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A Systematic Review on Maritime Decarbonization: The Synthesis, Implications, and Strategies of a Decade of Alternative Fuels for Shipping

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Abstract

The maritime industry faces an unprecedented challenge to achieve the net-zero emissions goal by or around 2050. While numerous alternative fuels are undergoing intense evaluation, the industry remains trapped in a profound 'technological deadlock' driven by the irreconcilable trade-offs of current options, where fuel might offer excellent environmental profiles but fail on economic viability or safety acceptance. This study addresses this uncertainty by systematically reviewing 39 studies published from 2015 to 2025 that evaluated alternative fuels for the shipping industry using various criteria. Unlike traditional reviews, this study employs a horizontal synthesis across environmental, economic, technical, safety, and social criteria. By cross-examining these fragmented dimensions, this study maps the core friction points that prevent the scalable deployment of alternative fuels. The synthesis indicates that the regulatory framework should shift from static measures to dynamic, phased carbon pricing to address the immediate green premium of alternative fuels. Additionally, the analysis points to a looming global human capital bottleneck and a significant geographic risk of a two-tier global fleet. Most significantly, this study consolidates a decade of marine fuel evaluations into a practical, strategic fuel-deployment matrix that provides industry managers and global policymakers with a clear roadmap to overcome decision-making inertia and safely guide the maritime transition.

Keywords: maritime; decarbonization; shipping; alternative fuel; net zero; seafaring; life cycle assessment; green premium; techno-economic barriers

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1. Introduction

The decarbonization of the maritime industry and the adoption of alternative fuels for international shipping represent one of the most complex industrial challenges of the twenty-first century. Over the last hundred years, maritime logistics has relied on a monoculture of propulsion, powered almost exclusively by heavy fuel oil (HFO). However, the International Maritime Organization's (IMO) revision of its Greenhouse Gas (GHG) Strategy in 2023 marked a definitive end to this era, replacing vague aspirations with a concrete mandate for net-zero emissions by or around 2050 [1]. This regulatory framework is fundamentally altering the industry's operational logic. The operational strategies, such as energy-efficiency measures, such as slow steaming or hull optimization, which were once considered sufficient, are now merely palliative. The industry is currently forced to navigate

a radical energy transition toward alternative fuels such as ammonia, hydrogen, methanol, and biofuels [2]. Yet, as the regulatory timeline accelerates, the path to compliance has become increasingly opaque, characterized not by a lack of options but by an overwhelming surplus of technically feasible yet commercially unproven energy options.

Despite the urgency, the industry is currently trapped in a state of investment paralysis, or a technological deadlock. Shipowners are forced to make thirty-year asset decisions in an environment of extreme uncertainty, where the optimization of one variable often catastrophically compromises another [3]. For instance, while Liquefied Natural Gas (LNG) offers immediate commercial maturity and local emission reduction benefits, its long-term viability is threatened by methane slip and tightening well-to-wake (WtW) carbon accounting [4,5]. Conversely, hydrogen and ammonia offer the theoretical promise of zero tailpipe emissions, yet they impose severe penalties in terms of volumetric storage density, toxicity risks, and capital expenditure (CAPEX) [6,7]. This creates a dangerous first-mover disadvantage, where investing in the wrong fuel infrastructure could lead to massive asset stranding. The central problem facing the maritime sector is therefore not scientific, but systemic: how to reconcile the conflicting demands of environmental sustainability, economic viability, and operational safety in a market where no single silver bullet solution exists.

While a proliferation of academic literature has emerged during the last decade to address these challenges, the existing body of knowledge remains largely siloed. Engineering-focused reviews, such as those by Xing et al. [8], often provide rigorous thermodynamic analyses of hydrogen, methanol, and ammonia but fail to adequately account for the prohibitive green premium that currently renders them unbankable. Conversely, economic analyses, such as those by Ren & Lützen [9], frequently use Multi-Criteria Decision Making (MCDM) models that rank fuels based on cost and maturity, often underestimating the social license-to-operate constraints posed by toxic fuel handling in populated ports. There is a conspicuous scarcity of scholarship that synthesizes the interdependence between these domains. No recent study has effectively reviewed the juxtaposition of safety and environmental consensus to explain why the industry remains deadlocked. Consequently, stakeholders are left with fragmented evidence that obscures the necessary trade-offs required to move forward [10–12].

This study addresses this gap by departing from the traditional fuel-by-fuel review structure. Instead of analyzing each energy option in isolation, this paper adopts a horizontal, criterion-based synthesis of 39 peer-reviewed studies published in the last decade. By structuring the analysis across functional dimensions rather than fuel types, this review exposes the specific friction points that are stalling decarbonization. To systematically navigate this complex transition and address the fragmented nature of the current discourse, this review is guided by four primary research questions (RQs):

- *RQ1:* What alternative marine fuels and energy vectors are predominantly evaluated for deep-sea decarbonization within the current literature?
- *RQ2:* What multi-dimensional criteria are utilized by stakeholders to assess the viability of these alternative fuels?
- *RQ3:* What fundamental tensions, trade-offs, and friction points exist between these conflicting evaluation dimensions?
- *RQ4:* Based on the synthesis of these tensions, what are the actionable policy and managerial implications required to break the industry's technological deadlock?

While isolated engineering or maritime economics literature frequently evaluates alternative fuels in technical silos, navigating the deep-sea energy transition requires an integrated assessment that simultaneously spans environmental lifecycle impacts, economic viability, and social acceptance. By deploying a horizontal review or synthesis that simulta-

neously cross-examines the technical, economic, environmental, and social dimensions, this study connects directly with contemporary frameworks in interdisciplinary sustainability science. Ultimately, this study bridges the gap between raw marine engineering data and practical governance, offering an actionable decision-making framework for managing complex, long-term socio-technical transitions.

The remainder of the paper is structured as follows: Section 2 details the systematic literature selection process following PRISMA guidelines (Table S1). Section 3 offers a critical synthesis of evidence, analyzing fuels from environmental, economic, technical, and social perspectives. Section 4 discusses policy implications, focusing on current regulatory tools such as the Carbon Intensity Indicator (CII). Finally, Section 5 outlines managerial implications for industry stakeholders, and the concluding remarks highlighted in Section 6.

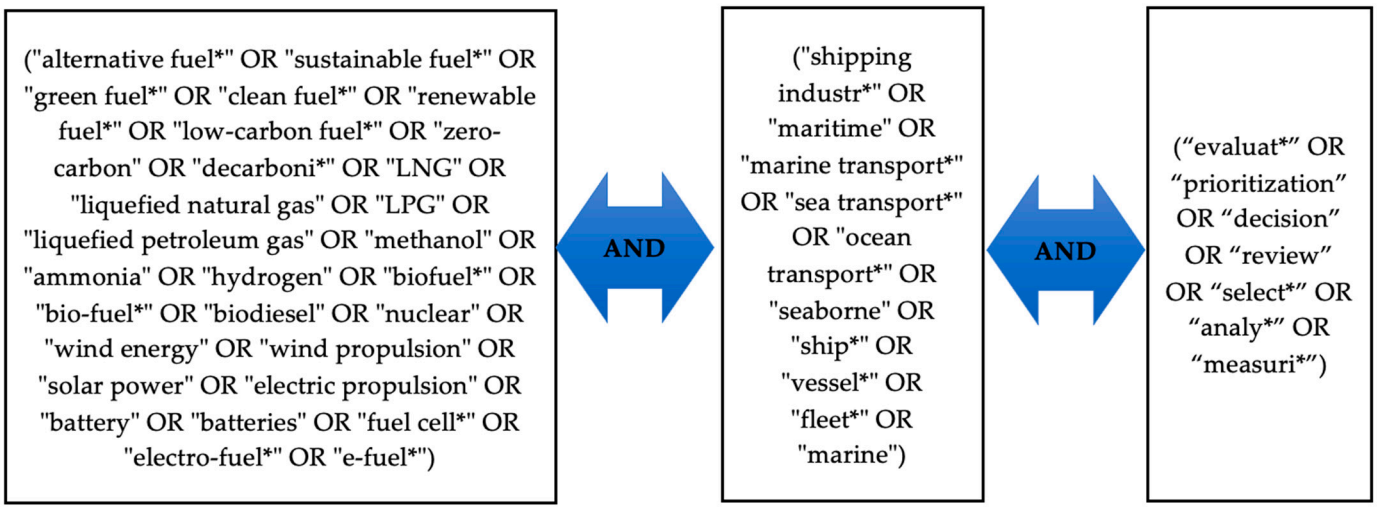
2. Methodology

To provide a comprehensive and unbiased evaluation of the studies about alternative fuels in the maritime domain, this study adopted a Systematic Literature Review (SLR) approach. The review process was designed to identify, screen, and synthesize high-quality peer-reviewed studies published during the last decade (2015 to 2025). The methodology follows the principles of transparency and reproducibility, ensuring that the selected literature accurately reflects the current state of decarbonization technologies for the international shipping industry.

2.1. Search Strategy and Data Sources

The primary literature search was conducted using the Scopus database, selected for its extensive coverage of engineering, energy, and transportation disciplines and its rigorous indexing of high-impact journals [13]. The choice to utilize Scopus as the primary search engine for this systematic review is grounded in established bibliometric methodologies. While multi-database strategies (e.g., combining Scopus with Web of Science) are common, comparative database analyses indicate that Scopus provides broader coverage of interdisciplinary sustainability, marine policy, and maritime engineering literature than other databases, while maintaining a significantly higher threshold for peer-reviewed quality control than unstructured engines like Google Scholar [14]. The inclusion of secondary databases often introduces significant empirical redundancy while increasing the risk of methodological noise [15]. Consequently, Scopus was selected to ensure maximum data consistency, rigorous peer-review filtering, and comprehensive metadata extraction capabilities for our horizontal synthesis. To mitigate any residual risk of omission, the Scopus search was supplemented with a manual 'snowballing' technique (backward and forward citation tracking) of the final selected articles, ensuring that no seminal paper was excluded.

To ensure reproducibility, the literature retrieval was executed using a comprehensive TITLE-ABS-KEY automated search string within the Scopus database. The inclusion logic targeted alternative marine energy vectors using the string:



Crucially, to align with this study's delimited focus on international deep-sea merchant shipping, an algorithmic exclusion protocol was applied to eliminate irrelevant maritime segments. The automated Boolean logic utilized the following exclusion modifiers: ***AND NOT (inland OR "short-sea" OR coastal OR ferry OR ferries OR naval OR "small craft" OR battery)***. This precise filtration prevented the dataset from being skewed by literature focused on domestic electrification and short-haul logistics, which possess fundamentally different techno-economic abatement profiles.

