Applied Skills and Knowledge Journal (ASK-J)
Vol 1 • No 1 • Dec (2026) • 077–094
e-ISSN: 2838-0541
DOI: 10.68949/askjv01i01a006

Use of Alternative Renewable Energy Sources in Shipping Industry

Riea Permata Sari Mohammad Razali[1]*

[1] Faculty of Maritime Studies, Universiti Malaysia Terengganu

* Corresponding author: riearazali@gmail.com

ARTICLE INFORMATION

Article type: Original Research
Received: 03 February 2026
Revised: 01 October 2026
Accepted: 12 October 2026
Published online: 07 November 2026

ABSTRACT

Decarbonisation of maritime transport requires decisions among alternative marine fuels and onboard renewable-energy technologies, each involving environmental, operational, safety, economic and infrastructure considerations. This study examines the potential, implementation barriers and strategic priorities of liquefied natural gas (LNG), methanol, ammonia, hydrogen, biofuels and a combined wind/solar/wave option. An exploratory mixed-methods approach integrates a literature review, stakeholder perspectives and an Analytic Hierarchy Process (AHP) assessment based on six evaluation criteria. Using the criterion weights presented in the analysis, wind/solar/wave ranks first (0.207), followed by LNG (0.195), methanol (0.171), biofuel (0.165), hydrogen (0.148) and ammonia (0.115). Recalculation of the six-by-six criterion-comparison matrix gives a principal eigenvalue of approximately 6.9738 and a consistency ratio (CR) of 0.157, exceeding the predefined acceptability threshold of 0.10. The resulting eigenvector weights also differ from the tabulated priorities: when applied to the local alternative scores, biofuel and methanol exchange third and fourth places. These results demonstrate the importance of consistency assessment and weight sensitivity when interpreting stakeholder rankings. The analysis provides an exploratory basis for considering renewable assistance and transitional marine fuels, while highlighting the need for more complete expert-judgement records, technology-specific comparisons and lifecycle evidence before broader implementation.

Keywords: alternative marine fuels; maritime decarbonisation; renewable energy technologies; analytic hierarchy process; stakeholder priorities

1. Introduction

International shipping enables a substantial proportion of global merchandise trade, but its dependence on fossil-derived bunker fuels also contributes to greenhouse-gas emissions and local air pollution. The sector therefore faces simultaneous pressures to maintain safe and economically viable transport services and to reduce the environmental impacts associated with propulsion and auxiliary energy supply. These two objectives cannot be evaluated through exhaust emissions alone: fuel production, handling, onboard conversion, infrastructure and regulatory compatibility may all affect the feasibility of a given alternative.

International shipping plays a central role in commercial transport and contributes materially to global greenhouse-gas emissions. The Fourth IMO Greenhouse Gas Study provides a sector-specific basis for evaluating shipping's contribution to climate change and the need for emissions-reduction measures (International Maritime Organization, 2020).

Conventional vessels have long relied on petroleum-derived marine fuels, including heavy fuel oil. Carbon dioxide from fuel combustion contributes to climate change, while sulphur oxides, nitrogen oxides and particulate matter raise additional air-quality concerns. Maritime emission regulations therefore address several different pollutants through distinct legal instruments. The IMO 2020 global 0.50% sulphur limit should not be confused with a target for equivalent greenhouse-gas reduction. Fuel substitution, energy-efficiency measures and renewable-energy assistance are being examined for their potential contributions to lower environmental impacts. The distinction between sulphur-content restrictions and greenhouse-gas objectives is documented by the International Maritime Organization (2019, 2020).

International regulatory developments have intensified interest in alternative marine fuels and renewable-energy applications. LNG, methanol, biofuels, hydrogen, ammonia, wind, wave and solar technologies offer different routes to reducing fossil-fuel dependence or improving onboard energy efficiency (Bouman et al., 2017). Renewably produced ammonia has potential as a maritime energy carrier, although its lifecycle performance and technical feasibility depend on production methods, conversion technologies and safe handling arrangements (Al-Aboosi et al., 2021; Hansson et al., 2020).

Despite their potential advantages, these alternatives face substantial constraints, including high capital and fuel costs, safety requirements, storage limitations and inadequate supply infrastructure. Effective deployment also depends on coherent regulation and policy incentives (Doraisamy, 2024; Munim et al., 2023). These interdependent challenges justify a structured assessment of their suitability for maritime applications.

1.1 Research problem and significance

Sulphur-emission control and greenhouse-gas reduction address related but distinct environmental objectives. The IMO 2020 global sulphur limit restricts sulphur content in marine fuel oil outside emission-control areas, whereas maritime decarbonisation requires reductions in greenhouse-gas emissions across relevant fuel and operational pathways. Compliance with a sulphur-content requirement therefore does not, by itself, demonstrate a corresponding reduction in carbon dioxide or lifecycle greenhouse-gas emissions (International Maritime Organization, 2019, 2020).

Sustainable biofuel deployment is constrained by feedstock availability, competing uses of biomass and the environmental impacts of fuel production. These factors, together with broader infrastructure and operational challenges, make it necessary to evaluate alternative marine-energy options across several dimensions rather than on their theoretical emissions-reduction potential alone.

Marine fuels and onboard renewable-energy systems should not be treated as fully interchangeable. LNG is generally fossil-derived and may be considered a transitional alternative marine fuel rather than a renewable energy source. Biofuels, methanol, hydrogen and ammonia may originate from different production pathways, leading to widely different lifecycle emissions. Wind propulsion assistance, solar generation and wave-energy concepts also differ from combustible fuels in power availability, scale and vessel integration. The research problem is consequently one of multi-criteria suitability, not proof that one energy source can replace every vessel's primary propulsion system.

1.2 Research questions and objectives

1. What are the potential applications and reported benefits of the considered alternative marine fuels and renewable-energy technologies?

2. What economic, safety, infrastructure, operational and policy barriers influence their implementation?

3. What implementation priorities and provisional pathways can be inferred from the stated stakeholder criteria and AHP preference scores?

The three research objectives are to identify the potential applications of alternative marine energy, analyse the barriers to adoption and propose strategies for implementation. The literature review and qualitative stakeholder component address the first two objectives, while AHP structures the comparative assessment underpinning the third. Because the evaluation relies on stakeholder judgements rather than direct lifecycle measurements or vessel trials, its scores cannot independently quantify actual greenhouse-gas savings, demonstrate equipment performance or establish a universal best fuel.

1.3 Scope, contribution and boundaries

This study examines the potential and implications of integrating alternative marine fuels and renewable-energy technologies into commercial shipping. The alternatives include LNG, hydrogen, ammonia, methanol, biofuels and wind, wave and solar systems. Their environmental performance varies according to feedstock, energy-conversion pathway and operating conditions; renewable production pathways may offer substantial advantages over conventional heavy fuel oil in some applications (Osman et al., 2024).

The analysis focuses on commercial shipping operations and evaluates reported potential, fuel availability, cost, infrastructure requirements and policy constraints. Previous energy-prioritisation work illustrates the relevance of evaluating these factors jointly rather than assessing fuels solely by their direct operational emissions (Munim et al., 2023; Osman et al., 2024).

Although the scope is international, regional differences in technology access, policy implementation and investment capacity are acknowledged. The study does not examine ship design or engine conversion in detail, but instead addresses the decision-making, regulatory and economic considerations affecting the maritime transition (Doraisamy, 2024; Scott, 2024).

This scope permits an integrated assessment of how alternative energy options may be adopted in maritime operations and which technical, economic and policy factors influence the transition.

