.; Livanos, G.A.; Aravossis, K.J.E. A Comprehensive Multicriteria Evaluation Approach for Alternative Marine Fuels. *Energies* **2023**, *16*, 7498.
13. Hansson, J.; Månsson, S.; Brynolf, S.; Grahn, M.J.B. Alternative Marine Fuels: Prospects Based on Multi-Criteria Decision Analysis Involving Swedish Stakeholders. *Biomass Bioenergy* **2019**, *126*, 159–173.
14. Mandić, N.; Ukić Boljat, H.; Kekez, T.; Luttenberger, L.R.J.A.S. Multicriteria Analysis of Alternative Marine Fuels in Sustainable Coastal Marine Traffic. *Appl. Sci.* **2021**, *11*, 2600.
15. Andersson, K.; Brynolf, S.; Hansson, J.; Grahn, M.J.S. Criteria and Decision Support for a Sustainable Choice of Alternative Marine Fuels. *Sustainability* **2020**, *12*, 3623.
16. DNV. Maritime Forecast to 2050. 2022.
17. Hsieh, C.-W.C.; Fang, C. *Biofuels for the Marine Shipping Sector*; IEA Bioenergy: 2017.
18. Law, L.C.; Foscoli, B.; Mastorakos, E.; Evans, S. A Comparison of Alternative Fuels for Shipping in Terms of Lifecycle Energy and Cost. *Energies* **2021**, *14*, 8502.
19. Bureau Veritas (BV). Alternative Fuels Outlook for Shipping. 2022.
20. Goldmeer, J.; Buck, C.; Suleiman, B.; Selim, H.; Tayebi, K.; Agostinelli, G.-L.; Dawood, A. Techno-Economic Analysis of Hydrogen and Ammonia as Low Carbon Fuels for Power Generation. In *Turbo Expo: Power for Land, Sea, and Air*; American Society of Mechanical Engineers: New York, NY, USA, 2023.
21. Lee, S.; Kim, J.; Kim, K.; Hwang, H. Electrochemical Performance of Direct Ammonia Solid Oxide Fuel Cell. *Electrochem. Soc. Meet. Abstr.* **2023**, *243*, 215. https://doi.org/1010.1149/MA2023-0154215mtgabs.
22. Chalaris, I.; Jeong, B.; Jang, H. Application of Parametric Trend Life Cycle Assessment for Investigating the Carbon Footprint of Ammonia as Marine Fuel. *Int. J. Life Cycle Assess.* **2022**, *27*, 1145–1163.
23. Van Rheenen, E.; Padding, J.; Slootweg, J.; Visser, K. Hydrogen Carriers for Zero-Emission Ship Propulsion Using PEM Fuel Cells: An Evaluation. *J. Mar. Eng. Technol.* **2024**, *23*, 166–183.
24. Wang, H.; Aung, M.Z.; Xu, X.; Boulougouris, E. Life Cycle Analysis of Hydrogen Powered Marine Vessels—Case Ship Comparison Study with Conventional Power System. *Sustainability* **2023**, *15*, 12946.
25. Maniscalco, M.P.; Longo, S.; Cellura, M.; Miccichè, G.; Ferraro, M. Critical Review of Life Cycle Assessment of Hydrogen Production Pathways. *Environments* **2024**, *11*, 108.
26. Wu, D.; Gao, Z.; Wu, S.; Xiao, R. Negative Net Global Warming Potential Hydrogen Production Through Biomass Gasification Combined with Chemical Looping: Environmental and Economic Assessments. *Int. J. Hydrog. Energy* **2024**, *66*, 24–32.
27. Garcia-Vallejo, M.C.; Alzate, C.A.C. Sustainability of Hydrogen Production Considering Alternative Technologies Towards a Neutral Carbon Society. *Int. J. Hydrog. Energy* **2024**, *64*, 853–863.

28. Pande, S.; Gahane, S. Waste Cooking Oil to Biodiesel—A Review. In *The Production of Biodiesel and Related Fuel Additives*; Springer: Berlin/Heidelberg, Germany, 2024; pp. 308–339.
29. Pramanik, A.; Sinha, A.; Chaubey, K.K.; Hariharan, S.; Dayal, D.; Bachheti, R.K.; Bachheti, A.; Chandel, A.K. Second-Generation Bio-Fuels: Strategies for Employing Degraded Land for Climate Change Mitigation Meeting United Nations-Sustainable Development Goals. *Sustainability* **2023**, *15*, 7578.