2.2. Inclusion and Exclusion Criteria

Following the initial retrieval from the Scopus database, a multi-stage screening process was applied to refine the dataset. The selection process was governed by strict inclusion and exclusion criteria (Table 1) to ensure the relevance and quality of the evidence base as suggested in previous studies [16,17].

Table 1. Inclusion and exclusion criteria for studies.

Category	Inclusion Criteria	Exclusion Criteria
1. Subject Area/Context	Maritime	Non-maritime
2. Publication Period	Published between 2015 and 2025 (capturing post-IMO 2020 Sulphur Cap and 2023 GHG Strategy frameworks).	Studies published before 2015.
3. Language	Published exclusively in the English language.	Studies published in any other language.
4. Document Type	Peer-reviewed journal articles containing empirical findings or qualitative/quantitative techno-economic simulation modeling designs.	Grey literature (theses, technical reports, letters to the editor); conference proceedings; book chapters; narrative reviews.
5. Operational Scope	Focus on international merchant shipping operations.	Focus exclusively on inland waterways, short-sea shipping, or non-merchant vessels (e.g., naval ships, fishing fleets, tugboats).
6. Synthesis Focus	Comparative, multi-fuel evaluations of alternative marine fuels addressing technical, economic, environmental, or safety dimensions.	Unidimensional analyses (e.g., focusing solely on engine thermodynamics without economic modeling); evaluations of a single fuel in isolation.

Timeline (2015–2025): The search was restricted to the last decade. This timeframe was selected to capture the most recent technological advancements and policy shifts

(such as the IMO 2020 sulphur cap [18] and the 2023 IMO GHG Strategy [19]) that have fundamentally altered the viability of specific fuels.

Document Type and Language: To ensure the academic rigor of the review, only peer-reviewed journal articles published in the English language were included. Conference proceedings, book chapters, and grey literature were excluded to prioritize validated research findings.

Subject Area: The search was refined to include key subject areas relevant to technical and economic assessment, including Engineering, Energy, Environmental Science, Mathematics, and Physics. The inclusion of Mathematics and Physics was deemed critical to capture studies utilizing MCDM frameworks and thermodynamic efficiency analyses.

The screening process was conducted in accordance with PRISMA guidelines. To minimize selection bias, a double-blind screening protocol was employed. Two independent reviewers initially screened the titles and abstracts of the retrieved literature. Any disagreements regarding paper eligibility were resolved through discussion and the intervention of a third senior researcher until a consensus was reached.

To ensure the synthesis was built upon methodologically sound evidence, a quality assessment was conducted on all full texts prior to final inclusion. Drawing upon principles from the Mixed Methods Appraisal Tool (MMAT), studies were evaluated based on three critical quality indicators: (1) transparency of the system boundaries (e.g., Well-to-Wake vs. Tank-to-Wake), (2) empirical validity of the techno-economic assumptions (e.g., carbon pricing inputs), and (3) peer-review status in Q1/Q2 indexed journals. Papers that lacked transparent data sources for their economic modeling or relied on opaque LCA system boundaries were excluded to maintain the rigor of the synthesis.

2.3. Screening and Relevance Assessment

The refined search yielded a total of 191 potential articles. A manual screening of titles and abstracts was subsequently performed to assess alignment with the research objectives. A central criterion for this review was the focus on international merchant shipping. Consequently, studies were excluded if they focused exclusively on inland waterways, short-sea shipping, or non-merchant vessels (e.g., naval ships, fishing fleets, or tugboats). Following this abstract screening, 113 papers were identified as eligible for full-text review. As illustrated in the PRISMA flow diagram (Figure 1), the significant reduction in the literature during the full-text screening phase (from 113 to 39 papers) was primarily driven by strict adherence to the inclusion criteria. Specifically, 52 papers were excluded because they conducted unidimensional analyses (e.g., focusing solely on engine thermodynamics without economic modeling), and 22 papers were excluded because they evaluated a single fuel in isolation rather than providing the comparative, multi-fuel assessment required to answer this study's research questions. Papers were retained only if they provided a comparative evaluation of one or more alternative fuels based on specific criteria (e.g., techno-economic analysis, environmental impact, or safety assessments) for the international shipping industry.

Following the selection of the final 39 studies, data extraction was conducted using a hybrid thematic coding approach. Initially, a deductive coding framework was applied to categorize the findings into four pre-established horizontal dimensions: Environmental Lifecycle, Economic Viability, Technical Maturity, and Safety/Social Acceptance. Subsequently, an inductive thematic analysis was performed within these categories to identify emergent patterns, barriers, and trade-offs (e.g., the recurrence of "ammonia toxicity" as a barrier within the social acceptance pillar).

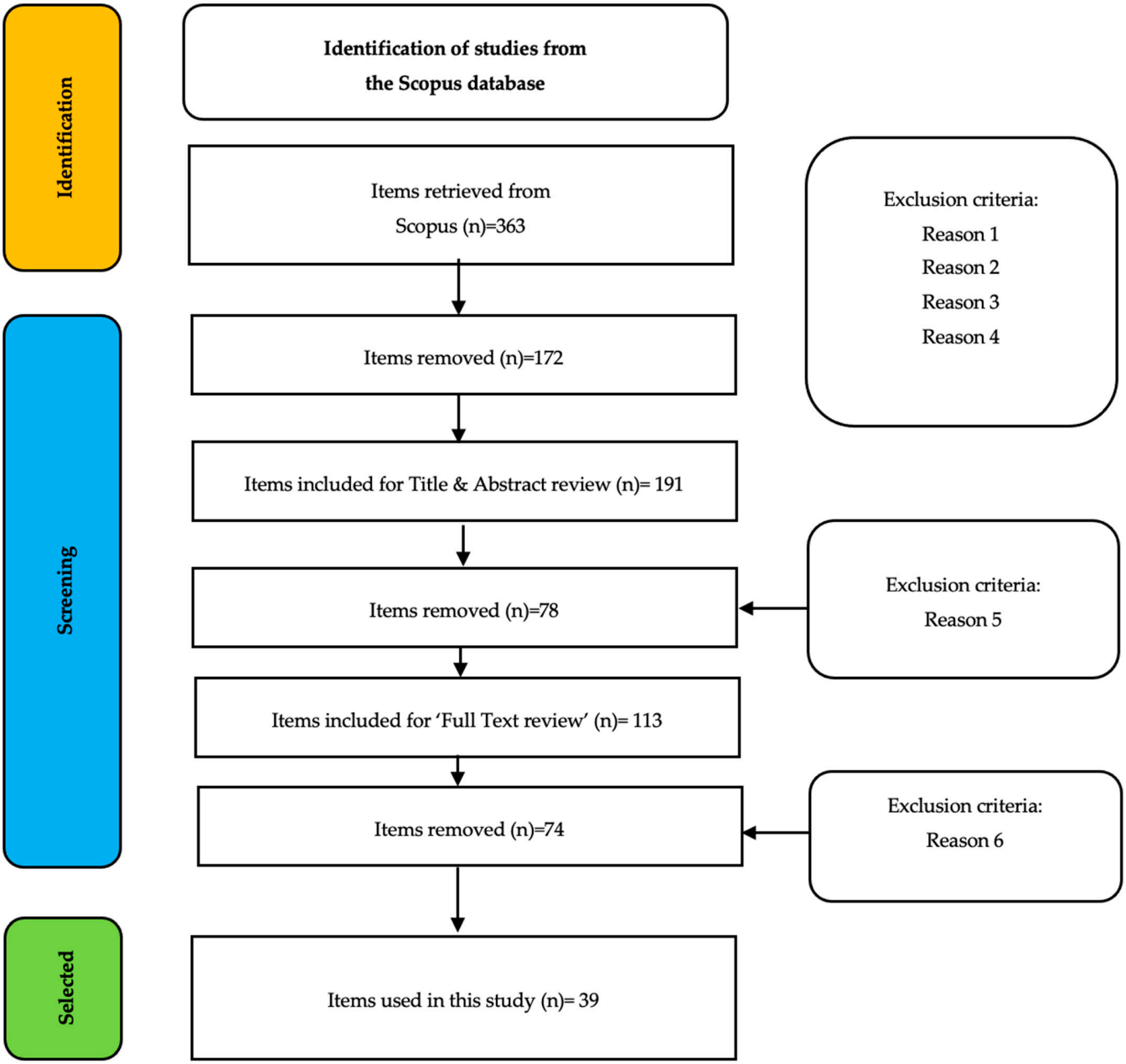


Figure 1. PRISMA flow diagram.

2.4. Backward Snowballing and Final Selection

Exclusive reliance on a single primary database may introduce an inherent risk of database bias, a structural limitation of this review. While Scopus overlaps extensively with alternative repositories such as Web of Science and IEEE Xplore, it is possible that highly localized, multidisciplinary, or grey literature on alternative marine fuels was omitted from the initial search matrix. To mitigate the limitations of keyword-based searching and ensure the comprehensiveness of the review, a "backward snowballing" technique was employed [16,20]. The reference lists of the selected papers were examined to identify seminal studies or highly relevant comparative analyses that may have been omitted by the initial search string. This iterative process identified an additional 8 relevant articles within the timeframe of 2015 to 2025. These studies form the basis of the synthesis presented in the subsequent sections. This strategic safeguard ensured that seminal, cross-referenced studies were captured regardless of their primary indexing platform, thereby preserving the holistic integrity of the horizontal synthesis.

3. Review of the Evaluations of Alternative Fuels for Shipping

The maritime industry is actively exploring a wide range of alternative fuel options to achieve its ambitious decarbonization goals. Historically, academic research has primarily focused on Liquefied Natural Gas (LNG) as a main alternative to traditional shipping fuels. However, a noticeable shift is occurring in scholarly discussions, as increasing attention is now being directed toward alternative fuels such as methanol, ammonia, and hydrogen [21]. Beyond these, biofuels are also recognized for their potential to considerably cut lifecycle CO_2 emissions, offering a path toward a more sustainable maritime industry [4]. Additionally, electric propulsion systems are emerging as promising technologies for achieving zero-emission shipping, particularly for specific vessel types and operational profiles [22]. The trend of academic research shifting from LNG to fuels like methanol, ammonia, and hydrogen suggests a forward-looking consensus within the scientific community regarding the long-term viability and potential of these fuels for pragmatic decarbonization. Academic research often acts as an early indicator of future industry trends and technological breakthroughs. Hence, the shift suggests that significant research, development, and investment will focus on these areas in the years to come. This provides a strategic roadmap for stakeholders aiming to align with future regulations and market demands for sustainable shipping.