The shipping industry contributes substantially to global greenhouse-gas emissions (International Maritime Organization, 2020). Without additional measures, emissions may increase as international seaborne transport demand grows, although a quantified projection would require a clearly specified baseline and scenario (International Maritime Organization, 2020). This trajectory poses a substantial challenge to international climate goals and underscores the urgency for transformative measures within the sector.

Nevertheless, there are several obstacles in the way of switching to these alternative fuels. Uncertainties in technology, high production costs, and inadequate infrastructure prevent widespread implementation. According to Islam Rony et al. (2023), only 15% of the demand can be satisfied by the existing supply of biofuels, which is not enough to power the entire marine fleet sustainably. These challenges show how thorough research is required to assess the sustainability, environmental advantages, and workable implementation plans of incorporating renewable energy sources into the shipping industry.

The study aims to inform maritime policymakers, operators and other stakeholders by identifying implementation trade-offs and outlining potential pathways towards more sustainable shipping.

The principal contribution is the application of a six-criterion decision hierarchy to six maritime-energy alternatives, supported by a qualitative interpretation of their opportunities and constraints. The assessment considers international commercial shipping broadly, rather than a particular vessel, route, energy-demand profile, fuel-supply region or lifecycle boundary. Consequently, the rankings are context-dependent and cannot substitute for vessel-specific feasibility assessments.

2. Literature review

2.1 Decarbonisation and fuel pathways

International climate commitments provide an important context for maritime decarbonisation. The Paris Agreement establishes a wider climate-policy framework, while the International Maritime Organization's 2023 greenhouse-gas strategy sets out the ambition to achieve net-zero greenhouse-gas emissions from international shipping by or around 2050. These instruments differ in legal scope and operational application. Achieving deep emissions reductions is likely to require multiple complementary technologies, fuel pathways and efficiency measures rather than a single universal solution (International Maritime Organization, 2020; Pretlove, 2024).

Alternative fuels such as hydrogen, ammonia and methanol are prominent candidates in shipping decarbonisation discussions, but their comparative benefits depend on production pathways, safety and cost considerations, and infrastructure development (MARPRO, 2023). Research into renewable energy across other industries illustrates the growing role of low-emission energy carriers, although maritime applications must also satisfy vessel-specific operational constraints (Romasheva & Ilinova, 2023).

The growth of global shipping and port activity creates pressure to improve environmental performance across the maritime system. Port authorities are exploring cleaner energy, improved operating practices and digital technologies to support greener infrastructure and services (Fadiga et al., 2024). Policy coordination, investment and technology development will influence progress toward maritime emissions reduction. Improvements to air quality, public health and energy security are potential wider benefits, but their size depends on the location, technology and implementation pathway; they are not measured directly in the present study.

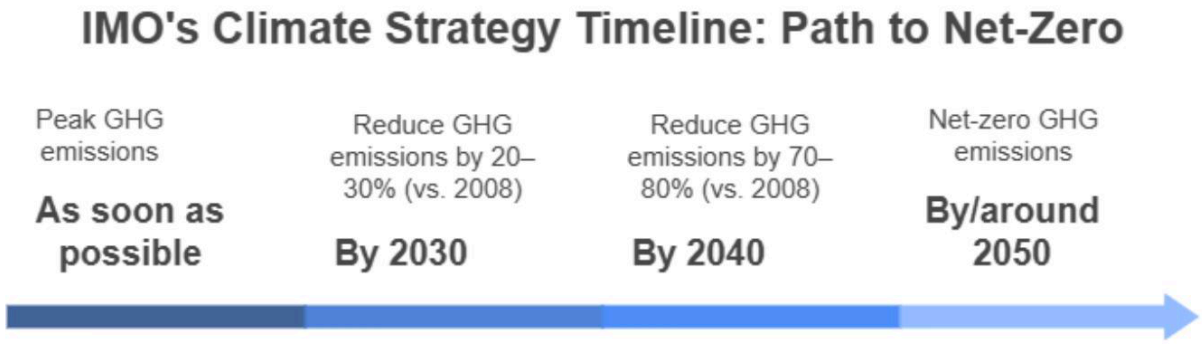


Figure 1. Overview of IMO maritime decarbonisation objectives.

The environmental assessment of alternative fuels should consider production as well as use. Fuel combustion characteristics alone cannot establish a green fuel's lifecycle benefit. Similarly, renewable energy generation on a ship may displace part of the auxiliary or propulsion energy requirement without eliminating the vessel's need for dispatchable power. This distinction is especially important when different technologies are evaluated under the same broad 'GHG reduction' criterion.

2.2 Stakeholder readiness and safety

The maritime energy transition depends on coordinated decisions by shipowners, operators, port authorities, fuel suppliers, regulators and seafarers. Their responsibilities and readiness differ, making stakeholder perspectives important when assessing the feasibility of alternative marine fuels and renewable-energy technologies.

Shipowners and operators must consider investment requirements, vessel modifications, operating costs and the maturity of competing technologies. Uncertainty about future fuel availability and regulatory requirements can delay investment in new vessels or retrofits. Stakeholder priorities may therefore reflect not only emissions objectives but also the cost, reliability and ease of adopting unfamiliar energy systems (Mukundan, 2023).

Port authorities influence adoption by developing bunkering, storage and supporting facilities for emerging fuels. Their investment decisions depend on anticipated vessel demand, safety standards, public incentives and coordination with fuel suppliers and ship operators. Effective stakeholder collaboration is consequently an essential component of maritime energy infrastructure planning (Fadiga et al., 2024).

Seafarers require appropriate training to operate and maintain alternative fuel systems safely, particularly where toxic, flammable or cryogenic materials are involved. New technologies may affect fuel transfer, emergency preparedness, monitoring and onboard maintenance. The energy transition therefore involves workforce development alongside vessel and infrastructure investment (Scott, 2024).

Stakeholder readiness is multidimensional: shipowners face fleet investment and operating risks; ports face fuel availability and bunkering infrastructure requirements; engineers and surveyors evaluate conversion and safe operations; policymakers influence market conditions and technical standards; and seafarers require familiarisation and competence for new equipment and hazardous fuels. These viewpoints motivate purposive expert sampling, while also potentially generating divergent pairwise judgements. Diversity of job titles does not substitute for reporting the number or consistency of responses.

2.3 Economic and market barriers

One of the greatest barriers to green-shipping investment is the initial capital needed for new vessels, retrofits and supporting infrastructure. Shipping-market volatility and uncertainty over future fuel costs can make such investments difficult to finance. Investment decisions become more complex when technologies are not yet

mature or fuel supply is geographically limited (Doraisamy, 2024).

The absence of a clearly dominant future marine fuel creates a risk of stranded investments. Shipowners may favour dual-fuel capability or gradual adoption as an approach to managing technical uncertainty, although this flexibility also introduces additional capital and operating requirements.

Regulatory inconsistency further complicates planning. Uncertainty about future carbon requirements, safety standards and policy incentives can discourage long-term commitments to alternative fuels. Developing economies may face additional financing and infrastructure challenges, making coordinated policy and investment support particularly important (Doraisamy, 2024).

Maritime decarbonisation therefore presents a combined financial, technical and regulatory challenge. The environmental rationale for adopting cleaner technologies is clear, but implementation depends on reliable investment conditions, fuel availability and consistent regulatory frameworks.

Several uncertainties are therefore linked rather than independent: policy credibility affects investment appetite; investment determines bunkering development; infrastructure affects demand; and availability influences shipowner fuel selection. Technology maturity and the possibility of stranded assets further complicate simple comparisons between already-deployed transitional fuels and emerging carbon-free alternatives. AHP can make the trade-offs explicit, but its numerical output remains conditional on the questions posed, the expert panel and the quality of the judgement matrix.

