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Alternative Marine Fuels: A Pathway to Carbon-Neutral Shipping

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ABSTRACT

Shipping decarbonization requires fuel-selection decisions that account for emissions across the full fuel lifecycle as well as machinery adaptation, economic feasibility, shipboard safety and bunkering availability. This study evaluates liquefied natural gas (LNG), methanol, ammonia, hydrogen and advanced biofuels using a seven-criterion weighted-sum multi-criteria decision analysis (MCDA), supported by a structured technical literature synthesis. Criteria are well-to-wake CO_2 reduction, NO_x or SO_x reduction, volumetric energy density, engine compatibility, fuel cost, operational safety and supply-chain maturity. Under the stated scenario inputs and weights, the ranking is advanced biofuels (0.752), LNG (0.669), methanol (0.655), ammonia (0.559) and hydrogen (0.539). The figures are reproduced from the declared input matrix, including fixed five-point denominators for qualitative scores. A five-scenario sensitivity analysis reveals that LNG ranks first if the weight on cost rises to 0.40, while advanced biofuels retain first place under the carbon- and safety-priority scenarios. These results are conditional decision scores rather than validated lifecycle emission factors or a fleet-wide fuel hierarchy. The evidence indicates that drop-in biofuels may support near-term deployment where credible feedstock certification is available; low-carbon methanol and hydrogen-derived fuels require expansion of renewable production and distribution; and LNG requires scrutiny of methane slip and upstream methane leakage. Fuel transitions should therefore be evaluated by verified pathway-specific well-to-wake emissions, ship operational profiles and risk controls rather than nominal fuel identity alone.

Keywords: maritime decarbonization; alternative fuels; MCDA; well-to-wake assessment; LNG

1. Introduction

International shipping underpins global freight transport but remains challenging to decarbonize because oceangoing vessels need substantial onboard energy storage, reliable worldwide bunkering and long-lived propulsion systems. The International Maritime Organization (IMO) adopted its 2023 greenhouse-gas (GHG) strategy with an ambition to achieve net-zero GHG emissions from international shipping by or around 2050. The strategy establishes indicative total-emission checkpoints of at least 20% reduction by 2030 and 70% by 2040, relative to 2008, and a goal for zero- or near-zero-GHG technologies and fuels to represent at least 5% of shipping energy use by 2030 (IMO, 2023). These are not equivalent to a 70% carbon-intensity reduction by 2050.

The relevant metric is increasingly the climate impact of the entire energy pathway. Well-to-wake (WTW) accounting combines well-to-tank (WtT) emissions from production and supply with tank-to-wake (TtW) emissions from fuel use onboard, including methane and nitrous oxide where relevant. IMO's 2024 lifecycle guidelines provide a common basis for identifying and verifying marine-fuel emissions factors (International Maritime Organization, 2024). Lifecycle studies show that the same chemical fuel can have markedly different impacts depending on feedstock, process energy and engine technology (Huang et al., 2022; Wang et al., 2025; Zamboni et al., 2024).

Five fuel groups dominate the comparative literature: LNG, methanol, ammonia, hydrogen and advanced biofuels. LNG is relatively mature, but methane losses can undermine climate benefits. Methanol is a liquid at ambient conditions and may be compatible with emerging dual-fuel machinery, but fossil methanol is not inherently low-carbon. Ammonia and hydrogen offer carbon-free end-use pathways, yet production-route emissions, storage, toxicity, combustion by-products and port readiness matter. Advanced biofuels may be compatible with existing marine systems, although feedstock sustainability, fuel quality and globally scalable supply remain constraints (Rony et al., 2023; Wang & Wright, 2021).

An evaluation focused solely on WTW emissions could neglect storage penalties, crew safety, retrofit costs and regional supply. Conversely, choosing only established fuels may create infrastructure lock-in. This study integrates environmental, technical, economic, safety and supply-chain factors in a transparent MCDA comparison, then tests whether its conclusions are robust to changing decision priorities. The aims are (a) to review operational opportunities and constraints for each candidate, (b) to reproduce an explicitly weighted seven-criterion comparison, and (c) to formulate a staged deployment and verification framework for shipowners, ports and policymakers.

2. Technical Literature Review

2.1 LNG: established technology and the methane constraint

Liquefied natural gas is mainly methane, stored cryogenically at approximately −162 °C. Its established dual-fuel engine options and expanding bunkering network distinguish LNG from fuels still at early demonstration stages. Onboard combustion normally reduces sulphur emissions and particulate matter relative to high-sulphur oil fuels, and its high gravimetric energy content can help with voyage endurance. However, tank volume and insulation requirements increase the space allocated to fuel storage, and boil-off gas needs engineered management (Wang & Wright, 2021; Klopott et al., 2023).