Adopting the right alternative fuel is crucial as it significantly impacts a shipping company's decarbonization strategies and future fleet growth. Factors such as technological readiness, cost efficiency, infrastructure availability, and regulatory compliance create ambiguity in choosing the most appropriate fuel option, leading the industry to await and see' strategy [23]. Additionally, different fuels have different economic, environmental, infrastructural, and safety-related advantages and disadvantages [24]. Decision-makers often face conflicting considerations when selecting the most sustainable fuel that offers the best overall economic, environmental, technical, and safety performance. Therefore, previous studies heavily focused on assessing alternative fuels from diverse perspectives. This study synthesizes the evaluation of alternative marine fuels during the last decade under four critical dimensions: (a) environmental performance and life cycle assessment, (b) economic viability and cost dynamics, (c) infrastructure readiness and technical maturity, and (d) safety, risk, and social acceptance.

3.1. Environmental Performance and Life Cycle Assessment

The environmental efficacy of alternative fuels is the primary criterion in most reviewed studies, yet the literature shows a pronounced divergence between results from tank-to-wake (TtW) analyses and those from well-to-wake (WtW) life cycle assessments (LCA). WtW is a comprehensive lifecycle assessment (LCA) perspective that evaluates greenhouse gas emissions from initial fuel production through to its final end-use by a ship [25]. WtW is calculated as the sum of Well-to-Tank (WtT) emissions—encompassing extraction, conversion, and bunkering. On the other hand, Tank-to-Wake (TtW) emissions—focusing exclusively on direct downstream emissions generated during a vessel's operations [5,26]. This distinction is non-trivial; it fundamentally alters the ranking of transitional fuels such as Liquefied Natural Gas (LNG) and Methanol.

3.1.1. The Methane Slip Controversy

Evaluating LNG as a sustainable marine fuel reveals considerable volatility over the past decade. In the initial stages of the review, LNG was widely regarded as the best solution for immediate environmental compliance. Research by Deniz and Zincir [27], Ren and Lützen [9] and Hansson et al. [28] highlighted LNG as a superior alternative to Heavy Fuel Oil (HFO), mainly because of its near-complete elimination of SO_x (99%) and

Particulate Matter (PM), along with a potential CO_2 reduction of 20–25%. These early assessments typically adopted tank-to-wake boundaries, focusing only on emissions from ship combustion, which allowed LNG to perform well in multi-criteria decision-making (MCDM) analyses.

However, a significant shift in this consensus emerges in the literature after 2019, with a focus on more accurate accounting of methane slip—the unburned methane that escapes from engines. Recent studies by Zincir and Arslanoglu [4] and Wang and Iris [5] dispute the earlier positive portrayal of LNG, providing evidence that the Global Warming Potential (GWP) of methane (28–34 times that of CO_2 over a century) effectively diminishes its carbon advantages when low-pressure dual-fuel engines are used. In stark contrast, to earlier studies by Deniz and Zincir [27] and Hansson et al. [28] where LNG was considered as a highly sustainable option, the latest lifecycle studies by Al-Enazi et al. [29], Lee et al. [26] and Zamboni et al. [25] classify LNG as only a transitional fossil fuel with limited long-term relevance in a net-zero framework. Trend analysis indicates a hardening of scholarly opinion against LNG; it is increasingly seen not as an ultimate solution but as a temporary compliance measure, with its environmental credibility waning as upstream emissions, leakage, and slip are more thoroughly measured. Crucially, the synthesized literature emphasizes that methane slip is not a uniform penalty but is heavily dictated by engine architecture. Studies consistently highlight a stark contrast: Low-Pressure Dual-Fuel (LPDF) engines operating on the Otto cycle can exhibit slip rates of 2% to over 3%, depending on engine load, severely compromising their well-to-wake GHG profile. Conversely, High-Pressure Dual-Fuel (HPDF) engines operating on the Diesel cycle have effectively minimized unburned methane to approximately 0.2%. Therefore, the environmental viability of LNG depends on shipowners selecting more complex, capital-intensive engine technologies.

3.1.2. Well-to-Wake (WtW) Emissions

A similar methodological tension arises in the evaluation of hydrogen and ammonia, where the literature strictly distinguishes between their theoretical potential and production reality. When it comes to combustion, there is universal agreement: Foretich et al. [30] and Xing et al. [8] identified hydrogen and ammonia as the only true zero-emission fuels because they produce no CO_2 during propulsion. This view is also supported by Ren and Liang [31]. Consequently, studies focusing on 'exhaust' emissions, such as the stakeholder analysis by Hansson et al. [28] and Strantzali et al. [32], find that government authorities consistently rank hydrogen as the most attractive alternative fuel for the shipping industry because it perfectly aligns with national decarbonization goals.

Yet, when the system boundary is expanded to a well-to-wake perspective, this environmental superiority is often dismantled. Comparative assessments by Al-Enazi et al. [29], Ramsay et al. [2] and Tomos et al. [33] emphasize that over 95% of current global hydrogen and ammonia production is fossil-fuel-based (grey or brown pathways), resulting in lifecycle carbon footprints that often exceed those of conventional marine diesel. Xing et al. [8] provide a detailed critique, noting that while green ammonia produced via electrolysis powered by renewables reduces GHG emissions by over 90%, the current energy mix renders grey ammonia environmentally counterproductive. This body of evidence underscores a critical caveat for the industry: the environmental validity of hydrogen and ammonia is not intrinsic to the molecules themselves but is entirely contingent on the decarbonization of the upstream electrical grid. Therefore, the literature from 2023 to 2025 increasingly treats these fuels not as solutions in situ but as dependent variables within the broader energy transition.

3.1.3. Biofuels Feedstock Constraints

In the domain of drop-in fuels, the literature presents a unique conflict between scalability and sustainability. Biofuels (FAME, HVO) are consistently identified by researchers such as Kesieme et al. [34] and Hellström et al. [35] as the most effective immediate intervention for the existing fleet, offering GHG reductions of 70% to 90% without requiring engine retrofits. Unlike the speculative infrastructure required for hydrogen, biofuels are praised for their compatibility with current two-stroke and four-stroke engine architectures [36].

However, biofuels are primarily produced from biomass, plant-based sources, or waste animal fats [34]. As a result, enthusiasm for biofuels is tempered by persistent concerns about Indirect Land Use Change (ILUC) and feedstock availability. Islam Rony et al. [37] showed that the current supply of feedstock can meet only 15% of the current fleet's demand. Kesieme et al. [34] explicitly highlight the 'food vs. fuel' ethical dilemma, arguing that first-generation biofuels derived from crops fail to meet sustainability criteria when arable land displacement is factored into the life-cycle assessment. This contrasts with the findings of Tomos et al. [33], who argue that waste-derived biofuels bypass these ethical concerns and offer the highest immediate carbon reduction potential of any liquid fuel.

The synthesis of these studies points to a bifurcated conclusion: while biofuels are technically the lowest-hanging fruit for decarbonization, their long-term viability is constrained by inelastic feedstock supply. The literature suggests they will likely serve as a premium niche solution rather than a scalable replacement for the 300 million tons of HFO used annually by the shipping industry. To circumvent the 'food versus fuel' ethical dilemma and the associated land-use constraints of first-generation crops (e.g., FAME), recent literature increasingly points toward advanced alternatives. Second-generation biofuels (derived from lignocellulosic biomass and agricultural residues) and third-generation biofuels (algae-based synthetic fuels) theoretically decouple marine decarbonization from global food security. However, the current consensus across the reviewed studies indicates that these advanced generations have not yet achieved the commercial scalability or cost parity required to service the deep-sea fleet's immense volumetric demands.

3.1.4. Synthesis of Environmental Trends

A longitudinal analysis of the literature elucidates a paradigm shift in the definition of environmental sustainability, moving from a compliance-based focus on exhaust composition to a holistic evaluation of lifecycle carbon intensity. Early studies, particularly those before 2020, prioritized LNG and scrubbed HFO because these solutions satisfied the immediate regulatory pressures of the IMO 2020 Sulphur Cap. However, the post-2020 literature demonstrates a radical expansion of system boundaries from TtW to WtW. This methodological pivot has inverted the environmental hierarchy of marine fuels. Solutions previously lauded for clean combustion, such as LNG and Grey Hydrogen, are increasingly categorized as environmental liabilities in recent life-cycle assessment studies due to upstream methane leakage and fossil-intensive production pathways [38].

A coherent trend emerging from this synthesis is the bifurcation of fuel roles. Literature no longer seeks a single silver bullet but rather identifies distinct tactical roles for different fuels. Biofuels are solidified by Kesieme et al. [34] and others as the primary mechanism for decarbonizing the existing fleet, offering immediate carbon abatement without methane slip risks and high retrofitting costs. Conversely, ammonia and hydrogen are universally recognized as the destination fuels for future ships. However, the consensus comes with a critical caveat that their environmental validity is not intrinsic to the fuel itself but contingent upon the decarbonization of the global electrical grid. As a result, a clear trend is visible: LNG is losing its status as a green solution, biofuels are cemented as a constrained

transitional tactic, and the long-term environmental promise of ammonia and hydrogen is entirely suspended on the future availability of surplus renewable electricity.

3.2. Economic Viability and Cost Dynamics

Although early studies placed greater emphasis on environmental aspects [34], recent studies acknowledge that, while environmental performance dictates the desirability of alternative fuels, the industry's bottom line ultimately determines adoption. The existing literature shows a clear consensus: without substantial market support, zero-carbon fuels cannot compete financially with traditional HFO. This section synthesizes evidence across three main economic aspects: Capital Expenditure (CAPEX) for vessel construction and retrofitting; Operating Expenditure (OPEX), which is affected by fuel price volatility; and the impact of Market-Based Measures (MBMs), such as carbon pricing, in addressing these challenges. When assessing OPEX, the literature demonstrates extreme cost disparities. Anchored against a baseline of conventional VLSFO/HFO prices (averaging 2023–2024 market data), scalable zero-emission fuels such as e-ammonia and e-methanol are currently projected at a 200% to 400% premium. Given this extreme price delta and anticipated market volatility, some techno-economic analyses suggest that shipowners will be forced to employ aggressive financial risk mitigation strategies, such as long-term fuel price hedging and advanced forward contracts, which represent new complexities in maritime commercial operations.

3.2.1. CAPEX Constraints

The capital investment required to transition to alternative fuels extends beyond engine costs and is fundamentally linked to the physical properties inherent to the fuels themselves. A recurrent theme in the literature is the inverse correlation between a fuel's sustainability and its energy density, which results in substantial CAPEX penalties. Xing et al. [8] and Al-Enazi et al. [29] demonstrate that the low volumetric energy density of hydrogen necessitates storage tanks that are four to five times larger than those used for marine diesel. This imposes a double penalty on shipowners: not only does the cryogenic storage system incur significantly higher construction costs due to insulation requirements at −253 °C, but the increased tank size also reduces cargo space. Consequently, the CAPEX encompasses not only the initial hardware costs but also the lifetime opportunity costs associated with the lost revenue-generating volume.