2.4 Research gap

The literature presents a broad range of potential technical and environmental pathways, but practitioners still require a transparent interpretation of competing evaluation criteria. The present analysis attempts to address this decision-support gap through a criterion-weighted ranking. It does not close the separate empirical gap concerning lifecycle fuel emissions, actual vessel performance, total-cost modelling or safety validation. Those questions require independent evidence and should not be inferred solely from preference scores.

3. Methodology

3.1 Study design and workflow

An exploratory sequential mixed-methods design was adopted to identify alternative-energy opportunities and implementation constraints before structuring the decision problem through AHP. Literature-based assessment and stakeholder input informed six evaluation criteria and six maritime-energy alternatives. AHP was then used to estimate comparative priorities and support a discussion of implementation strategies. The workflow is illustrated in Figures 2 and 3. Mixed-methods designs can integrate qualitative evidence and quantitative assessment within a common research framework (Creswell, 2014).

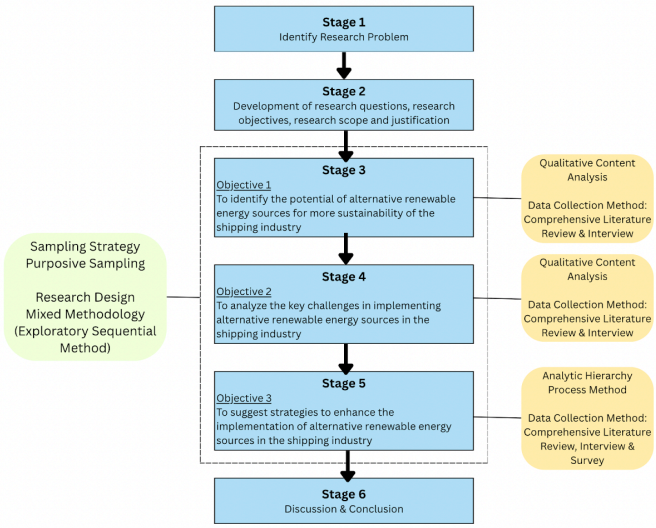


Figure 2. Research workflow and stages of the study.

The research was organised into six stages: defining the research problem; establishing questions, objectives and scope; identifying alternative-energy potential; examining implementation barriers; evaluating strategic priorities through AHP and stakeholder perspectives; and interpreting the results. The evidence available for the quantitative analysis consists of the consolidated criterion-comparison matrix and local alternative priority scores.

The first objective was addressed through a review of alternative marine fuels and renewable-energy technologies, including their potential applications, environmental benefits and implementation considerations. Stakeholder perspectives were considered alongside the literature to identify attributes relevant to the evaluation.

The second objective concerned the technical, economic, safety, infrastructure and policy barriers to adoption. Semi-structured stakeholder interviews and literature-based qualitative content analysis formed the stated basis for identifying these issues.

For the third objective, AHP structured the comparative evaluation of the six alternatives against six criteria. The questionnaire approach used expert comparisons to represent preferences concerning environmental impact, cost, efficiency, safety, regulation and readiness. The resulting priorities informed the ranking analysis and the proposed implementation discussion.

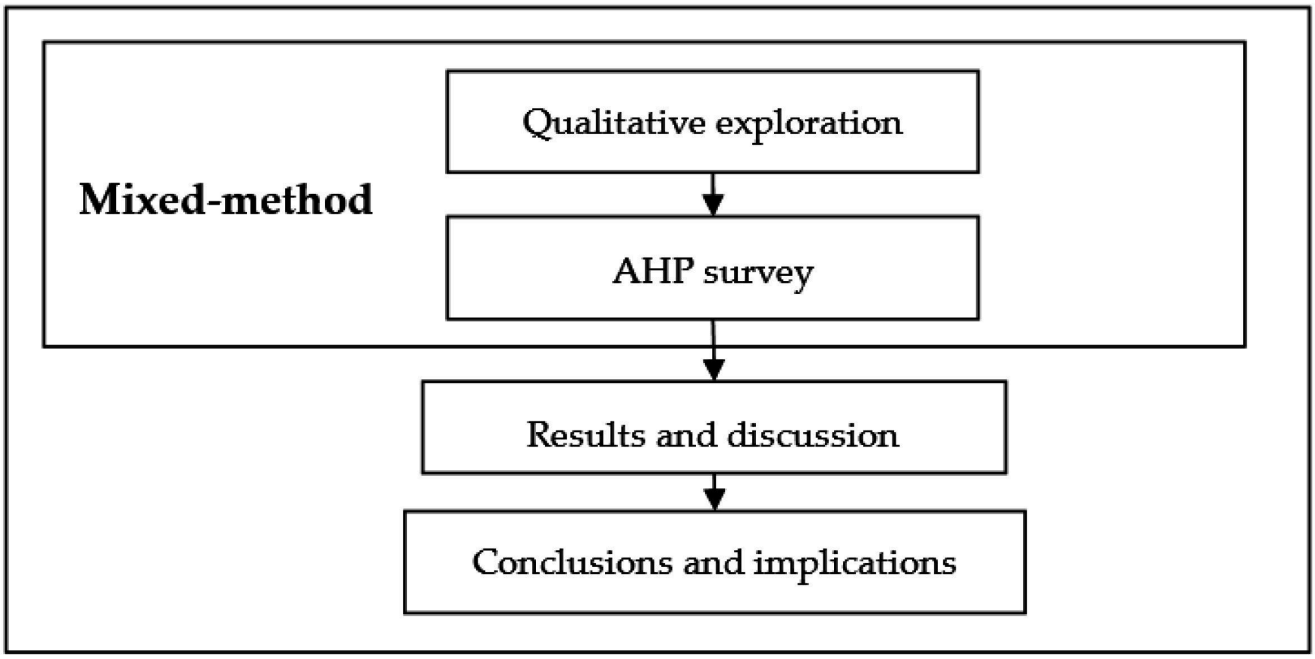


Figure 3. Mixed-methods approach incorporating AHP.

3.2 Data collection for the three objectives

For the first objective, literature and stakeholder interviews informed identification of alternative-energy potential. For the second, semi-structured interviews and qualitative synthesis addressed economic, technical, safety, infrastructure and policy barriers. For the third, AHP compared evaluation criteria and energy alternatives. Table 1 summarises these evidence streams. The analysis uses aggregated quantitative results; respondent-level interview transcripts, coding records and individual pairwise-comparison questionnaires are not available for further analysis.

Table 1. Research objectives and analytical approaches

Objective	Research approach	Main analytical output
1: Potential	Literature and stakeholder qualitative input	Summary of potential benefits and constraints
2: Challenges	Semi-structured interviews and content analysis	Themes describing implementation barriers
3: Implementation	Expert AHP questionnaire and synthesis	Criterion priorities, alternative scores and proposed strategies

3.3 Sampling and stakeholder categories

This study employs a purposive (judgmental) sampling technique to identify and select respondents with specialized expertise and direct decision-making experience in the maritime industry. This non-probability approach is deliberately chosen because the Analytic Hierarchy Process (AHP) relies on informed expert judgment rather than statistical representation of a broad population (Creswell, 2014; Leal, 2020). The target population comprises maritime stakeholders who possess operational, technical, or strategic insight into shipping energy systems. These groups were selected for their direct involvement in evaluating operational feasibility, cost implications, safety, and regulatory compliance which critical factors for assessing alternative marine renewable energy sources (Hansson et al., 2019).