LNG's WTW performance is not captured by its relatively low combustion CO_2 factor alone. Methane slip from certain engine architectures and fugitive losses along the gas value chain may substantially affect total GHG intensity, especially when methane's climate forcing is included. Comparative ship-route LCAs therefore distinguish engine type, upstream methane supply and operational loading rather than assigning a single unconditional LNG reduction value (Huang et al., 2022; Wang et al., 2025; Zamboni et al., 2024). LNG can be considered a transitional compliance option only when the actual supply pathway and engine slip are quantified.

Operational controls include double-wall or otherwise protected fuel piping, leak detection, forced ventilation, hazardous-area segregation, cryogenic protection, emergency shutdown and bunkering procedures. Crew competence and local port permits are indispensable during custody transfer and hose/connection management. Engineering practices developed for LNG offer a reference for other cryogenic fuels, but their differing ignition and dispersion properties preclude direct substitution of safety assumptions (Depken et al., 2022; Nerheim et al., 2021).

Economically, vessel retrofits and newbuilds face capital expenditure on tanks, gas supply and safety systems. Bunker pricing and geographically uneven availability create operating uncertainty. Investment should consider the vessel's remaining service life, potential transition to bio-LNG or synthetic methane, methane measurement and regulatory evolution rather than treating LNG infrastructure as automatically future-proof (Solakivi et al., 2022; Wei et al., 2023).

2.2 Methanol: liquid handling and pathway dependence

Methanol can be handled as an ambient-temperature liquid and is increasingly supported by marine dual-fuel engines, fuel supply partnerships and pilot bunkering operations. Its volumetric energy density is appreciably below conventional diesel fuels, so voyages of equal duration may require more tank volume or more frequent

bunkering. Fuel-system conversion must address material compatibility, tank arrangements, fuel conditioning and the need for approved ignition or pilot-fuel systems (DNV, 2023; Nunes, 2025; Wu & Lin, 2025).

Combustion of methanol can lower sulphur emissions and some local air pollutants, but fossil-derived methanol does not automatically deliver WTW GHG benefits. Renewable methanol produced using low-carbon hydrogen and biogenic or atmospheric carbon can show a more favourable lifecycle profile, with sensitivity to renewable electricity mix, CO_2 source, synthesis yield and transport distance. Accordingly, a nominal "80% reduction" used in a comparative scenario is a conditional assumed value rather than a verified attribute of every methanol bunker (Huang et al., 2022; Wang et al., 2025).

Toxicity, flammability, low flash point and leakage control are major implementation considerations. Methanol flames may be difficult to detect visually; procedures therefore require fuel-appropriate detection, exposure protection, ventilation, firefighting arrangements and emergency plans. Recent barrier-oriented studies show that familiarisation, operations management and interface controls are as important as hardware readiness (Ismail et al., 2025).

Fuel prices and storage penalties must be evaluated together with retrofit economics and emission-related costs. Commercial prospects improve if reliable low-carbon methanol production, origin certification and regional bunkering availability develop in parallel. Collaboration between producers, ports and shipping companies is particularly important for high-volume container and liner applications (Alamoush et al., 2023; Klopott et al., 2023; Wu & Lin, 2025).

2.3 Ammonia: carbon-free molecule, non-zero system risks

Ammonia contains no carbon and therefore produces no direct CO_2 when it is completely combusted, but this does not make every ammonia supply chain climate neutral. Conventional fossil-based production is energy-intensive; renewable ammonia requires hydrogen production, nitrogen separation and synthesis powered by low-emission energy. Lifecycle performance is sensitive to these upstream processes as well as potential nitrous oxide emissions and any pilot-fuel requirements onboard (Ishaq & Crawford, 2024; Huang et al., 2022; Fullonton et al., 2025).

As a marine fuel, ammonia can be stored as a liquid under refrigeration or pressure but has lower volumetric energy density than conventional marine oils. Engine development must address low flame speed, difficult ignition, ammonia slip, NO_x and N_2O formation, as well as suitable materials and after-treatment. Technical and economic analyses suggest a plausible future role but not automatic equivalence with mature liquid-fuel engines (Karvounis et al., 2022; Mallouppas et al., 2022).

Acute toxicity is the defining shipboard and port-interface safety challenge. Effective designs require leak containment, ventilation, gas detection, isolation, personnel-protection arrangements, exclusion zones and rigorous emergency procedures. Dispersion modelling and bunkering risk studies show that consequences depend on release location, ventilation and atmospheric conditions; generic safety scores cannot replace design-specific risk assessment (Yadav & Jeong, 2022; Duong et al., 2024). IMO interim ammonia safety guidelines recognise the need for fuel-specific measures and ongoing revision as operational experience grows (International Maritime Organization, 2025).