In contrast, the economic argument for using drop-in biofuels and methanol mainly relies on their lower infrastructure barriers [10,39]. Kesieme et al. [34] and Foretich et al. [30] highlight that biofuels require negligible CAPEX for existing vessels, as they function within standard compression-ignition engines and storage parameters. Similarly, methanol, being liquid at normal temperatures, can be stored in converted ballast tanks with minimal retrofitting costs, unlike pressurized ammonia systems. This stark CAPEX dichotomy explains why stakeholders, as noted by Ashrafi et al. [40], prioritize fuels that minimize hull design changes, while marginalizing hydrogen in the short-to-medium term despite its environmental allure.

Beyond these macroscopic storage penalties, the core energy-conversion hardware itself faces significant maturity barriers at the fundamental materials level. Current proton exchange membrane (PEM) fuel cells remain constrained by the challenge of developing durable membrane materials; specifically, utilizing advanced non-fluorinated alternatives, such as sulfonated polyether ether ketone (SPEEK) composite membranes, requires balancing high proton conductivity against long-term mechanical stability before commercial-scale marine deployment is viable [41].

3.2.2. OPEX Differentials

An analysis of OPEX across previous studies reveals a persistent economic dominance of the status quo. Despite the environmental imperative, Zou and Yang [42] provide robust quantitative evidence that operating vessels on HFO with scrubbers remains the most cost-efficient strategy under current regulatory frameworks. Even when scrubbers are excluded, LNG still maintains a substantial OPEX advantage over zero-carbon alternatives. Studies by Deniz and Zincir [27], Hansson et al. [28] and later reaffirmed by Strantzali et al. [32] indicate that LNG prices have historically tracked below low-sulphur distillates, providing shipowners with a 15–20% operational cost saving. This immediate financial incentive has created a lock-in effect, in which economic rationality drives the fleet toward fossil-based LNG, directly contradicting the IMO's long-term decarbonization goals.

On the other hand, the operational costs of green fuels are highly volatile and carry steep premiums. Data from Lee et al. [26] and Wang and Iris [5] indicate that e-ammonia and e-methanol are priced 200–400% higher than their fossil-based counterparts, mainly due to the high cost of renewable electricity and electrolysis processes. Unlike the well-established LNG supply chain, the pricing strategies for these electro fuels remain unclear. Mäkitie et al. [43] argue that this uncertainty in operating expenses causes investment uncertainty among shipowners. Their behavioral analysis identifies two main groups: 'early adopters,' who are willing to accept higher OPEX for reputational gain or niche contracts, and 'laggards', who are strictly cost-focused and will consider transition only once the price gap decreases.

3.2.3. Role of Carbon Pricing

Given the insurmountable cost gap between fossil and renewable fuels, the recent literature shifts focus to the necessity of MBMs. There is a strong consensus that alternative fuels cannot achieve market parity through technological learning curves alone; they require regulatory intervention. Wang and Iris [5] utilize stochastic programming to demonstrate that a carbon price is the single most sensitive variable in fleet renewal strategies. Their modeling suggests that without a carbon tax exceeding \$150–\$200 per ton of CO_2, the best economic choice for a shipowner is to build LNG vessels or retrofit for biofuels.

This finding is corroborated by Lee et al. [26], who argue that the economic viability of the green ammonia pathway is impossible without strict carbon taxation or subsidies for renewable hydrogen production. The literature thus presents a clear chronological evolution in economic thought: pre-2020 studies often debated which fuel was cheaper, whereas post-2023 studies fundamentally agree that all zero-carbon fuels are economically unviable under a laissez-faire market. The synthesis indicates that the industry has moved beyond a search for a "cheap" alternative fuel and is now grappling with the realization that decarbonization will inherently inflate the cost of maritime transport [44].

3.2.4. Synthesis of Economic Trends

The economic evidence suggests a stratified future for marine propulsion. A clear fissure exists between retrofit-ready solutions (biofuels, methanol), which optimize for low CAPEX but face high fuel costs, and novel-propulsion solutions (hydrogen, ammonia), which incur high costs across both CAPEX and OPEX. The overwhelming trend in the literature is that LNG remains the economic sanctuary for the industry—providing the lowest total cost of ownership today—while the viability of genuine zero-carbon fuels remains entirely theoretical, contingent on future regulatory interventions that monetize carbon emissions.

Furthermore, a critical methodological limitation observed across the synthesized literature is the pervasive reliance on static CAPEX and OPEX comparisons. While current

studies effectively demonstrate the immediate 'Green Premium' of alternative fuels, static cost snapshots are fundamentally insufficient to support the multi-decade investment decisions required by shipowners. A vessel represents a 30-year lifecycle asset; therefore, true commercial viability must be evaluated through dynamic Life Cycle Costing (LCC) and Net Present Value (NPV) analyses. The current literature frequently fails to account for the time value of money, appropriate discount rates, and the dynamic inflation of both fuel prices and carbon levies over time. The absence of these longitudinal, dynamic economic models in the academic discourse exacerbates the technological deadlock, as stakeholders are left without the sophisticated financial forecasting necessary to justify the immense capital risks associated with scalable zero-emission fuels.

3.3. Infrastructure Readiness and Technical Maturity

While economic models predict the potential adoption of alternative fuels, practical constraints in marine engineering set strict limits on their implementation. The literature reveals a clear division in technical maturity: drop-in solutions like biofuels and e-methanol that work with existing propulsion systems, versus disruptive options such as hydrogen and ammonia that require a complete redesign of vessel structures and port facilities. Moreover, this volumetric penalty creates a significant divergence in technical feasibility between newbuilds and existing-fleet retrofits. While incorporating dual-fuel capability into a newbuild enables optimized naval architecture and integrated tank placement, retrofitting existing vessels for low-density fuels like methanol or ammonia is often deemed technically prohibitive. The literature highlights that retrofits demand substantial structural modifications to accommodate larger tanks, which irreparably cannibalize revenue-generating cargo space and fundamentally alter the vessel's stability profile, making it a viable option only for a fraction of the youngest global fleet. This section synthesizes the evidence regarding Technology Readiness Levels (TRL), volumetric storage issues, and the persistent 'chicken-and-egg' challenge related to bunkering infrastructure.

3.3.1. Storage Constraints

The most pervasive technical obstacle identified throughout the review period is the inverse relationship between a fuel's decarbonization potential and its volumetric energy density. Studies by Al-Enazi et al. [29] and Xing et al. [8] provide rigorous thermodynamic comparisons, demonstrating that zero-carbon fuels impose significant spatial constraints on vessel design. Liquid hydrogen (LH2) is consistently recognized as the most technically challenging energy carrier because it requires cryogenic storage at −253 °C to remain in its liquid state. Xing et al. [8] calculate that, owing to the requirement for thick insulation and its low density, LH2 storage systems demand a volume approximately 4–5 times greater than that of conventional HFO tanks to achieve equivalent nautical range. This results in a parasitic load on the vessel, in which the fuel system itself displaces revenue-generating cargo space. Thereby, it renders hydrogen technically unsuitable for long-haul, deep-sea voyages under prevailing naval architectural standards.

In stark contrast, ammonia and methanol offer more manageable engineering compromises. Al-Enazi et al. [29] note that while ammonia requires storage at −33 °C or mild pressurization, this is a well-understood industrial process comparable to LPG transport. Consequently, technical literature ranks ammonia significantly higher than hydrogen for deep-sea applications, as it offers a higher energy density without the extreme cryogenic demands. However, Foretich et al. [30] highlight that methanol is the technical optimum in this category. Being liquid at ambient temperature and pressure, it eliminates the need for complex thermal management systems entirely, allowing storage in slightly modified ballast tanks. The synthesis of these engineering studies suggests a clear technical hi-

erarchy: methanol is ready now for general cargo application, ammonia is feasible for specialized newbuilds, while hydrogen remains technically immature for international deep-sea merchant shipping.

3.3.2. Supply Chain Fragility

For the current fleet, the literature emphasizes the technical superiority of biofuels as the only practical drop-in option. Kesieme et al. [34] and Hellström et al. [35] confirm that HVO and FAME have physical properties close enough to marine diesel to allow for immediate substitution in two-stroke and four-stroke engines without retrofitting. This compatibility places biofuels at the top of all alternative options in terms of system readiness.

However, Kesieme et al. [34] raises a critical technical caveat regarding oxidation stability. Unlike fossil fuels, biodiesel degrades over time when exposed to oxygen, forming sediments that can clog fuel filters and injectors. This technical limitation makes first-generation biofuels risky for vessels with irregular operating profiles or long idle periods. Additionally, Foretich et al. [30] describe the supply chain infrastructure as brittle. Unlike the widespread heavy fuel oil network, biofuel bunkering is limited by geography. Thus, the literature indicates that technical feasibility is not limited by the engine but by shoreside logistics; the capacity to produce compliant fuel at scale falls significantly short of the fleet's theoretical capacity to consume it.

3.3.3. The Nuclear Paradox

A subset of the literature examines nuclear propulsion as a zero-emission alternative, presenting a paradox of maturity. In an MCDM analysis, Ren and Lützen [9] identified nuclear power as the most technically mature non-fossil option, citing more than 60 years of operational data from naval submarines and icebreakers. Their analysis shows that nuclear scores highest of all in reliability and energy density.

Despite its high technical reliability, this technology faces significant challenges due to immature commercial deployment and regulatory hurdles. The review indicates that while the reactor technology, specifically pressurized water reactors, is TRL 9, the regulatory frameworks remain at TRL 1. Ren and Lützen [9] and later other researchers, such as Moshiul et al. [45], highlight that civilian ports lack the necessary infrastructure for nuclear refueling and waste disposal, and that insurance policies for commercial nuclear vessels are absent. Therefore, the literature views nuclear technology not as a technical issue but as a systemic integration problem: it remains a stranded technology that functions in isolation but fails to integrate into the broader maritime industry.

Within the context of this study's four-pillar framework, the 'Nuclear Paradox' serves as the ultimate case study of the safety and social acceptance dimension, completely overriding technical and economic viability. The literature indicates that the barrier to commercial nuclear shipping is no longer engineering; rather, it is the insurmountable hurdle of public perception [9,45]. The prospect of civilian, flag-of-convenience merchant vessels operating mobile nuclear reactors triggers severe NIMBYism (Not In My Backyard) responses, leading to preemptive port entry bans by coastal states. Until the industry can establish an internationally recognized, civilian regulatory framework that fundamentally alters public risk perception, nuclear propulsion will remain isolated to naval and specialized state-owned icebreaker fleets, disconnected from the mainstream commercial transition.