Table 2. Stakeholder roles and their principal evaluation interests

Stakeholder category	Primary evaluation perspective
Shipowner/operator	Cost-effectiveness; fuel availability
Port authority representative	Infrastructure readiness
Maritime engineer/technical officer	Technical feasibility; safety

Stakeholder category	Primary evaluation perspective
Environmental/sustainability officer	GHG reduction potential
Policymaker/regulator	Policy and regulatory compliance
Surveyor/consultant	Energy efficiency

Purposive sampling targeted maritime professionals with operational, technical, environmental or regulatory expertise. The study describes an expert-panel range of 10–30, but a confirmed final participant count and respondent-level profile are not available in the analytical dataset. Consequently, the expert-panel composition cannot be independently characterised. Expert suitability in AHP depends on professional relevance and judgement quality, while the transparency of sample composition, response completeness and aggregation procedures remains important (Ho et al., 2016).

Table 3. Implications of purposive expert recruitment

AHP sampling consideration	Methodological implications
Pairwise judgements	Experience may improve relevance, but consistency must be tested for the actual data.
Criterion weighting	Professional diversity may diversify priorities; respondent counts and aggregation must be provided.
Alternative ranking	Preference scores apply to the stated panel, assumptions and time frame, not all shipping markets.

3.4 AHP decision model, assumptions and calculations

The decision hierarchy consists of one goal, six criteria and six alternatives (Table 4). Wind, solar and wave are grouped as a single renewable-assistance option. The evaluation criteria are greenhouse-gas emissions reduction (C1), cost-effectiveness (C2), energy efficiency (C3), safety and handling requirements (C4), regulatory and policy compliance (C5), and infrastructure and technology readiness (C6). Expert comparisons are represented by a reciprocal judgement matrix A, where $a_{ii} = 1$ and $a_{ji} = \frac{1}{a_{ij}}$. Criterion weights may be estimated using the normalised dominant right eigenvector. The completed respondent-level questionnaires and their aggregation procedure are not available for further verification. Similar multi-criteria approaches have been applied to maritime fuel assessment (Hansson et al., 2019; Munim et al., 2023).

Table 4. Evaluation criteria and marine-energy alternatives

Code	Evaluation criterion	Alternative code	Alternative
C1	GHG emissions reduction	A1	LNG
C2	Cost-effectiveness	A2	Methanol
C3	Energy efficiency	A3	Ammonia
C4	Safety and handling requirements	A4	Hydrogen
C5	Regulatory and policy compliance	A5	Biofuel
C6	Infrastructure and technological readiness	A6	Wind / solar / wave

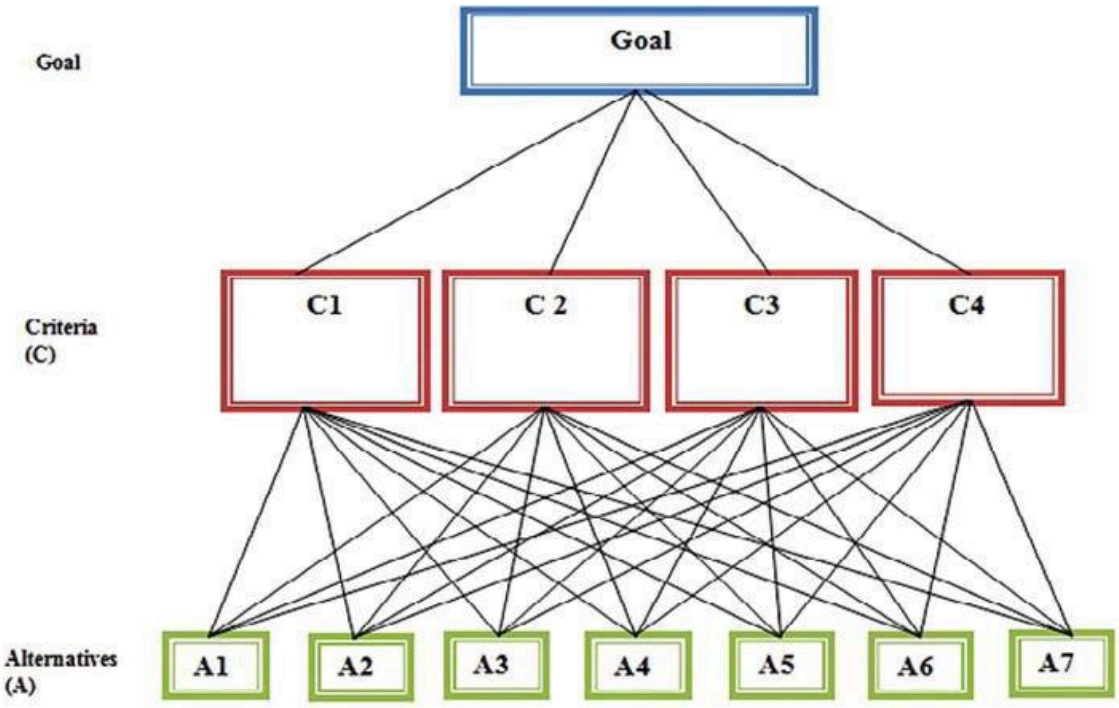


Figure 4. Illustrative AHP decision hierarchy.

The evaluation used five intensity descriptors: 1 = least important, 2 = moderately important, 3 = strongly important, 4 = very strongly important and 5 = extremely important. This five-point scale is narrower than the conventional Saaty scale, which may affect discrimination among preferences. Reciprocal values represent inverse comparisons. Although the criterion matrix is reciprocal, numerical reciprocity does not guarantee judgement consistency (Leal, 2020; Rostampoor, 2023).

Table 5. Symbolic criterion-pairwise comparison matrix

Criteria	C1	C2	C3	C4	C5	C6
C1	$\frac{C1}{C}1$	$\frac{C1}{C}2$	$\frac{C1}{C}3$	$\frac{C1}{C}4$	$\frac{C1}{C}5$	$\frac{C1}{C}6$
C2	$\frac{C2}{C}1$	$\frac{C2}{C}2$	$\frac{C2}{C}3$	$\frac{C2}{C}4$	$\frac{C2}{C}5$	$\frac{C2}{C}6$
C3	$\frac{C3}{C}1$	$\frac{C3}{C}2$	$\frac{C3}{C}3$	$\frac{C3}{C}4$	$\frac{C3}{C}5$	$\frac{C3}{C}6$
C4	$\frac{C4}{C}1$	$\frac{C4}{C}2$	$\frac{C4}{C}3$	$\frac{C4}{C}4$	$\frac{C4}{C}5$	$\frac{C4}{C}6$
C5	$\frac{C5}{C}1$	$\frac{C5}{C}2$	$\frac{C5}{C}3$	$\frac{C5}{C}4$	$\frac{C5}{C}5$	$\frac{C5}{C}6$
C6	$\frac{C6}{C}1$	$\frac{C6}{C}2$	$\frac{C6}{C}3$	$\frac{C6}{C}4$	$\frac{C6}{C}5$	$\frac{C6}{C}6$

Table 6. Five-point judgement intensity scale

Judgement value	Description
1	Least Important
2	Moderate Important
3	Strong Important
4	Very Strong Important
5	Extremely Important

$$CR = \frac{CI}{RI} \tag{1}$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

For an AHP matrix of order n, the consistency index is $CI = \frac{\lambda_{max}-n}{n-1}$, and the consistency ratio is $CR = \frac{CI}{RI}$, where RI denotes the random index for the matrix size. For the six-criterion matrix, $n = 6$ and $RI = 1.24$. The predefined acceptability standard is $CR \leq 0.10$. Given criterion weights w_i and alternative priority p_{ij} under criterion i, the global score for alternative j is $S_j = \sum_i (w_i p_{ij})$. AHP rankings should be interpreted cautiously when comparison matrices do not satisfy the consistency threshold.