30. Lin, C.-Y. The Influences of Promising Feedstock Variability on Advanced Biofuel Production: A Review. *J. Mar. Sci. Technol.* **2022**, *29*, 714–730.
31. Wang, W. Agricultural and Forestry Biomass for Meeting the Renewable Fuel Standard: Implications for Land Use and GHG Emissions. *Energies* **2022**, *15*, 8796.
32. Datta, D.; Ghosal, R.K.; Biswas, S.; Mandal, E.; Das, B. Biofuel Production: An Ecofriendly Way to Produce Sustainable Energy. *Emerging Sustainable Technologies for Biofuel Production*; Springer: Berlin/Heidelberg, Germany, 2024; pp. 67–99.
33. Parris, D.; Spinthiropoulos, K.; Panitsidis, K.; Tsanaktsidis, C. Transition to the New Green Maritime Era—Developing Hybrid Ecological Fuels Using Methanol and Biodiesel—An Experimental Procedure. *Eng* **2024**, *5*, 1863–1884.
34. Prakash, G.S.G. Long-Term Sustainability Through Carbon Dioxide Capture and Conversion: The Methanol Economy. In *Electrochemical Society Meeting Abstracts*; The Electrochemical Society, Inc.: Pennington, NJ, USA, 2024; Volume 245.
35. Chianese, L.; Meloni, E.; Vaiano, V.; Iervolino, G.; Palma, V. Environmental Challenges and Economical Assessment of Methanol's Production Feedstock. *Heliyon* **2024**, *in press*.
36. Jiang, P.; Li, L.; Zhao, G.; Zhang, H.; Ji, T.; Mu, L.; Lu, X.; Zhu, J. Seeking the Low-Carbon Route of Methanol Production with Sustainable Resources by Tracking Energy and Environment Indicators. *Ind. Eng. Chem. Res.* **2024**, *63*, 8261–8272.
37. Pavlenko, N.; Comer, B.; Zhou, Y.; Clark, N.; Rutherford, D. *The Climate Implications of Using LNG as a Marine Fuel*; Swedish Environmental Protection Agency: Stockholm, Sweden, 2020.
38. Balcombe, P.; Brierley, J.; Lewis, C.; Skatvedt, L.; Speirs, J.; Hawkes, A.; Staffell, I. How to Decarbonise International Shipping: Options for Fuels, Technologies and Policies. *Energy Convers. Manag.* **2019**, *182*, 72–88.
39. Jang, H.; Jeong, B.; Zhou, P.; Ha, S.; Nam, D. Demystifying the Lifecycle Environmental Benefits and Harms of LNG as Marine Fuel. *Appl. Energy* **2021**, *292*, 116869.
40. Pachauri, R.K.; Allen, M.R.; Barros, V.R.; Broome, J.; Cramer, W.; Christ, R.; Church, J.A.; Clarke, L.; Dahe, Q.; Dasgupta, P. *Climate Change 2014: Synthesis Report*; IPCC: Geneva, Switzerland, 2014.
41. IMO. Comprehensive Impact Assessment of Short-Term Measure Approved by MEPC 75—Full Report on the Impacts on the Fleet and on States (MEPC 76/INF.68/Add.1). 2021.
42. Bei, Z.; Wang, J.; Li, Y.; Wang, H.; Li, M.; Qian, F.; Xu, W. Challenges and Solutions of Ship Power System Electrification. *Energies* **2024**, *17*, 3311.
43. Zamboni, G.; Scamardella, F.; Gualeni, P.; Canepa, E. Comparative Analysis Among Different Alternative Fuels for Ship Propulsion in a Well-to-Wake Perspective. *Heliyon* **2024**, *10*, e26016.
44. Taljegard, M.; Brynolf, S.; Grahn, M.; Andersson, K.; Johnson, H. Cost-Effective Choices of Marine Fuels in a Carbon-Constrained World: Results from a Global Energy Model. *Environ. Sci. Technol.* **2014**, *48*, 12986–12993.
45. MWH. *Sustainable Energy Handbook*; MWH: Broomfield, CO, USA, 2016.
46. DNV GL—Maritime. *Assessment of Selected Alternative Fuels and Technologies*; DNV GL: Oslo, Norway, 2018.
47. Horvath, S.; Fasihi, M.; Breyer, C. Techno-Economic Analysis of a Decarbonized Shipping Sector: Technology Suggestions for a Fleet in 2030 and 2040. *Energy Convers. Manag.* **2018**, *164*, 230–241.