3.3.4. Infrastructure Deadlock

The transition to alternative fuels is characterized in the literature as a classic 'chicken-and-egg' infrastructure paradox. Mäkitie et al. [42] provide a behavioral analysis of shipowners, revealing that technical uncertainty is a stronger barrier to adoption than capital cost. Their study finds that laggard firms are hindered by the lack of standardized

bunkering infrastructure for ammonia and hydrogen. Unlike LNG, which benefited from decades of standardization in gas carriers, the transfer protocols for toxic ammonia or cryogenic hydrogen in a commercial port environment are currently undefined.

This uncertainty is fueling a shift toward dual-fuel technologies. Analyzing trends from 2020 to 2025 reveals a significant rise in research supporting fuel-flexible engine systems, such as dual-fuel methanol/diesel or ammonia/diesel, to hedge risks. Since no single infrastructure network has become dominant, the technical success will depend not on the most efficient fuel, but on which one can achieve widespread bunkering infrastructure first [5]. Currently, LNG is the only alternative fuel that meets this widespread infrastructure criterion, which further reinforces the lock-in effect discussed in Section 3.2.

3.3.5. Synthesis of Technical Trends

The technical evidence base points to a fractured future. The dream of a single, universal fuel to replace HFO is dismantled by the physical constraints of storage and safety. The synthesis suggests a divergence in fleet topology: short-sea and coastal segments may adopt hydrogen or battery-electric systems where volumetric density is less critical, while deep-sea shipping is technically channeled toward ammonia for newbuilds or methanol/biofuels for the existing fleet. The universal solution of the 20th century is being replaced by the specialized solutions of the 21st.

3.4. Safety, Risk, and Social Acceptance

Although early research focused mainly on techno-economic analyses, recent studies highlight safety and social acceptance as critical, non-negotiable factors in decarbonization efforts. The move from HFO to diesel has been gradual, but transitioning to zero-carbon fuels introduces new hazards, such as extreme cryogenic risks and lethal toxicity, that the current maritime safety systems are not fully prepared to handle [11]. Beyond localized 'Not In My Backyard' (NIMBY) resistance from port communities regarding toxic storage, the broader social dimension is increasingly shaped by global environmental NGOs and public advocacy groups. The literature indicates a growing macro-level pressure from these stakeholders who view transitional fuels—particularly LNG—as unacceptable fossil lock-ins. This creates a severe social-regulatory squeeze for shipowners: local communities reject the localized risks of ammonia, while global environmental factions reject the climate profile of LNG, leaving operators with no socially universally accepted fuel pathway. This section reviews evidence on occupational risks, explores the trade-offs between flammability and toxicity, and examines how differing stakeholder motivations are causing fragmented industry responses.

3.4.1. Stakeholder Valuation Conflicts

The literature reveals an alarming safety clash between the two leading zero-carbon candidates: hydrogen and ammonia. Xing et al. [8] provide a detailed risk assessment that frames this as a choice between explosion risk and inhalation risk. Hydrogen is characterized by its extreme volatility, with a flammability range of 4–75% in air and very low ignition energy, necessitating advanced explosion-proofing that is much more rigorous than LNG standards. However, Xing et al. [8] note that hydrogen flames radiate low heat and disperse upward rapidly, potentially mitigating crew risk in open spaces.

On the contrary, ammonia has a hazard profile that Foretich et al. [30] describe as 'uniquely problematic' for maritime operations. Although it has low flammability, its toxicity can be lethal at concentrations as low as 300 ppm. Xing et al. [8] emphasize that, unlike LNG leaks—which pose fire hazard—ammonia leaks produce a toxic, heavier-than-air cloud that can suffocate crew members in engine rooms or lower decks. This physical behavior results in different port safety procedures: hydrogen requires explosion zones, while ammonia necessitates large evacuation zones during bunkering, which can be impossible to implement in crowded ports like Singapore or Rotterdam. Overall, safety data indicate that while hydrogen is more challenging to engineer safely, ammonia presents greater risks in the event of a catastrophic failure. In addition, the study of Xu, Brito and Beullens [12] highlights another aspect of fragmentation among the stakeholders. By examining Norway and Singapore models as benchmarks, they showed how different green transition approaches affect stakeholder decisions regarding port infrastructure and land transport.

3.4.2. Human Element

The reintroduction of these hazardous molecules has elevated occupational health and safety (OHS) from an operational checkbox to a primary design constraint. Ashrafi et al. [40] surveyed maritime stakeholders and found a striking divergence in risk perception: while shipowners prioritized fuel costs, naval architects ranked safety as their top criterion. This finding is critical as it indicates that the engineers responsible for vessel design are currently more risk-averse than the commercial operators, specifically citing the lack of mature redundancy systems for toxic fuel handling.

This fear factor is further substantiated by Foretich et al. [30], who classify biofuels and methanol as the only socially low-risk options. Methanol is a liquid at ambient temperature and dissolves in water, reducing fire risk compared with oil sheens. Moreover, it faces the lowest barrier to crew acceptance. In contrast, managing cryogenic liquids, such as hydrogen at −253 °C, presents additional risks, including cold burns and hull embrittlement, which current seafarers are not trained to handle. The literature suggests a significant training gap, indicating that hardware is evolving faster than the human capital needed to operate it safely. The implications of this human capital deficit are profound and multifaceted. First, the regulatory framework governing seafarer competency—specifically the STCW Convention—is significantly lagging behind the pace of technological deployment. While the IGF Code provides a baseline for low-flashpoint fuels like LNG, standardized, globally recognized STCW training protocols for handling highly toxic (ammonia) or highly flammable (hydrogen) zero-carbon fuels remain dangerously underdeveloped. Consequently, the literature points to a looming, severe workforce bottleneck in the 2030s; a multi-fuel future will require hundreds of thousands of seafarers to be reskilled concurrently.

Furthermore, the financial burden of this massive, global retraining initiative represents a hidden OPEX that is rarely quantified in the existing techno-economic literature, yet it will heavily impact shipowners' bottom lines. Finally, the stakes of crew incompetence with these new energy vectors are existential. Unlike conventional Heavy Fuel Oil (HFO) spills, which are primarily environmental disasters, an accidental release of pressurized liquid ammonia—stemming from operational error in a densely populated port or near a passenger vessel—would result in immediate, catastrophic loss of human life. The literature consensus suggests that such a safety failure would not merely be a 'company-ending' financial liability; it would trigger a profound collapse in public trust, potentially revoking the maritime industry's social license to operate toxic alternative fuels globally.

3.4.3. Divergent Hazard Profile

Beyond the deck of ships, the review identifies a deep fracture in stakeholder motivations that is stalling the transition. Hansson et al. [28] use Multi-Criteria Decision Analysis (MCDA) to quantify this conflict, revealing that government authorities and shipowners are effectively optimizing for different variables. Authorities consistently rank hydrogen and electricity as top choices, driven by a political mandate for zero local emissions and public health benefits. Conversely, shipowners rank LNG and biofuels highest, driven by the imperative of commercial reliability and asset liquidity. Ren and Lützen [9] illustrate the extreme limit of this social friction through the case of nuclear propulsion. Despite scoring highest on technical reliability and emissions reduction, nuclear is effectively disqualified by social acceptance. The authors note that the "Not In My Back Yard" (NIMBY) phenomenon prevents nuclear merchant vessels from entering most commercial ports, rendering the technology commercially void despite its engineering excellence.

Crucially, this systemic integration deadlock manifests acutely in the vessel's electrical distribution network during the transition to hydrogen-based powertrains. The literature underscores that integrating multi-stack fuel cell (MSFC) systems into isolated shipboard power grids introduces severe power-quality vulnerabilities; specifically, executing necessary online health diagnostics can trigger substantial transient DC bus voltage fluctuations that threaten micro-grid stability [46]. Mitigating these localized power deviations demands an evolution away from conventional power management. It requires the implementation of advanced, highly complex control architectures—such as multi-resonant extended state observers—thereby confirming that the deep-sea transition is fundamentally throttled by intricate electrical and systems-engineering integration barriers rather than isolated chemical limitations.

3.4.4. Synthesis of Social Trends

The trajectory of the literature points to a rising 'social license to operate' hurdle. Mäkitie et al. [42] conclude that the hesitancy of laggard firms is rational behavior in the face of this social uncertainty; they are waiting not just for the price of ammonia to drop, but for the safety regulations to stabilize. The synthesis suggests that industry is drifting away from radical fuels, such as Nuclear and hydrogen, due to safety complexities, and towards pragmatic fuels like methanol and LNG, where human and social risks are manageable, even if environmental performance is inferior. Figure 2 highlights the most promising marine alternative fuels and their evaluation criteria.

To elevate this framework from a theoretical construct to a pragmatic managerial tool, the four dimensions in Figure 2 have been assigned quantitative weight ranges. These ranges were synthesized from the subset of the reviewed literature that utilized MCDM methodologies. Across the synthesized MCDM models, the Economic Viability dimension consistently commands the highest aggregate weighting range (16–42%), reflecting the capital-intensive nature of maritime assets. Technical Maturity closely follows (11–45%), driven by the increasing stringency of IMO compliance mechanisms. Environmental Lifecycle (23–34%) and Safety and Social Acceptance (5–22%) account for the remaining weight distribution. However, as the literature indicates, these ranges are highly dynamic; while commercial shipowners inherently skew towards the upper bound of the economic weightings, port authorities and regulators increasingly prioritize safety and environmental metrics. Therefore, these MCDM-derived ranges offer industry managers a calibrated, evidence-based baseline for conducting their own multi-criteria fuel selection analyses.