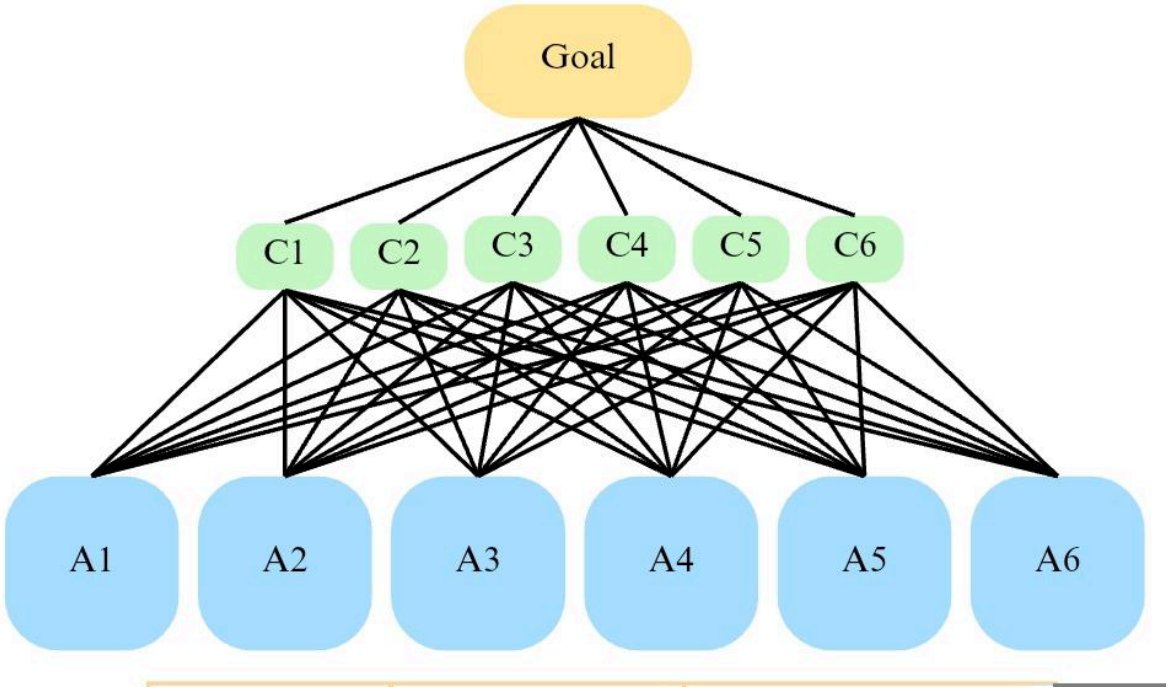


Figure 5. Six-criteria and six-alternatives decision hierarchy.

Source: Study AHP computation framework.

$$\text{Priority of Alternative}_i = \sum_{j=1}^{m} \left(w_{\text{criterion}_j} \times w_{\text{alternative}_i \text{ under criterion}_j} \right) \tag{3}$$

3.5 Analytical data and reproducibility

The quantitative analysis is based on a consolidated six-by-six criterion-comparison matrix and six sets of local alternative priorities. Individual expert questionnaires, respondent-specific matrices and local alternative-comparison matrices are not available, so the expert aggregation procedure and local alternative consistency cannot be reconstructed. The dataset also lacks a verified interview count, qualitative coding schema and common vessel or lifecycle assessment boundary. The numerical reassessment is therefore limited to values calculable from the documented criterion matrix and alternative priority scores.

4. Results

4.1 Criterion judgement matrix

Table 7 presents the reciprocal six-criterion comparison matrix. Safety and handling requirements (C4) receive strong comparisons relative to several other criteria. In the calculated priorities, C4 has the greatest importance, whereas greenhouse-gas emissions reduction (C1) has the lowest weight. This finding indicates that safety considerations dominate this particular set of criterion judgements.

Table 7. Criterion pairwise-comparison matrix

Criterion	C1	C2	C3	C4	C5	C6

Criterion	C1	C2	C3	C4	C5	C6
C1	1	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{3}$
C2	4	1	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$
C3	4	3	1	$\frac{1}{4}$	$\frac{1}{4}$	3
C4	4	4	4	1	4	4
C5	4	4	4	$\frac{1}{4}$	1	4
C6	3	4	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{1}{4}$	1

4.2 Criterion weights and consistency assessment

The six reported criterion priorities sum to 1.000 but differ from the normalised principal eigenvector of the criterion matrix. Direct calculation gives $\lambda_{max} = 6.973776$, $CI = 0.194755$ and $CR = 0.157061$ when $RI = 1.24$. The matrix therefore exceeds the predefined 0.10 consistency threshold. Table 8 presents the reported weights alongside the recomputed eigenvector values. Because no further expert judgements were collected for this calculation, the recomputed weights constitute a numerical sensitivity comparison rather than a new elicitation exercise.

Table 8. Criterion priorities from reported values and eigenvector calculations

Criterion	Criterion weight used in ranking	Recomputed eigenvector weight	Difference (recomputed − ranking)
C1	0.036	0.041518	**+0.005518**
C2	0.091	0.067050	-0.023950
C3	0.173	0.139340	-0.033660
C4	0.318	0.401052	**+0.083052**
C5	0.255	0.250262	-0.004738
C6	0.127	0.100779	-0.026221

The intermediate values 0.36, 0.91, 1.73, 3.18, 2.55 and 1.27 are labelled as row sums in the available calculation table, but they are not the arithmetic row sums of the reciprocal matrix. The criterion priorities therefore cannot be reproduced through the stated row-summation procedure. A transparent record of the weight derivation and aggregation procedure is needed to assess reproducibility.

4.3 Alternative priority weights

The local priorities for the six alternatives are shown in Table 9. Each row sums to 1.000, as expected for normalised alternative priorities under an individual criterion. However, normalisation alone does not demonstrate AHP consistency. The underlying six alternative-comparison matrices and their respective consistency ratios would be required for full verification.

Table 9. Local alternative priority scores by criterion

Criterion	LNG	Methanol	Ammonia	Hydrogen	Biofuel	Wind/solar/wave
C1	0.20	0.20	0.10	0.15	0.10	0.25
C2	0.15	0.20	0.10	0.10	0.25	0.20
C3	0.20	0.25	0.15	0.20	0.10	0.10
C4	0.20	0.10	0.10	0.15	0.20	0.25
C5	0.20	0.20	0.10	0.15	0.15	0.20
C6	0.20	0.15	0.15	0.10	0.15	0.25

4.4 Weighted alternative ranking and numerical sensitivity

Table 10 presents global alternative scores calculated using (a) the reported criterion weights and (b) the eigenvector weights derived from the displayed comparison matrix. The tabulated rounded values are 0.195, 0.171, 0.115, 0.148, 0.165 and 0.207 for LNG, methanol, ammonia, hydrogen, biofuel and wind/solar/wave, respectively. Their sum is 1.001 because of rounding; calculation from the underlying component weights gives a total of 1.000 before rounding. This minor rounding issue is distinct from the larger criterion-matrix consistency concern.

Table 10. Conditional rankings under two weight vectors

Alternative	Score with reported weights	Score with eigenvector weights	Rank: reported weights	Rank: eigenvector
LNG	0.195450	0.196648	2	2
Methanol	0.170500	0.161823	3	4
Ammonia	0.115000	0.112006	6	6
Hydrogen	0.147750	0.148576	5	5
Biofuel	0.164550	0.167715	4	3
Wind / solar / wave	0.206750	0.213233	1	1

With the recalculated eigenvector weights, biofuel moves to third and methanol to fourth, while the wind/solar/wave composite and LNG remain first and second. Hydrogen and ammonia remain fifth and sixth. The renewable composite obtains relatively favourable local scores under emissions reduction, safety and infrastructure readiness. LNG receives moderate and comparatively uniform local priorities across the criteria. These two weighting scenarios demonstrate sensitivity of the middle ranks but are not sufficient to establish full robustness in the absence of consistent criteria judgements and independent alternative matrices.