48. Abma, D.; Atli-Veltin, B.; Verbeek, R. *Feasibility Study for a Zero Emission, Battery-Electric Powertrain for the Gouwenaar II*; TNO: Den Haag, The Netherlands, 2019.
49. Abma, D.; Atli-Veltin, B.; Verbeek, R.; van der Groep, R. *Feasibility Study for a Zero Emission, Hydrogen Fuel Cell Powertrain for the Gouwenaar II*; TNO: Den Haag, The Netherlands, 2019.
50. De Vries, N. *Safe and Effective Application of Ammonia as a Marine Fuel*; TNO: Den Haag, The Netherlands, 2019.
51. Ghenai, C.; Bettayeb, M.; Brdjanin, B.; Hamid, A.K. Hybrid Solar PV/PEM Fuel Cell/Diesel Generator Power System for Cruise Ship: A Case Study in Stockholm, Sweden. *Case Stud. Therm. Eng.* **2019**, *14*, 100497.
52. Kim, K.; An, J.; Park, K.; Roh, G.; Chun, K. Analysis of a Supercapacitor/Battery Hybrid Power System for a Bulk Carrier. *Appl. Sci.* **2019**, *9*, 1547.
53. Jahangir, M.H.; Shahsavari, A.; Rad, M.A.V. Feasibility Study of a Zero Emission PV/Wind Turbine/Wave Energy Converter Hybrid System for Stand-Alone Power Supply: A Case Study. *J. Clean. Prod.* **2020**, *262*, 121250.
54. Kim, K.; Roh, G.; Kim, W.; Chun, K. A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. *J. Mar. Sci. Eng.* **2020**, *8*, 183.
55. Lloyd's Register. *Techno-Economic Assessment of Zero-Carbon Fuels*; Lloyd's Register: London, UK, 2020.
56. Hassan, I.A.; Ramadan, H.S.; Saleh, M.A.; Hissel, D. Hydrogen storage technologies for stationary and mobile applications: Review, analysis and perspectives. *Renew. Sustain. Energy Rev.* **2021**, *149*, 111311.
57. IEA. *The Future of Hydrogen*; International Energy Agency: Paris, France, 2019.
58. Collins, L. A Wake-Up Call on Green Hydrogen: The Amount of Wind and Solar Needed Is Immense. Available online: https://www.rechargenews.com/transition/a-wake-up-call-on-green-hydrogen-the-amount-of-wind-and-solar-needed-is-immense/2-1-776481 (accessed on 20 July 2023).

59. Shiozawa, B. The Cost of CO2-Free Ammonia. Available online: https://www.ammoniaenergy.org/articles/the-cost-of-co2-free-ammonia/ (accessed on 20 May 2023).
60. IEF. *Ammonia: The Missing Link in the Energy Transition?* IEF: Riyadh, Saudi Arabia, 2021.
61. Energy SGH2. Cost Comparison. Available online: https://www.sgh2energy.com/economics (accessed on 20 July 2023).
62. Hedreen, S. Blue Hydrogen Runs 'Significant Risk' of Becoming Stranded Asset—Advisory Firm. Available online: https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/blue-hydrogen-runs-significant-risk-of-becoming-stranded-asset-8211-advisory-firm-71222790 (accessed on 20 May 2023).
63. Perčić, M.; Vladimir, N.; Jovanović, I.; Koričan, M. Application of Fuel Cells with Zero-Carbon Fuels in Short-Sea Shipping. *Appl. Energy* **2022**, *309*, 118463.
64. Bunker, S. Rotterdam Bunker Prices. Available online: https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam#LNG (accessed on 20 November 2024).
65. Methanol, M. Fuel Price Comparison. Available online: http://marinemethanol.com/?nav=meohp (accessed on 15 July 2023).
66. Oil Monster. Bunker Fuel Prices in West & Northern Europe. Available online: https://www.oilmonster.com/bunker-fuel-prices/west-northern-europe/44 (accessed on 20 July 2023).
67. NESTE. Biodiesel Prices (SME & FAME). Available online: https://www.neste.com/investors/market-data/biodiesel-prices-sme-fame#ccc969da (accessed on 10 July 2023).
68. Department for Business, Energy, and Industrial Strategy. Energy Prices International Comparisons. GOV.UK. 2022.
69. DNV, Comparison of Alternative Marine Fuels. 2019.
70. Directorate for Energy and Climate Change. *Reducing Greenhouse Gas Emissions*; Scottish Government: Edinburgh, Scotland, 2023.