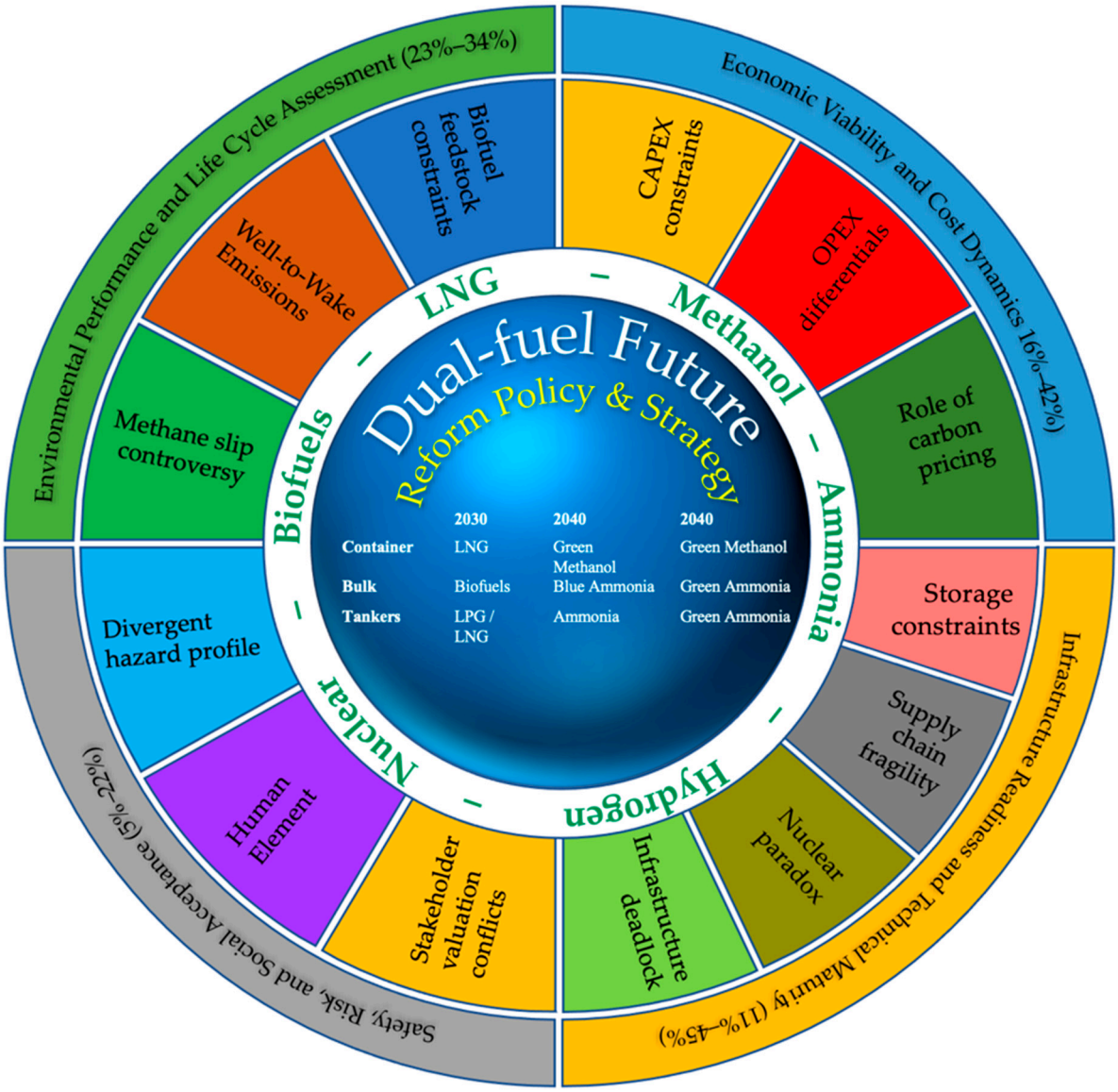


Figure 2. Alternative fuel evaluation framework.

3.5. Methodological Divergences in Current Literature

The methodological landscape of maritime decarbonization research is characterized by a significant shift from static, single-perspective assessments to dynamic, hybrid frameworks that aim to capture the inherent uncertainties of the field, as shown in Table 2. Early decision-support studies primarily utilized the Analytic Hierarchy Process (AHP) to rank alternative fuels, relying on expert pairwise comparisons to generate crisp weighting values [27]. However, as the field matured, researchers identified critical limitations in traditional MCDM, particularly regarding the vagueness of human judgment and the incomplete information typical of emerging technologies. To address this, more recent studies have introduced fuzzy logic and Dempster-Shafer theory to handle subjective ambiguity [9]. Furthermore, there is a clear methodological shift toward hybridizing the Best-Worst Method (BWM) with the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to reduce the cognitive burden on experts and mitigate the rank-reversal issues common in earlier AHP models [23,44]. Critically, the environmental assessments across these studies exhibit fundamental differences in system boundaries and functional units, which complicates direct comparisons. While many studies adopt a TtW approach focused on operational emissions, there is an increasing insistence on the WtW perspective

to prevent the upstream relocation of carbon footprints [5,25]. Methodological divergence is also evident in how researchers reach consensus; for instance, while bibliometric analyses provide a quantitative mapping of historical research trends [21,47], iterative Delphi studies are employed to forecast the economic and technical feasibility of fuels across different shipping segments [35]. Finally, a distinct but limited methodological branch focuses on human factors and adoption behavior, using Analysis of Variance (ANOVA) to categorize shipowners by their technological readiness and perceived adoption barriers [43]. This evolution from deterministic engineering models to nuanced socio-technical frameworks reflects the industry's recognition that the transition depends as much on stakeholder consensus and regulatory alignment as it does on technical viability.

Table 2. Descriptive overview of the included studies.

Studies	Fuels Evaluated	Evaluation Criteria	Stakeholders and Methodology	Key Findings (Best Fuel(s) Identified)
[27]	$n = 4$	$N = 11$	Analytic Hierarchy Process (AHP)	LNG
[9]	$n = 3$	$N = 10$	Trapezoidal Fuzzy Analytic Hierarchy Process (TFAHP),	Nuclear
[31]	$n = 3$	$N = 17$ (Sub-criteria under 3 main criteria)	Fuzzy logarithmic least squares and fuzzy TOPSIS	Hydrogen
[34]	$n = 3$	$N = 3$	Secondary data analysis	SVO (Straight Vegetable Oil), biodiesel, and bio-LNG
[28]	$n = 7$	$N = 10$ (Sub-criteria under 4 main criteria)	Analytic Hierarchy Process (AHP)	No single best fuel
[8]	$n = 7$	$N = 10$	Qualitative ranking	Methanol (global), hydrogen and ammonia (domestic)
[30]	$n = 12$	$N = 20$ (Sub-criteria under 5 main criteria)	Qualitative ranking	No single best fuel
[29]	$n = 4$	$N = 1$ (Life-cycle emissions)	Literature review	LNG (transitional); hydrogen, ammonia (future)
[40]	$n = 8$	$N = 18$ (Sub-criteria under 3 main criteria)	Descriptive Statistics of 70 stakeholders' data using IBM SPSS	No single best fuel
[10]	$n = 5$	$N = 2$	Bi-objective integer optimization model with a Supramax case study	LH2 (for zero-emission), LNG, biofuels, respectively
[44]	$n = 7$	$N = 9$	Bayesian Best-Worst Method (BWM) and PROMETHEE-GAIA	HFO, LNG, and HFO-Wind hybrids
[24]	$n = 9$	$N = 5$	Systematic Literature Review (SLR)	No single best fuel
[42]	$n = 4$	$N = 3$	Mathematical modeling: Life Cycle Assessment (LCA)	Methanol (social); HFO (economic); H2 and NH3 (long-term)
[45]	$n = 8$	$N = 15$	TOPSIS	No single best fuel
[26]	$n = 9$	$N = 3$	Mathematical modeling: Life Cycle Assessment (LCA)	Bio-fuels and NG-based ammonia with CCS (short- to mid-term), and e-methanol and e-ammonia (long-term)
[33]	$n = 8$	$N = 1$ (100% GHG reduction capacity)	Mathematical modeling: Life Cycle Assessment (LCA)	Bio-methanol, FAME bio-diesel, and green hydrogen
[25]	$n = 3$	$N = 3$	Mathematical modeling: Life Cycle Assessment (LCA)	Ammonia (renewables)
[4]	$n = 17$	$N = 8$	Mathematical modeling: Life Cycle Assessment (LCA)	Marine bio-oil followed by LNG, E-FT-diesel, and E-methanol

Table 2. *Cont.*

Studies	Fuels Evaluated	Evaluation Criteria	Stakeholders and Methodology	Key Findings (Best Fuel(s) Identified)
[35]	$n = 11$	$N = 2$	Delphi method with 39 experts	Methanol
[5]	$n = 4$	$N = 2$	Mathematical modeling: Two-stage stochastic programming model	No single best fuel
[23]	$n = 5$	$N = 24$ (Sub-criteria under 5 main criteria)	BWM, TOPSIS	Methanol followed by hydrogen, biofuels, ammonia, and LNG, respectively
[11]	$n = 4$	$N = 4$	A multi-criteria sustainability assessment method is developed	Hydrogen
[12]	$n = 7$	$N = 4$	Analytic Hierarchy Process (AHP)	No single best fuel
[21]	$n = 8$	$N = 10$ (Sub-criteria under 5 main criteria)	Bibliometric analysis	LNG
[32]	$n = 7$	$N = 11$	Promethee II	LNG, MGO, and HFO
[36]	$n = 9$	$N = 1$ (Econometric-TCO)	Econometric analysis for Total Cost of Ownership (TCO) using Microsoft Excel	Methanol
[37]	$n = 9$	$N = 5$	Literature review with qualitative evaluations	Biofuels (biomethanol and biodiesel) and LNG
[38]	$n = 7$	$N = 7$	Systematic Literature Review (SLR)	No single solution
[2]	$n = 5$	$N = 6$	Literature review and Life Cycle Assessment (LCA)	Hydrogen and ammonia
[7]	$n = 7$	$N = 4$	Mathematical modeling: Empirical ship design models for Tank-To-Wake (TTW) emission	Biodiesel, followed closely by ammonia and hydrogen
[39]	$n = 2$	$N = 2$	Lifecycle Cost-Effectiveness Analysis (LCEA)	Methanol
[48]	$n = 5$	$N = 3$	Well-to-Wake (WTW) Life Cycle Assessment (LCA) built from the ISO 14040 LCA steps [49]	No single fuel path
[50]	$n = 10$	$N = 2$	Statistical analysis and Well-to-Wake emission assessment	e-hydrogen, followed by e-methanol and e-diesel
[51]	$n = 3$	$N = 2$	Literature review (Secondary data analysis)	Green methanol and green ammonia for short-term while green hydrogen for long-term
[52]	$n = 15$	$N = 3$	Parametric analysis with chemical equilibrium calculations	Hydrogen and ammonia
[53]	$n = 2$	$N = 4$	Life cycle assessment (LCA)	No single best solution (dual-fuel engines are recommended)
[54]	$n = 3$	$N = 9$	Fuzzy AHP	No single most suitable fuel
[55]	$n = 2$	$N = 6$	Analytic Hierarchy Process (AHP)	LNG
[56]	$n = 5$	$N = 10$	AHP and Simple Additive Weighting (SAW)	Electric propulsion (Battery)

Note: 'n' corresponds to the number of fuels evaluated in a study, and 'N' corresponds to the number of criteria considered in the study.

4. Policy Implications and Recommendations

One of the fundamental conclusions of this study is that the decarbonization of the international shipping industry represents a market failure that cannot be corrected solely

through technological innovation. The existing literature shows that the current regulatory framework is misleading in light of the techno-economic realities of alternative fuels. While the adoption of the 2023 IMO GHG Strategy marked a paradigm shift, the evidence indicates that the current calibration of these instruments will likely lead to compliance gaming rather than the intended capital-intensive fuel switching. Consequently, the role of policy must shift from target-setting (e.g., IMO 2030/2050 goals) to market-making. The following implications outline the specific legislative amendments required to bridge the gap between the theoretical promise of alternative fuels and their commercial reality [19].