Economic barriers include production capacity, storage and bunker infrastructure, new engine systems and crew competence. The supply chain for fertiliser does not directly guarantee safe availability of fuel-grade ammonia at maritime bunkering locations. Roadmaps identify coordinated vessel orders, offtake contracts, port investment, financing and standards alignment as prerequisites (Balci et al., 2024; Fullonton et al., 2025).

2.4 Hydrogen: strong gravimetric energy, difficult volumetric storage

Hydrogen's high energy content per unit mass contrasts with its very low ambient-pressure volumetric density. Compressed gas or cryogenic liquid storage imposes substantial tank, insulation, boil-off and space constraints, particularly for long-distance ships. Hydrogen fuel cells offer the possibility of high-efficiency propulsion with no direct carbon emissions, whereas hydrogen combustion can create NO_x under some operating conditions. Hybrid configurations can combine fuel cells, batteries and engines depending on vessel duty cycle (Van Hoecke et al., 2021; Nerheim et al., 2021).

The WTW climate outcome depends on hydrogen production. Renewable-electrolysis hydrogen may achieve low lifecycle GHG intensity if electricity and system boundaries are appropriate; fossil-derived hydrogen without effective emissions controls may not. Compression, liquefaction, storage and distribution add energy demand. For this reason, representing all hydrogen with an identical "99% WTW reduction" is a scenario assumption, not a physical constant (Wang et al., 2025; Wang & Wright, 2021).

Safety design must account for broad flammability limits, low ignition energy, rapid buoyant dispersion, embrittlement susceptibility in some materials and potentially hard-to-see flames. Controlled ventilation, gas sensors, classified equipment, appropriate relief arrangements and validated separation distances are essential. Computational studies show that ventilation and release location strongly affect enclosed-space consequences (Depken et al., 2022; Ryu et al., 2023).

Near-term hydrogen applications are more practical for short-sea, ferry and port service routes with regular refuelling and controlled terminal infrastructure than for energy-intensive intercontinental voyages. Marine supply-chain development requires coordinated production scale, storage standards, bunkering infrastructure and workforce preparation (Van Hoecke et al., 2021; Wei et al., 2023).

2.5 Advanced biofuels: compatibility, feedstock and certification

Advanced biofuels comprise multiple products and pathways, including hydrotreated vegetable oil (HVO), fuels from waste oils and residues, and synthetic hydrocarbons derived from biomass or waste processing. Some products can be blended or used as drop-in substitutes with relatively limited changes to existing marine engines and bunker systems, while others differ in material compatibility, stability and operating properties. Fuel specification compliance and manufacturer approval remain essential rather than assumed universal interchangeability (Rony et al., 2023; Stathatou et al., 2022).

The climate benefit of a biofuel must be evaluated over land-use and feedstock boundaries, collection and conversion energy, transport and combustion. Waste-derived and sustainably produced second-generation fuels can achieve large lifecycle GHG reductions, but feedstock constraints, indirect land-use effects and inconsistent certification can erode presumed benefits. Marine biofuel lifecycle studies highlight wide variation across technologies and input materials; a fixed 90% reduction cannot be applied to every biofuel batch (Masum et al., 2023; Wang et al., 2025).

An ocean-going bulk-vessel trial demonstrated the practical relevance of directly measuring emissions and comparing lifecycle impacts of alternative liquid fuel blends (Stathatou et al., 2022). This kind of operational evidence is valuable because laboratory or sector-average estimates may not capture fuel quality, engine load, power demand and actual bunkering practice. Fuel stability, oxidation, microbial growth, cold-flow behaviour and emissions interactions also warrant attention in handling protocols.

For the transition period, existing-engine compatibility may give advanced biofuels a significant adoption advantage. However, the maritime sector competes with aviation, road transport and chemicals for constrained feedstocks. Techno-economic assessments show strong sensitivity to conversion technology, plant scale and policy treatment, while regional logistics determine bunker availability (Gartland & Pruyn, 2022; Li et al., 2022). A favourable MCDA result must therefore be conditional on sustainability certification and scalable eligible supply.

2.6 Cross-fuel implications for ports, regulation and safety

The relative merit of each alternative shifts by vessel age, cargo-space requirements, route, port calls, emissions-accounting boundaries, bunker availability and safety case. Ports play a coordinating role in storage, emergency response, procedures and training, and fuel-supply readiness remains geographically uneven (Alamoush et al., 2023; Klopott et al., 2023; Wei et al., 2023). The evidence therefore supports a conditional, application-specific comparison rather than a single fuel recommendation for every vessel class. This motivates a transparent MCDA followed by scenario and sensitivity appraisal.