4.5 Qualitative synthesis of potential and barriers

The qualitative findings identify differing implementation characteristics across technologies. LNG benefits from established applications and bunkering development but continues to involve fossil carbon and potential methane-related lifecycle emissions. Methanol can offer handling and logistics advantages, although its environmental performance depends on how it is produced. Biofuels may be compatible with parts of the existing fleet, but their sustainability and availability depend on feedstocks and production pathways. Hydrogen requires careful management of storage, safety, energy conversion and supply-chain emissions. Ammonia involves toxicity, combustion-related emissions and infrastructure challenges despite its potential for low-carbon production. Wind, solar and wave technologies may provide complementary renewable energy, but differ in maturity, scalability and onboard integration.

5. Discussion

5.1 Interpretive meaning of the ranked outcome

The final ranking reflects priorities under the selected criteria and alternative scores, not a universal engineering comparison. The wind/solar/wave option aggregates distinct technologies, while the fuel alternatives are affected by production pathways and lifecycle assumptions. Suitability may differ substantially by vessel type, propulsion demand, route, climate, fuel availability and retrofit constraints.

Safety and handling requirements (C4) have the greatest weight under both sets of criterion priorities, followed by regulatory and policy compliance (C5). The high-scoring renewable composite therefore reflects not only its emissions-related attributes but also favourable assigned scores for safety and readiness. These judgements should be assessed against technology maturity, operational context and actual vessel-system requirements before being treated as evidence of field performance.

5.2 Wind, solar and wave energy technologies

The combined wind/solar/wave option ranks first in the six-alternative comparison. Wind assistance can reduce propulsive energy demand, photovoltaic systems can supply electrical power and wave-energy concepts may provide additional renewable energy under suitable conditions. Such systems could contribute to hybrid ship-energy arrangements, although technical capabilities and integration requirements vary. Their energy yield depends on weather, vessel route, equipment design and available installation space. Renewable onboard generation may reduce conventional fuel use, but it cannot be assumed to eliminate a vessel's total greenhouse-gas emissions (Bouman et al., 2017; Pretlove, 2024).

The composite option scores 0.20675 using the reported criterion weights. This result applies to the combined category, not independently to each technology. Wind propulsion assistance and solar photovoltaic generation operate through different physical mechanisms, while marine wave devices involve distinct technical and operational constraints. No vessel-specific generation dataset is available to determine the share of propulsion or auxiliary energy that these systems could supply during a voyage.

5.3 Liquefied natural gas

LNG ranks second, reflecting its infrastructure development, technology maturity and established marine applications. It may serve as a transitional fuel where conventional-fuel substitution is operationally practical, although fossil-derived LNG continues to produce greenhouse-gas emissions. Its long-term suitability depends on lifecycle emissions, particularly methane losses, as well as future policy, fuel availability and the development of lower-carbon options (Usiagu et al., 2024).

An industry report recorded 151 new LNG-fuelled ship orders and a total orderbook of 805 vessels for its reporting period. These historical market indicators illustrate growing interest in LNG propulsion but should not be interpreted as current fleet totals (Concord, 2022).

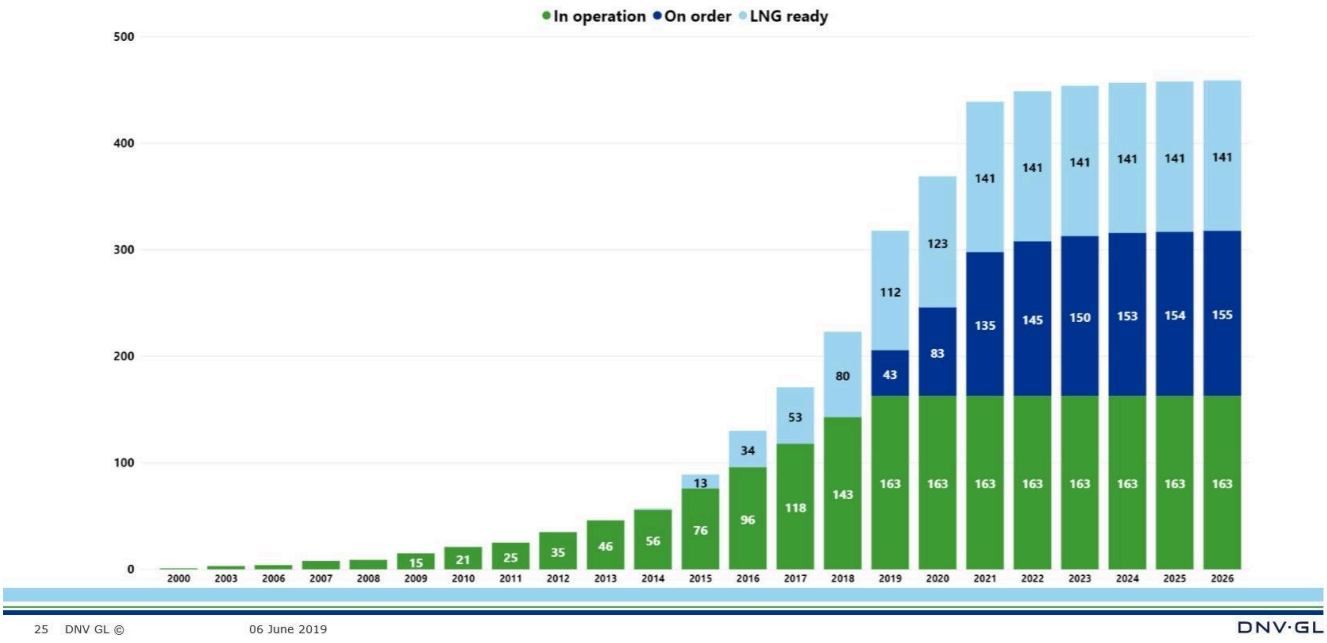


Figure 6. Historical growth of LNG-fuelled vessels. (SAFETY4SEA, 2019).

The LNG score is 0.19545, placing it second within the evaluated alternatives. Established operating experience and infrastructure in certain markets may support its transitional role; nevertheless, LNG is not intrinsically renewable, and any net climate benefit depends on comprehensive lifecycle assessment. Historic fleet-growth data alone cannot demonstrate future bunker availability or emissions performance.

5.4 Methanol

Methanol ranks third under the reported criterion weights, indicating a moderate overall evaluation across the six criteria. It can offer handling and storage advantages relative to some alternative fuels, but its greenhouse-gas performance varies between fossil-based and low-carbon production routes. Cost, fuel availability and bunkering infrastructure remain important constraints (Schorn et al., 2021).

Schorn et al. (2021) estimated that renewable methanol produced from green hydrogen and carbon dioxide could be imported at approximately €370–€600 per tonne by 2030 under specified assumptions. This overlaps with the fossil-methanol reference price of about €400 per tonne used in their analysis, depending on hydrogen and carbon dioxide costs. The study also identified potential transport and handling advantages for methanol relative to selected alternatives. These estimates are scenario-dependent rather than current marine fuel-market quotations.