4.1. The Necessity of Aggressive and Harmonized Market-Based Measures (MBMs)

The most consistent finding across the reviewed studies is the existing cost gap between fossil fuels and zero-carbon alternatives, often called the 'Green Premium'. The current price difference between Heavy Fuel Oil (HFO) and e-fuels like e-ammonia or e-methanol ranges from 200% to 400% [5,26,48]. This clearly indicates that voluntary adoption alone will not be effective. Policymakers need to enforce strict Market-Based Measures (MBMs) to account for the external costs of carbon emissions. The IMO's proposed GHG Fuel Intensity (GFI) standard strives to gradually lower the allowable carbon content in marine fuels. However, the economic analysts suggest that the current GFI reduction curve is too shallow to bridge the so-called 'Green Premium' [5,26]. The literature indicates that a modest levy (such as \$50/ton CO_2) for exceeding GFI limits would act merely as a levy on fossil fuels, which shipowners will absorb as a cost of doing business rather than switching to green fuels, which remain 2–3 times more expensive. Stochastic modeling of Wang and Iris [5] shows that a carbon price above \$150–\$200 per ton CO_2 is needed to make zero-carbon ammonia competitive with LNG. Without adequate redistribution of levies, the high capital costs identified by Munim et al. [44] will restrict market entry to only the largest conglomerates, potentially leading to oligopolistic market distortions.

Another emerging theme in the latest literature is the administrative burden of regulatory fragmentation. Hansson et al. [28] noted that shipowners struggle with regulatory uncertainty. This issue will become more complex in the future as the simultaneous application of the EU Emissions Trading System (ETS), FuelEU Maritime, and the IMO GFI creates conflicting compliance signals [50].

Policy Recommendation: Regulatory agencies, particularly the International Maritime Organization (IMO) and the European Union (through the ETS), must structure carbon pricing mechanisms to be revenue-neutral but behaviorally punitive. The IMO has proposed the GFI standard with an economic pricing mechanism, often termed as the 'Green Balance Mechanism' in the literature. However, a critical question remains pertinent whether this mechanism will be able to generate adequate levies to bridge the green premium with the proposed rate per CO_2 ton. As a result, the IMO should reconsider the proposed rate and redistribution mechanism. To effectively address the green premium market failure, policymakers must discard static carbon pricing models in favor of a phased, dynamic escalation trajectory. Rather than an immediate, market-shocking tax, the literature supports implementing an introductory pricing floor in the short term, which then aggressively scales to the \$150–\$200 per ton of CO_2 equivalent threshold during the critical 2030–2040 transitional window. This phased approach provides shipowners with the necessary financial predictability to justify long-term zero-carbon capital expenditures while actively penalizing delayed action.

To mitigate the severe compliance complexities generated by regulatory fragmentation, there is an urgent need for structural harmonization between regional policies (e.g., the EU ETS and FuelEU Maritime) and the IMO's global GHG strategy. Policymakers should establish formal frameworks for the mutual recognition of compliance credits and

pooling mechanisms across jurisdictions. This alignment will prevent operators from being penalized multiple times for the same emissions and will streamline the administrative burden of operating a multi-fuel global fleet. If the IMO GFI standard is weaker than the EU standard, the literature predicts that a two-tier market will emerge: a clean, EU-compliant fleet and a dirty shadow fleet operating in unregulated waters, undermining global decarbonization goals. To prevent the emergence of a 'two-tier' global fleet heavily reliant on older, highly polluting vessels operating in less regulated waters, global policy must integrate an equitable transition mechanism. It is highly recommended that a portion of the revenue generated from any global maritime carbon pricing instrument be ring-fenced to support the Global South. By directing these funds toward targeted technology transfer mechanisms and the subsidization of zero-emission bunkering infrastructure in developing nations, the IMO can transform these regions from passive compliance risks into active, integral producers within the green maritime supply chain.

On the other hand, the review of FuelEU Maritime by Tomos et al. [33] highlights another crucial risk, called 'compliance pooling', where a fleet buys one methanol ship to offset ten HFO ships. Regulators must set strict limits on this pooling issue to prevent it from delaying the retrofit of the broader fleet.

4.2. Standardization of Life Cycle Assessment (LCA) Boundaries

A critical regulatory loophole identified in previous studies is the inconsistency in emissions accounting. Previous regulatory instruments often focused on tank-to-wake emissions, inadvertently incentivizing fuels that are clean at the funnel but dirty at the source. Studies by Zincir and Arslanoglu [4] and Al-Enazi et al. [29] confirm that grey ammonia and LNG with high methane slip frequently perform worse than HFO on a true Well-to-wake basis. Similarly, the distinction between grey and green hydrogen is often invisible in many regulatory frameworks [51]. As noted by Al-Enazi et al. [29], a hydrogen vessel powered by steam-methane reforming without carbon capture and storage (CCS) creates more lifecycle emissions than a diesel vessel. The study by Bayramoğlu et al. [52] shows a rise in alternative fuel use, with LNG leading at 10–30% by 2030. Zero-carbon fuels such as hydrogen and ammonia, which reduce CO_2 emissions by about 95%, will help meet 2030 goals, but widespread use is not expected. Stricter 2040 targets will demand carbon-neutral fuels with CCS, making up 60–80% of marine fuels. By 2050, hydrogen and ammonia (>60%) may surpass traditional fuels, but if zero-carbon fuels do not dominate, CCS must be widely adopted to meet emissions targets.

Policy Recommendation: Policy frameworks must universally adopt a well-to-wake certification standard for marine fuels. A global certification scheme should be established that explicitly accounts for not only the combustion phase but also upstream extraction, grid-intensity emissions, infrastructure transport, and—most critically for transitional fuels—the precise quantification of fugitive emissions, including methane (CH_4) and nitrous oxide (N_2O) slip. Vessels should receive regulatory credits (e.g., under the CII rating) only if they can prove that their fuel was produced via electrolysis using renewable energy rather than through fossil-based pathways. This prevents resource shuffling, where the maritime sector consumes dirty industrial ammonia while claiming green credentials. Regulators must introduce strict methane slip limits for dual-fuel engines and mandate the use of advanced technologies, such as high-pressure injection or exhaust after-treatment systems, for LNG vessels to qualify as sustainable [53].

4.3. Standardization of Operational Measures and Regulatory Instruments

There is a perverse incentive within the current operational measures, particularly CII and EEXI (Energy Efficiency Existing Ship Index). As noted by Zou and Yang [42], the

easiest way to improve a vessel's CII rating is not to switch to alternative fuels but simply to reduce speed or apply a shaft power limitation. While slowing steaming reduces emissions, it is a dead-end strategy that does not drive investment in the green fuel infrastructure required for 2050. The literature warns that CII is currently promoting an aging, slower fleet rather than a newer, greener one. Moreover, the EEDI (Energy Efficiency Design Index) and EEXI formulas currently do not penalize methane slip [57].

Furthermore, the transition to ammonia and hydrogen introduces unique hazard profiles that are currently outside the scope of the SOLAS conventions. Study shows that the lack of regulatory certainty regarding safety is a primary barrier for ship designers [40]. In addition, the current IGF Code (International Code of Safety for Ships using Gases or other Low-flashpoint Fuels) is heavily biased toward LNG and does not adequately address the toxicity containment required for ammonia.

Policy Recommendation: The IMO should introduce fuel technology correction factors into the CII calculation. A vessel running on green fuel, even if inefficiently, should receive a higher rating than a highly efficient HFO vessel sailing slowly. Moreover, the EEXI is currently a one-time certification. It should be converted into a dynamic standard that is tightened every 5 years, forcing the retirement or deep retrofitting of vessels that cannot adopt alternative fuels. Moreover, the EEXI calculation for LNG carriers should be revised to include the slip factor. The IMO must accelerate the expansion of the IGF Code to specifically address the unique risks of hydrogen and ammonia. Regulations must define safe bunkering distances in populated ports, potentially requiring offshore bunkering zones to mitigate toxic cloud risks in the event of a spill, as also noted by Xing et al. [8]. Standards for cryogenic materials and leak detection must be harmonized to prevent the risks of embrittlement identified in the engineering literature. Without these codified safety standards, the insurance industry will not be able to underwrite these vessels, rendering them commercially unviable regardless of their environmental performance.

4.4. Public–Private Partnerships for the Chicken-And-Egg Dilemma

The chicken-and-egg dilemma described by Mäkitie et al. [42], in which ships wait for port infrastructure and ports wait for an adequate number of ships, cannot be resolved by the private sector alone because of the sheer scale of capital investment required. The storage requirements for green fuels, such as hydrogen, necessitate a complete reconstruction of bunkering terminals.

Policy Recommendation: National governments must treat maritime fuel infrastructure as critical national assets. Policy should direct sovereign wealth or infrastructure funds toward developing green shipping corridors, where bunkering infrastructure for green fuels is subsidized. This targeted approach enables the creation of localized ecosystems where technology can be proven before global scaling. Furthermore, port authorities should be empowered to offer significant reductions in port dues for zero-emission vessels to offset the higher port-call complexity associated with these fuels.

5. Business and Managerial Implications and Strategies

For maritime executives, shipowners, and investors, the era of fuel homogeneity is over. The transition from a single-fuel regime to a multi-fuel landscape presents the industry's most significant strategic challenge in modern history. The findings of this study suggest that the traditional business model, characterized by cost minimization, and asset longevity, must be replaced by a strategy of flexibility, collaboration, and technological hedging. The following managerial implications provide a blueprint for navigating this period of high volatility.

5.1. Strategic Hedging and Asset Optionality

The most dangerous risk shipowners face today is not high fuel prices but asset obsolescence. The wait-and-see approach of the laggards is becoming increasingly risky as regulatory windows tighten [43]. However, betting on the wrong fuel, e.g., investing heavily in ammonia before safety standards are resolved, is equally perilous. While deterministic financial modeling and NPV calculations rely heavily on proprietary route profiles and volatile future carbon prices, the literature highlights the trade-offs for fleet managers. They face a choice between 'wait-and-see'—delaying CAPEX but risking regulatory obsolescence—or investing in dual-fuel readiness with an immediate CAPEX premium (10–20%), offering a hedge against future fuel supply issues. The literature recommends that large operators adopt 'portfolio optimization', spreading investments across LNG dual-fuel, methanol-ready, and ammonia-ready vessels to manage technological failures or fuel shortages. This bifurcation in managerial strategies and the move toward technological hedging are evident in the global order book, reflecting the constraints discussed in this review. Industry leaders like A.P. Moller-Maersk and CMA CGM focus on methanol-enabled ships, prioritizing technological maturity and cargo space over long-term fuel efficiency. Meanwhile, operators such as NYK Line, with different risk profiles and cargo needs, are pioneering ammonia pathways, exemplifying that no single solution fits all. Success depends on aligning vessel profiles with appropriate fuel strategies.