3. Materials and Methods

3.1 Study design and scope

A structured comparative technical review was combined with a deterministic weighted-sum MCDA. The analysis contrasts five fuel options against seven criteria and then changes the criterion priorities to explore rank sensitivity. The unit of comparison is a stylised fuel option rather than a specific bunker batch, production route or vessel propulsion installation. Literature sources were used to establish technical context, but the numerical decision matrix is an explicit illustrative scenario. It is not a meta-analysis, lifecycle certification exercise, calibrated economic model or expert-elicited weighting study.

The evaluation procedure is summarised in Figure 1. Criteria and alternatives are specified before the scoring and weighting steps, and the resulting rankings are checked under alternative priorities. The framework prevents the reported ranking from being mistaken for an experimentally observed emissions comparison.

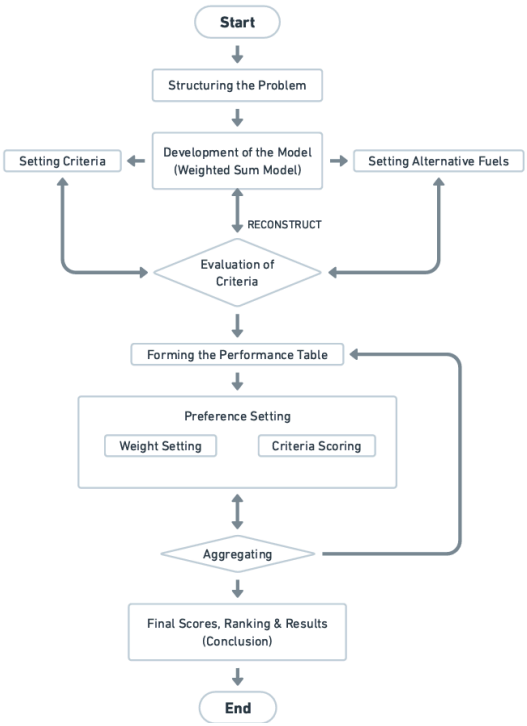


Figure 1. MCDA research sequence, from problem definition and criterion selection to weighted scoring and ranking.

3.2 Criteria, units, directions and weights

Table 1 identifies the evaluation criteria and assigned weights. $WTWCO_2$ reduction, local pollutant reduction, energy density, engine compatibility, operational safety and supply-chain readiness are treated as benefit criteria; fuel cost is a cost criterion. The two emission criteria are reported as scenario percentages, not certified emissions savings, and the single $\frac{NO_x}{SO_x}$ score is a simplified composite rather than a complete air-quality inventory.

Table 1. Evaluation criteria and baseline weights.

Criterion	Unit or scale	Direction	Weight
$WTWCO_2$ reduction	% relative to scenario reference	Benefit	0.25
$\frac{NO_x}{SO_x}$ reduction	Combined illustrative %	Benefit	0.10
Volumetric energy density	MJL^{-1}	Benefit	0.15
Engine compatibility	Judgement 1–5	Benefit	0.10
Fuel cost	Illustrative $USDGJ^{-1}$	Cost	0.20
Operational safety	Judgement 1–5; higher safer	Benefit	0.10
Supply-chain maturity	Judgement 1–5	Benefit	0.10

Table 2 displays the input decision matrix. Economic and WTW values are assumed for a stylised comparative case and should not be interpreted as 2026 spot bunker quotations or universal certified fuel-pathway factors. Engine compatibility, safety and supply-chain maturity are ordinal assessments; no respondent panel, pairwise comparison matrix or reliability testing was used to estimate them.

Table 2. Scenario inputs for the five marine fuel alternatives.

Fuel	$CO_2\%$	$\frac{NO_x}{SO_x\%}$	$\frac{MJ}{L}$	Engine /5	USD/GJ	Safety /5	Supply /5
LNG	15	89.1	22.5	5	12.5	3	4
Methanol	80	69.3	15.8	4	22.5	3	3
Ammonia	99	50	11.5	3	37.5	2	2
Hydrogen	99	95	7.05	2	42.5	2	1
Advanced biofuels	90	55	34.5	5	32.5	4	3