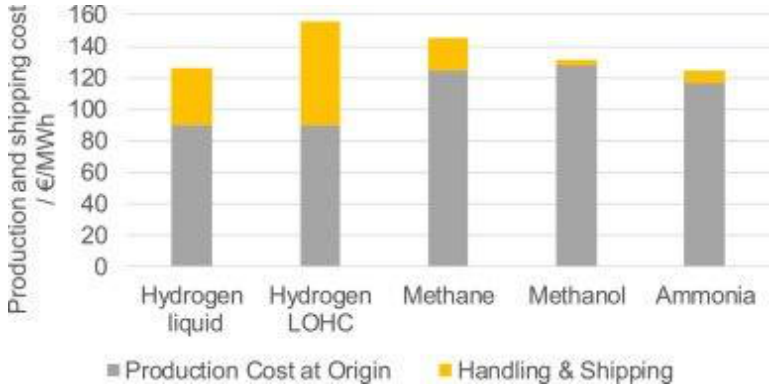


Figure 7. Production and shipping cost comparison for selected energy carriers (Schorn et al., 2021).

Methanol obtains a score of 0.17050 using the reported criterion weights. Its cost and environmental competitiveness remain sensitive to feedstock selection, conversion efficiency, transport assumptions and the emissions intensity of the energy used in production. The AHP outcome consequently indicates comparative preferences rather than measured lifecycle economic superiority.

5.5 Biofuels

Biofuels rank fourth using the reported criterion weights. Renewable diesel and certain biodiesel blends may offer compatibility with existing marine fuel systems, making them attractive for near-term deployment in suitable vessels. Nevertheless, allowable blends, equipment approval, fuel specifications, feedstock availability and lifecycle emissions influence their practical suitability (Sevim & Zincir, 2022).

Lifecycle emissions savings from sustainable biofuels can be substantial under favourable feedstock and production conditions, but reported reductions depend on the selected fuel pathway and comparison baseline. Economic attractiveness also varies with supply, fuel price and competing mitigation technologies. Biofuels therefore offer a potentially useful short- or medium-term option rather than a universally low-emission substitute (Kanchiralla et al., 2024).

The biofuel score is 0.16455 using reported criterion weights. Its position reflects the balance between fleet compatibility and constraints associated with sustainable feedstocks and market availability. The analysis does not include a fuel-specific well-to-wake assessment, so it cannot determine the emissions savings of an individual biofuel pathway.

5.6 Hydrogen

Hydrogen ranks fifth. Its evaluation reflects concerns about storage, safe handling, infrastructure, technology maturity and production cost. Although hydrogen has the potential to support low-carbon maritime energy systems when produced through appropriate pathways, shipboard feasibility depends on the complete storage and energy-conversion arrangement.

Hydrogen is widely investigated for long-duration energy storage and power-system balancing. Grid-scale storage concepts, including underground storage and other stationary solutions, illustrate its flexibility as an energy carrier but do not directly establish commercial shipboard feasibility. Maritime assessment must also consider volumetric energy density, cryogenic or high-pressure containment, bunkering arrangements, fuel-cell or combustion performance and operational safety (Scheller et al., 2023; Yan et al., 2023).

Hydrogen's score is 0.14775 under the reported weights. The separate technical challenges of onboard hydrogen use mean that energy-system findings from stationary applications cannot be directly transferred to a particular ship design. The results point to the importance of specific safety, storage and infrastructure assessments.

5.7 Ammonia

Ammonia ranks sixth and is best considered a longer-term candidate requiring further technical and regulatory development. Renewably produced ammonia offers potential for low-carbon marine energy, but cost, toxicity, fuel handling and combustion performance are major challenges (Hansson et al., 2020). Ammonia combustion may produce nitrous oxide and other undesirable emissions, and safe deployment requires suitable onboard systems, crew training and effective controls. Its use in fuel cells and advanced combustion systems remains dependent on further technology development. Large-scale renewable ammonia supply could also create competition with existing industrial demand, including fertiliser production (Schwarzkopf et al., 2023).

In summary, ammonia is central to the long-term decarbonization strategy, but its environmental efficacy is highly dependent on the combustion technology employed. The more immediately feasible engine technology presents a trade-off: it reduces fossil CO_2 but introduces new challenges in the form of N_2O emissions and large-scale atmospheric ammonia release. The more advanced technology promises better overall outcomes but may face greater implementation hurdles by mid-century.

The ammonia score is 0.11500, the lowest in the evaluated set. This reflects the selected preferences and assumptions rather than proof of technological inferiority across all future operating conditions. The environmental outcome must be assessed for each fuel-production and onboard conversion pathway, including possible nitrous oxide emissions and ammonia releases.

5.8 Implementation interpretation and suggested pathway

A phased maritime-energy transition offers a practical interpretation of the combined findings. Near-term measures may include efficiency improvements, selected renewable-energy assistance systems and transitional fuels where infrastructure is available. Sustainable methanol and biofuels warrant evaluation for suitable routes and vessels as supply chains mature. Hydrogen and ammonia may play a larger role when production, safety standards, onboard systems and bunkering infrastructure support reliable operation. These stages represent strategic recommendations informed by the analysis, not separate dated AHP rankings.

5.9 Limitations, data reliability and further validation

The principal quantitative limitation is that the criterion-comparison matrix does not meet the adopted consistency criterion ($CR = 0.157 > 0.10$). This reduces confidence in the stability of criterion priorities. The available dataset also lacks a confirmed final expert count, respondent-specific judgements, an explicit group-aggregation procedure, local alternative-comparison matrices and a documented interview coding process. Comparing reported weights with the recomputed eigenvector illustrates numerical sensitivity but does not constitute validation by an independent expert panel.

A further limitation is the aggregation of wind, solar and wave into one category alongside fuel-specific alternatives without a common functional unit for energy delivery, transport work, cost or lifecycle impact. The lack of vessel-specific operating and emissions data also constrains external applicability. Future work should obtain complete and consistent expert judgements, establish comparable technology boundaries and incorporate verified emissions, safety and economic performance indicators.

6. Conclusions

This study evaluates six alternative marine-fuel and renewable-energy options using an AHP framework supported by literature review and stakeholder perspectives. Under the reported criterion weights, the combined wind/solar/wave option ranks first, followed by LNG, methanol, biofuel, hydrogen and ammonia. These findings suggest that renewable-energy assistance and transitional fuels may have complementary roles, while practical fuel selection must account for infrastructure, cost, safety, policy and operational context.

The criterion matrix yields $CR = 0.157$, exceeding the adopted acceptance threshold of 0.10. Its principal-eigenvector weights differ from the reported criterion priorities; applying them to the local alternative scores exchanges biofuel and methanol in third and fourth place. The consistency shortfall and incomplete respondent-level records constrain the confidence and generalisability of the rankings, which should be interpreted as exploratory decision-support outputs.

Further research should document the expert sample and qualitative analytical procedures, obtain consistent pairwise comparisons, disaggregate wind, solar and wave applications and evaluate specific vessel-route scenarios. Integration of lifecycle emissions, safety analysis and techno-economic assessment would enable more

reliable comparisons and strengthen the basis for investment and policy decisions.

Acknowledgement

The authors gratefully acknowledge the support of Universiti Malaysia Terengganu and thank Capt. Dr. Mohammed Ismail Russtam Suhrab for his supervision, guidance and encouragement. Appreciation is also extended to the study respondents, interviewees, lecturers, colleagues, friends and family members for their contributions and support throughout the research.

Declaration of generative AI and AI-assisted technologies in the writing process

Artificial intelligence tools were used as supplementary aids for language refinement, structural organisation and clarity. All research judgements, interpretations, analyses and conclusions remain the responsibility of the authors.

Funding

This research was completed as an undergraduate Final Year Project and did not receive a specific research grant from public, commercial or not-for-profit funding agencies.

Conflict of Interest

The author(s) declare that there is no conflict of interest regarding the research, authorship, and publication of this article.

Author Contributions

Data Availability Statement

No publicly available data are associated with this study.

Ethics Statement

The author(s) have complied with all applicable research ethics requirements throughout the conduct of this study.