3.3 Normalisation and weighted aggregation

The benefit criteria that have physical units are normalised by the maximum observed among the five alternatives. The cost criterion is normalised using the minimum observed value divided by each fuel's cost. The three ordinal criteria are intentionally divided by the fixed scale ceiling of 5, rather than the highest value attained by any fuel. This fixed-scale convention is essential: dividing safety by 4 or supply-chain maturity by 4 would alter the published scores and ranking. Equations (1)–(3) show the calculation:

$$\text{Benefit (physical criterion):} \quad r_{ij} = \frac{x_{ij}}{\max_k(x_{kj})} \tag{1}$$

$$\text{Cost:} \quad r_{ij} = \frac{\min_k(x_{kj})}{x_{ij}} \; ; \quad \text{ordinal 1--5:} \quad r_{ij} = \frac{x_{ij}}{5} \tag{2}$$

$$\text{Weighted fuel score:} \quad S_i = \sum_j w_j r_{ij}, \quad \sum_j w_j = 1 \tag{3}$$

Here, i indexes the five fuel alternatives, j the seven decision criteria, x_{ij} is the criterion input in the unit stated in Table 1, r_{ij} is its dimensionless normalised score, w_j is the criterion weight and S_i is the overall score (0 to 1 under the stated transformation). The comparison contains no observed measurement error estimates and therefore does not support hypothesis testing or confidence intervals. All arithmetic uses unrounded input values; values displayed to three decimals are presentation rounding.

Table 3 presents the complete normalised criterion matrix and enables recalculation of every fuel total. The safety scale, in particular, reflects ordinal judgement about operational risk and not a measured accident rate or a substitute for fuel-specific risk assessment.

Table 3. Normalised values across the seven criteria.

Fuel	CO_2	$\frac{NO_x}{SO_x}$	Density	Engine	Cost	Safety	Supply
LNG	0.152	0.938	0.652	1.000	1.000	0.600	0.800
Methanol	0.808	0.729	0.458	0.800	0.556	0.600	0.600
Ammonia	1.000	0.526	0.333	0.600	0.333	0.400	0.400
Hydrogen	1.000	1.000	0.204	0.400	0.294	0.400	0.200
Advanced biofuels	0.909	0.579	1.000	1.000	0.385	0.800	0.600

3.4 Sensitivity scenarios

Five weight configurations were assessed to test whether first-place selection is an artefact of the baseline weighting. In addition to the baseline, carbon-priority, cost-priority, infrastructure-priority and safety-priority cases increase the corresponding criterion weights and rebalance the remainder to sum to one. These are transparent policy preference scenarios, not empirically measured decision-maker preferences. The complete weights and scores are shown in Table 5 following the main ranking results.

4. Results

4.1 Recalculated overall rankings

Table 4 reports the weighted contributions and the final rank for each fuel. Advanced biofuels have the highest score, followed by LNG, methanol, ammonia and hydrogen, when the specified scenario values and weights are used. The sums reproduce the main numerical ranking without relying on rounded intermediate entries.

Table 4. Weighted contributions, aggregate MCDA scores and ranks.

Fuel	C1	C2	C3	C4	C5	C6	C7	Total	Rank
LNG	0.038	0.094	0.098	0.100	0.200	0.060	0.080	0.6695	2
Methanol	0.202	0.073	0.069	0.080	0.111	0.060	0.060	0.6548	3
Ammonia	0.250	0.053	0.050	0.060	0.067	0.040	0.040	0.5593	4
Hydrogen	0.250	0.100	0.031	0.040	0.059	0.040	0.020	0.5395	5
Advanced biofuels	0.227	0.058	0.150	0.100	0.077	0.080	0.060	0.7521	1

The overall spread is visualised in Figure 2, which emphasises that the leading advanced-biofuel score is only about 0.083 points above LNG, while LNG and methanol are separated by approximately 0.015 points. Such differences are meaningful inside the assumed calculation, but do not imply measurable real-world superiority without pathway-specific evidence.

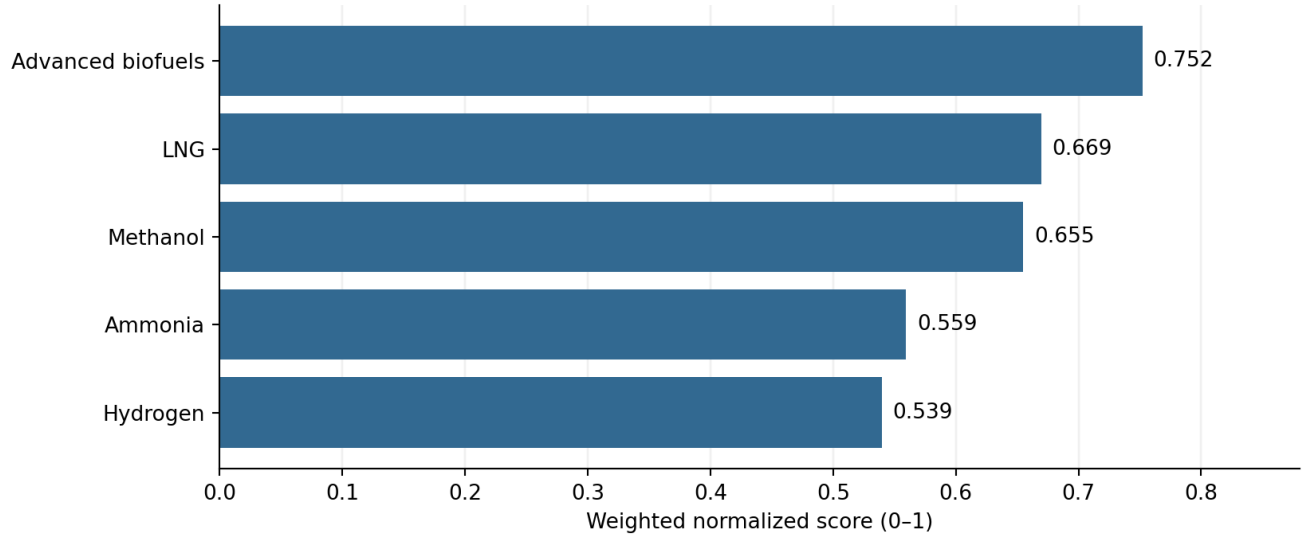


Figure 2. Weighted-sum scores for the five alternative fuel groups under baseline criterion weights.

4.2 Contribution of individual criteria

As illustrated in Figure 3, advanced biofuels score highly in the assumed energy-density and engine-compatibility dimensions, whereas LNG benefits from assumed cost and supply-chain maturity. Ammonia and hydrogen score well on the illustrative $WTWCO_2$ criterion but are penalised by cost, storage or readiness assumptions. The display highlights trade-offs that a single aggregate score can conceal.



Figure 3. Normalised criterion values for all fuel alternatives. Higher values are preferable in every displayed column after transformation.

4.3 Sensitivity to evaluation priorities

Table 5 specifies all scenario weights and resulting scores. In the cost-priority case, LNG rises to first place (0.817), ahead of advanced biofuels (0.653); the infrastructure-priority case also narrowly favours LNG (0.742 versus 0.732). In the carbon- and safety-priority cases, advanced biofuels retain first place. Sensitivity thus establishes that the baseline result is not invariant to the decision-maker's objectives.

Table 5. Alternative decision weights and leading options by scenario.

Scenario	CO_2	Air	Density	Engine	Cost	Safety	Supply	First-place fuel
Baseline	0.250	0.100	0.150	0.100	0.200	0.100	0.100	Advanced biofuels
Carbon priority	0.450	0.100	0.100	0.075	0.075	0.100	0.100	Advanced biofuels
Cost priority	0.100	0.100	0.150	0.100	0.400	0.050	0.100	LNG
Infrastructure priority	0.150	0.100	0.100	0.150	0.150	0.100	0.250	LNG
Safety priority	0.150	0.100	0.100	0.100	0.150	0.300	0.100	Advanced biofuels

Figure 4 plots all five alternatives across the sensitivity scenarios. This comparison must be interpreted alongside the input limitations: uncertain fuel prices, carbon intensity, operational safety characteristics and infrastructure status may change independently of the weights, and this exercise does not substitute for multi-parameter uncertainty propagation.