References

Al-Aboosi, F. Y., El-Halwagi, M. M., Moore, M., & Nielsen, R. B. (2021). Renewable ammonia as an alternative fuel for the shipping industry. Current Opinion in Chemical Engineering, 31, 100670. https://doi.org/10.1016/j.coche.2021.100670

ASUENE. (2025, April 22). IMO's maritime decarbonization strategy: Steering global shipping toward net-zero by 2050. https://asuene.com/us/blog/imos-maritime-decarbonization-strategy-steering-global-shipping-toward-net-zero-by-2050

Bouman, E. A., Lindstad, E., Rialland, A. I., & Strømman, A. H. (2017). State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping: A review. Transportation Research Part D: Transport and Environment, 52, 408–421. https://doi.org/10.1016/j.trd.2017.03.022

Creswell, J. W. (2014). Research design: Qualitative, quantitative, and mixed methods approaches (4th ed.). SAGE Publications.

Doraisamy, P. (2024, March 18). The current and future opportunities and challenges of green shipping and sustainability. PDLegal LLC. https://www.pdlegal.com.sg/the-current-and-future-opportunities-and-challenges-of-green-shipping-and-sustainability/

Fadiga, A., Ferreira, L. M. D. F., & Bigotte, J. F. (2024). Decarbonising maritime ports: A systematic review of the literature and insights for new research opportunities. Journal of Cleaner Production, 452, 142209. https://doi.org/10.1016/j.jclepro.2024.142209

Hansson, J., Brynolf, S., Fridell, E., & Lehtveer, M. (2020). The potential role of ammonia as marine fuel—Based on energy systems modeling and multi-criteria decision analysis. Sustainability, 12(8), 3265. https://doi.org/10.3390/su12083265

Hansson, J., Månsson, S., Brynolf, S., & Grahn, M. (2019). Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders. Biomass and Bioenergy, 126, 159–173. https://doi.org/10.1016/j.biombioe.2019.05.008

Ho, F. H., Abdul-Rashid, S. H., & Raja Ghazilla, R. A. (2016). Analytic hierarchy process-based analysis to determine the barriers to implementing a material efficiency strategy: Electrical and electronics' companies in the Malaysian context. Sustainability, 8(10), 1035. https://doi.org/10.3390/su8101035

International Maritime Organization. (2019, December 20). IMO 2020—Cleaner shipping for cleaner air. https://www.imo.org/en/MediaCentre/PressBriefings/Pages/34-IMO-2020-sulphur-limit-.aspx

International Maritime Organization. (2020). Fourth IMO greenhouse gas study 2020. https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx

Islam Rony, Z., Mofijur, M., Hasan, M. M., Rasul, M. G., Jahirul, M. I., Ahmed, S. F., Kalam, M. A., Badruddin, I. A., Khan, T. M. Y., & Show, P.-L. (2023). Alternative fuels to reduce greenhouse gas emissions from marine transport and promote UN sustainable development goals. Fuel, 338, 127220. https://doi.org/10.1016/j.fuel.2022.127220

Kanchiralla, F. M., Brynolf, S., & Mjelde, A. (2024). Role of biofuels, electro-fuels, and blue fuels for shipping: Environmental and economic life cycle considerations. Energy & Environmental Science, 17(17), 6393–6418. https://doi.org/10.1039/D4EE01641F

Leal, J. E. (2020). AHP-express: A simplified version of the analytical hierarchy process method. MethodsX, 7, 100748. https://doi.org/10.1016/j.mex.2019.11.021

Marpro Group Editorial Team. (2023, March 7). The potential of alternative fuels in the shipping industry. Maritime Professionals. https://maritime-professionals.com/the-potential-of-alternative-fuels-in-the-shipping-industry/

Mukundan, G., Sivaprasad, K., & Satheesh Babu, P. K. (2024). Stakeholder perspectives on decarbonization: A comprehensive survey of technology priorities in the maritime industry. Journal of Harbin Engineering University, 45(11), 75–92. https://harbinengineeringjournal.com/index.php/journal/article/view/3672

Munim, Z. H., Chowdhury, M. M. H., Tusher, H. M., & Notteboom, T. (2023). Towards a prioritization of alternative energy sources for sustainable shipping. Marine Policy, 152, 105579. https://doi.org/10.1016/j.marpol.2023.105579

Osman, A. I., Nasr, M., Lichtfouse, É., Farghali, M., & Rooney, D. W. (2024). Hydrogen, ammonia and methanol for marine transportation. Environmental Chemistry Letters, 22(5), 2151–2158. https://doi.org/10.1007/s10311-024-01757-9

Romasheva, N., & Cherepovitsyna, A. (2023). Renewable energy sources in decarbonization: The case of foreign and Russian oil and gas companies. Sustainability, 15(9), 7416. https://doi.org/10.3390/su15097416

Rostampoor, M. (2023). Definition of analytical hierarchy process and its effect on environmental decisions in engineering for landfill siting. In F. De Felice & A. Petrillo (Eds.), Analytic hierarchy process: Models, methods, concepts, and applications. IntechOpen. https://doi.org/10.5772/intechopen.1001080

SAFETY4SEA Editorial Team. (2019, June 6). Number of ships using LNG, scrubbers to increase from 2020. SAFETY4SEA. https://safety4sea.com/number-of-ships-using-lng-scrubbers-to-increase-from-2020/

Scheller, F., Wald, S., Kondziella, H., Gunkel, P. A., Bruckner, T., & Keles, D. (2023). Future role and economic benefits of hydrogen and synthetic energy carriers in Germany: A review of long-term energy scenarios. Sustainable Energy Technologies and Assessments, 56, 103037. https://doi.org/10.1016/j.seta.2023.103037

Schorn, F., Breuer, J. L., Samsun, R. C., Schnorbus, T., Heuser, B., Peters, R., & Stolten, D. (2021). Methanol as a renewable energy carrier: An assessment of production and transportation costs for selected global locations. Advances in Applied Energy, 3, 100050. https://doi.org/10.1016/j.adapen.2021.100050

Schwarzkopf, D. A., Petrik, R., Hahn, J., Ntziachristos, L., Matthias, V., & Quante, M. (2023). Future ship emission scenarios with a focus on ammonia fuel. Atmosphere, 14(5), 879. https://doi.org/10.3390/atmos14050879

Scott, M. (2024, December 3). A sea-change for seafarers as the shipping industry gears up to decarbonise. Reuters. https://www.reuters.com/sustainability/climate-energy/sea-change-seafarers-shipping-industry-gears-up-decarbonise-2024-12-03/

Sevim, C., & Zincir, B. (2022). Biodiesel and renewable diesel as a drop-in fuel for decarbonized maritime transportation. In A. K. Agarwal & H. Valera (Eds.), Potential and challenges of low carbon fuels for sustainable transport (pp. 319–345). Springer. https://doi.org/10.1007/978-981-16-8414-2_10

Star Concord. (2022, June 2). DNV: Orders for LNG-fueled ships at record pace. https://starconcord.com.sg/dnv-orders-for-lng-fueled-ships-at-record-pace/

Usiagu, G. S., Adekoya, O. O., Okoli, C. E., Daudu, C. D., Ekemezie, I. O., & Ayorinde, O. B. (2024). LNG as a bridge fuel in the transition to renewable energy: A global perspective. World Journal of Advanced Research and Reviews, 21(2), 742–749. https://doi.org/10.30574/wjarr.2024.21.2.0480

Yan, H., Zhang, W., Kang, J., & Yuan, T. (2023). The necessity and feasibility of hydrogen storage for large-scale, long-term energy storage in the new power system in China. Energies, 16(13), 4837. https://doi.org/10.3390/en16134837