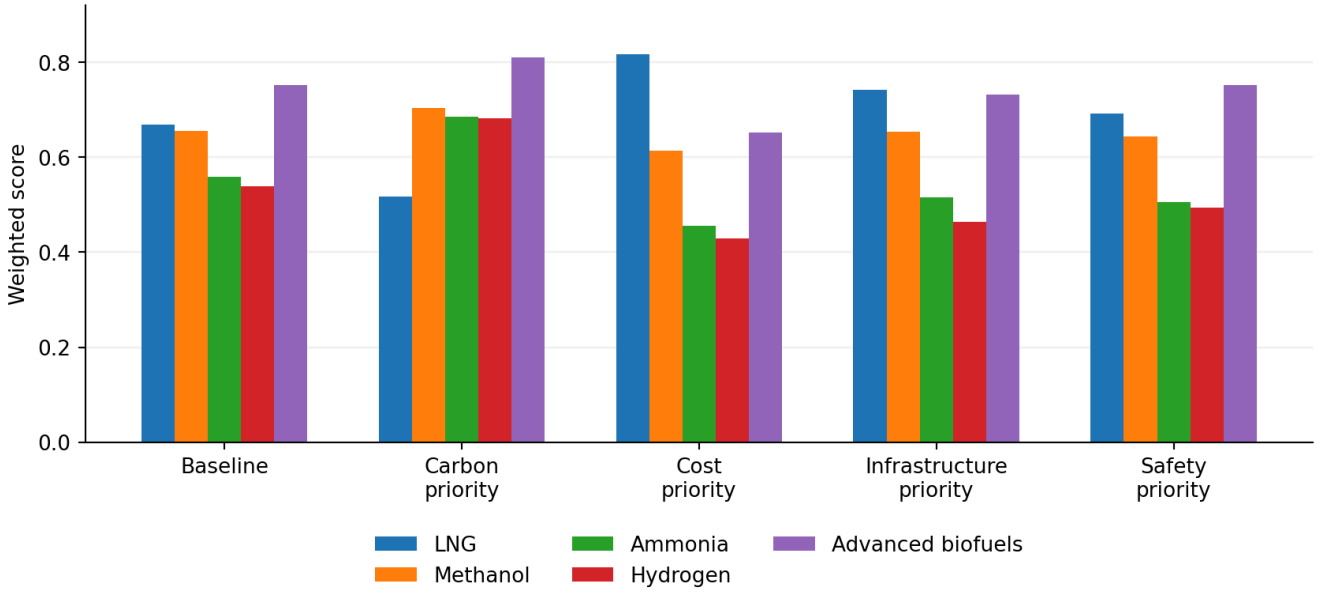


Figure 4. Fuel scores under baseline and four alternative criterion-weight configurations.

5. Discussion

5.1 Interpretation of the near-term results

Advanced biofuels rank highest because the base case assigns relatively strong scores to engine compatibility, energy density and WTW GHG potential. The outcome is consistent with evidence that certain renewable drop-in fuels can be used on existing vessel platforms, including demonstration work aboard oceangoing vessels (Stathatou et al., 2022). Nevertheless, feedstock availability, certification, full fuel specification and batch quality determine whether the presumed reductions are achievable. Life-cycle biofuel estimates vary markedly with technology, system boundary and feedstock allocation (Masum et al., 2023; Li et al., 2022).

LNG performs strongly on the cost and infrastructure dimensions, consistent with the maturity of its engine and bunkering ecosystem, but its apparently modest $WTWCO_2$ reduction is highly sensitive to upstream emissions and engine methane slip. LNG should therefore be assessed using measured or certified WTW values rather than averaged TTW claims. A transport operator selecting an LNG pathway because of lower capital or fuel costs may face a different climate outcome from an otherwise identical ship using renewable methanol or low-carbon biofuel (Huang et al., 2022; Solakivi et al., 2022).

Methanol's relatively close baseline score suggests that route-specific applications may invert the LNG/methanol order through changes in green-methanol supply, carbon accounting or storage arrangements. The engine-system and safety trade-offs do not disappear with increased availability of renewable methanol; protective controls for fuel toxicity and fire remain part of the operating case (Ismail et al., 2025; Nunes, 2025; Wu & Lin, 2025).

5.2 Long-term carbon-free molecules and technology readiness

Ammonia and hydrogen receive lower near-term aggregate values in the scenario, principally through energy-density, cost, engine integration and fuel-supply penalties. The figures do not demonstrate that their long-term emissions potential is inferior. With renewable production, effective management of fuel-cell or combustion emissions and wider bunkering networks, both fuels could improve substantially against the same framework (Ishaq & Crawford, 2024; Van Hoecke et al., 2021).

The operational risks remain fuel-specific. Ammonia requires robust toxic-gas containment and potential $\frac{NO_x}{N_2}O$ management. Hydrogen requires validated leak dispersion, ventilation, cryogenic or pressure storage and hydrogen-compatible materials. IMO safety guidance, model-specific consequence analyses and crew training should be integrated into vessel appraisal before any deployment recommendation (International Maritime Organization, 2025; Depken et al., 2022; Duong et al., 2024; Yadav & Jeong, 2022).

Future comparative studies should distinguish ammonia combustion engines from ammonia-to-hydrogen or fuel-cell pathways and should compare compressed and cryogenic hydrogen separately. Treating a chemical carrier as a homogeneous technology conceals operationally important differences. Bunkering, tank volume and trade-route design also make the favourable option for a harbour craft potentially different from that for an ocean-going tanker (Nerheim et al., 2021; Ryu et al., 2023).

5.3 Implementation strategy and decision governance

A credible maritime fuel transition begins with certified pathway-specific WTW factors and a defined vessel mission. Only then should investors compare total ownership costs, cargo-volume penalties, machinery changes, local emissions performance, emergency response and long-term supply contracts. Ports and flag administrations have important coordinating functions because vessels, terminals, training institutions and fuel producers must adopt compatible systems (Alamoush et al., 2023; Klopott et al., 2023; Wei et al., 2023).

Figure 5 summarises a practical four-stage planning sequence. It is proposed as a conceptual decision procedure for subsequent operational studies, not as an empirically evaluated intervention. Repeated reassessment is essential because verified lifecycle performance, fuel pricing and regulations will evolve.

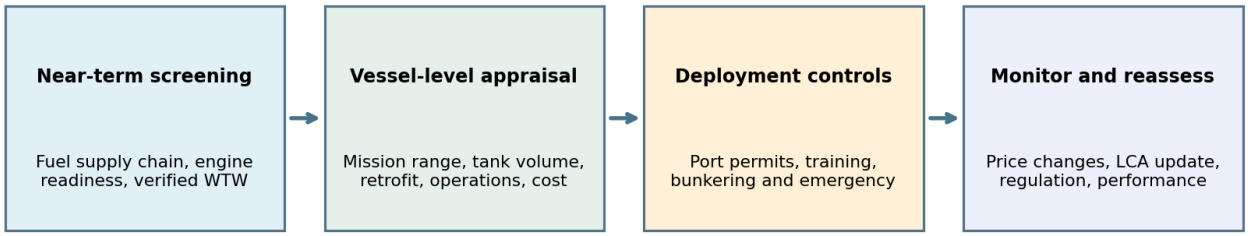


Figure 5. Proposed staged framework for fuel-pathway screening, vessel-level assessment, operational controls and ongoing review.

5.4 Methodological strengths and limitations

The main advantage of this MCDA is transparency: its raw values, transformation rules, weights and resulting ranking can all be inspected and recomputed. However, this is not a validated empirical ranking. The input values represent a stylised cross-fuel scenario and combine pathway-dependent lifecycle assumptions with engineering characteristics and judgement-based maturity scores. Uncertainty intervals are unavailable, and the air-pollutant criterion combines NO_x and SO_x reductions into one figure despite their distinct combustion and regulatory drivers.

Weighting is a normative decision rather than a statistical estimate. No Delphi process, analytic hierarchy pairwise matrix, stakeholder elicitation, expert consensus or Monte Carlo uncertainty assessment generated the weights. The sensitivity results illustrate the consequences of alternative priorities, not the likelihood that any policy outcome will occur. In particular, assigning the same $WTWCO_2$ reduction to all ammonia or hydrogen production routes would be scientifically inappropriate (IMO, 2024; Wang et al., 2025).

Finally, fuel options are not homogeneous. LNG engine methane slip, renewable methanol feedstock, ammonia N_2O controls, hydrogen storage route and biofuel conversion pathway can alter each criterion. Results should be recalculated for a specified ship, engine cycle, bunker corridor, fuel certificate and forecast price. Future work could use scenario-specific probability distributions, constrained optimisation, full lifecycle inventory, cost-of-ownership estimation and quantitative safety assessment.

6. Conclusion

This study compared five alternative marine-fuel families using a transparent seven-criterion weighted-sum MCDA and a detailed review of environmental, engineering, safety, economic and bunkering constraints. With the stated input assumptions and fixed qualitative-scale normalisation, advanced biofuels score 0.752, LNG

0.669, methanol 0.655, ammonia 0.559 and hydrogen 0.539. Cost-priority and infrastructure-priority weightings reverse the leading position in favour of LNG, confirming the conditional nature of the baseline result. Near-term opportunities for advanced biofuels depend on certified sustainable feedstocks and fuel quality; LNG and methanol require pathway-specific lifecycle assessment; and ammonia and hydrogen need further safety, technology and infrastructure development. The operationally defensible recommendation is a staged, vessel-specific appraisal based on verified WTW emissions, mission requirements, total cost and fuel-specific safety cases rather than a universal ranking. A transition toward net-zero shipping will depend on coordinated fuel supply, onboard engineering, port readiness and evolving regulatory assurance.

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

During the preparation of this work, the authors used ChatGPT in order to improve language and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Conflict of Interest

No competing-interest declared

Author Contributions

Amirulaminfirdaus Mohd Yusof contributed to the conceptualization of the research and reviewing and editing the manuscript.

Data Availability Statement

The MCDA scenario input matrix and calculated outputs are contained in Tables 1–5

Ethics Statement

This research is a literature-supported calculation-based assessment. No human-participant recruitment or experiments are reported.

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