Managerial Strategy: Shipowners must prioritize technological optionality over CAPEX minimization.

- ***Dual-Fuel Readiness:*** Investments in newbuilds should default to dual-fuel-ready designs. While a methanol-ready or ammonia-ready vessel commands a higher CAPEX (a 10–15% premium), this cost is essentially an insurance premium against future regulatory stranding.
- ***The Modular Design Philosophy:*** Managers should favor vessel designs with modular engine rooms and fuel tank spaces that allow for retrofitting. For instance, reserving space for the larger tanks required by methanol or ammonia prevents a vessel from becoming commercially obsolete if HFO is banned or taxed out of the market.
- ***Portfolio Diversification:*** Large fleet operators should avoid a monoculture of propulsion technologies. A mixed fleet, for example, with LNG for long-haul stability, biofuels for older tonnage compliance, and pilot methanol vessels for green corridors, provides a hedge against the volatility of any single commodity market.

5.2. Supply Chain Integration and Long-Term Offtake

The procurement model for marine fuel is shifting from a spot-market commodity transaction to a long-term chemical partnership. Unlike HFO, which is available on demand globally, green methanol and ammonia will be supplied for use across multiple industries, including aviation, agriculture, and heavy industry. Kesieme et al. [34] warn of feedstock constraints for biofuels, suggesting that relying on spot availability will lead to extreme price exposure.

Managerial Strategy: Shipping companies must vertically integrate or form strategic alliances with energy producers.

- ***Long-Term Offtake Agreements:*** Managers must be willing to sign 5- to 10-year offtake agreements with fuel producers to guarantee supply. This reduces the producer's risk by unlocking project finance, and it secures price stability for the shipowner.
- ***Cross-Sector Collaboration:*** Shipowners should look beyond the maritime silo. Partnering with agricultural firms for ammonia or with chemical giants for methanol can create economies of scale that a standalone shipping company cannot achieve. The era

of the independent shipowner buying fuel at the pump is ending, and a new model of energy partner is emerging.

5.3. Human Capital as a Competitive Advantage

The review highlights a critical bottleneck, the human element, which is often overlooked in boardrooms. Safety concerns raised by naval architects and crews [30,40] about toxic and cryogenic fuels pose a severe operational risk. A fleet of ammonia-powered vessels is useless without a willing workforce and certified to operate them.

Managerial Strategy: Human Resources (HR) strategy must be elevated to a central pillar of the decarbonization plan.

- ***Specialized Training Programs:*** Companies cannot rely on generic STCW training, which lags behind technological advances. Establishing proprietary training centers for cryogenic and toxic-fuel handling will serve as a competitive differentiator.
- ***Retention and Compensation:*** As demand for crews certified in green fuels outstrips supply, wage inflation for these specialized officers will occur. Managers must proactively adjust compensation structures to retain this intellectual capital. A safety incident involving ammonia due to crew error would not only be a tragedy but also a company-ending reputational event; investing in high-quality crews is an effective risk management strategy.

5.4. Commercializing the Green Premium

Finally, the economic analysis in Section 3.2 confirms that low-carbon shipping will inevitably cost more. The main managerial challenge is to pass these costs along the value chain. Existing freight rate structures do not properly reflect the price difference for green fuels.

Managerial Strategy: Commercial departments must innovate in contract structures to monetize their environmental performance.

- ***Scope 3 as a Product:*** Major cargo owners, including IKEA, Amazon, and Walmart, are under pressure to reduce their Scope 3 emissions. Shipowners using green fuels should not market transportation; they should market carbon-insetting. Selling verified emission reductions to customers willing to pay a premium is the only viable mechanism to bridge the OPEX gap before carbon taxes fully mature.
- ***Book and Claim Systems:*** Managers should advocate for and utilize digital book and claim systems. This allows a shipowner to burn green fuel on a specific route where available and sell the environmental credits to a customer on a different route, decoupling the physical fuel from the commercial benefit and maximizing fleet utilization.

6. Conclusions

This systematic literature review synthesizes evidence from peer-reviewed studies, providing a comprehensive evaluation of alternative fuels for the international shipping industry. The analysis reveals that the maritime sector has entered a critical period of technological fragmentation. The century-long era of mono-fuel propulsion, dominated by HFO, is going to be ended. However, contrary to the industry's desire for a direct replacement, the literature confirms that no single alternative fuel currently satisfies the impossible trinity of environmental sustainability, economic viability, and technical maturity.

The primary contribution of this study lies in its deployment of a horizontal synthesis approach. Whereas the preceding decade of literature has largely evaluated alternative marine fuels in isolated, unidimensional silos—focusing strictly on either thermodynamics or isolated OPEX—this review successfully cross-pollinates the environmental, economic, technical, and social dimensions. This holistic framework reveals that the maritime sector's

technological deadlock is not due to a lack of engineering solutions, but rather the irreconcilable friction between these four pillars. The central finding of this study is the existence of a persistent decarbonization deadlock driven by conflicting evaluation criteria. When evaluated through a rigorous well-to-wake lens, hydrogen and ammonia emerge as the only vectors capable of delivering the deep decarbonization required by the IMO's 2050 targets. However, their environmental legitimacy is currently theoretical, contingent entirely on the decarbonization of the upstream electricity grid. Conversely, techno-economic analyses consistently identify LNG and drop-in biofuels as the only commercially viable alternatives today. Yet the environmental literature warns that investing in LNG creates a methane lock-in risk that may ultimately fail future climate stress tests. From a safety and infrastructure perspective, methanol occupies the middle ground, offering the best balance of manageable handling risks and scalability potential, provided the green premium for e-methanol can be bridged. The synthesis suggests that the industry is not moving toward a single winner, but toward a dual-fuel future. In this scenario, selecting the most appropriate fuel path requires aligning vessel characteristics (type, operational area, and cargo nature) with short-term (2030), mid-term (2040), and long-term (2050) policy development.

From a policy perspective, this synthesis demonstrates that the 'Green Premium' market failure cannot be resolved through voluntary industry action. The critical policy contribution of this paper is the evidence-based assertion that bridging the commercial viability gap requires the immediate implementation of phased, dynamic carbon pricing scaling to $150–$200/ton, coupled with stringent Well-to-Wake (WtW) lifecycle regulations that penalize unburned fugitive emissions. Furthermore, the synthesis underscores the geopolitical imperative of integrating the Global South into the green maritime supply chain to prevent the emergence of a high-emitting shadow fleet.

Table 3 presents a strategic fuel deployment matrix. It is important to note that this is not a speculative forecast, but a direct, novel synthesis derived from the empirical constraints identified in the reviewed literature. The assignment of specific fuels to vessel segments is based on a rigid cross-examination of operational profiles against fuel characteristics: for example, volume-critical vessels (container ships) are matched with higher-density liquids (methanol) to prevent severe cargo-loss penalties, whereas weight-critical or hazardous-cargo vessels (Bulkers/Tankers) are aligned with Ammonia. To enhance the robustness of this matrix, qualitative confidence levels have been applied based on the degree of consensus in the reviewed literature. Pathways such as 'LNG for Deep-Sea Containers' currently exhibit a high consensus in the literature due to mature engine technology, whereas 'green Ammonia by 2030′ exhibits a Low Consensus due to unresolved safety and regulatory frameworks.

Based on the synthesis, Table 3 delineates the optimal fuel pathways for the deep-sea fleet. The analysis reveals a clear bifurcation based on operational priorities: volume-critical vessels (container ships) are projected to converge on liquid methanol to preserve revenue-generating cargo space, whereas weight-critical vessels (bulkers) and hazardous-cargo vessels (tankers) favor ammonia due to its lower long-term marginal cost and the crew's existing competency in handling toxic payloads. The matrix highlights a distinct transitional phase (2030–2040) dominated by LNG and drop-in biofuels, before a pivot to scalability-constrained hydrogen derivatives (green ammonia/methanol) becomes mandatory to meet the IMO's 2050 net-zero targets.

In addition to its managerial and policy contributions, the study also makes two important theoretical contributions to the fields of industrial decarbonization and socio-technical transitions. First, it challenges the traditional, siloed research approaches common in marine fuel studies. By proposing a multi-dimensional horizontal synthesis model, it offers a new framework that clearly identifies systemic friction points and trade-offs

between conflicting areas, such as the immediate economic benefits versus long-term environmental sustainability. Second, it advances socio-technical transition theory by showing that technological gridlocks are caused by structural issues—such as institutional, financial, and infrastructural misalignments—rather than by engineering or chemical hurdles alone. By viewing the maritime energy transition as a complex, co-evolving ecosystem rather than a simple technology swap, this paper lays the foundation for future research into decarbonization in other challenging sectors, such as global transport and heavy industry.

Table 3. Strategic Fuel Deployment for Deep-Sea Shipping (2030–2050).

Vessel Segment	Short-Term (2030) (20–30% Reduction)	Mid-Term (2040) (70–80% Reduction)	Long-Term (2050) (Net-Zero)
Container Ships (High speed, fixed route, volume-critical)	**LNG (Dual Fuel)** (Matures immediately; established bunkering.)	**Green Methanol** (Leading choice. Fixed routes allow green corridors setup. Remains dominant due to storage ease.)	**Green Methanol/e-Ammonia** (Split fleet. Methanol dominates if costs drop; Ammonia if safety zones allowed.)
Bulk Carriers (Low speed, irregular route, cost-critical)	**Drop-in Biofuels** (Low CAPEX; requires no engine retrofit; improve CII rating.)	**Blue Ammonia** (Lowest cost zero-carbon fuel. Toxic risk manageable on open deck.)	**Green Ammonia** (Accepts toxic risk for lower fuel price. High energy density needed for iron ore runs.)
Tankers (Hazardous cargo handling expertise exists)	**LPG/LNG** (Often used cargo-as-fuel.)	**Ammonia** (Crew already competent in hazardous handling.)	**Green Ammonia** (Ideal synergy. Ships can transport ammonia and burn it simultaneously.)

This study acknowledges several limitations to ensure its academic integrity. First, the evidence is heavily simulation dependent. Because deep-sea vessels powered by ammonia and hydrogen have yet to enter commercial service at scale, data on their safety performance and maintenance costs rely on theoretical modeling rather than empirical operational data. The real-world behavior of these fuels in a marine environment, particularly regarding long-term storage stability and crew interactions, remains a gap in current knowledge. Second, the selected literature shows a pronounced geographic bias. A significant portion of the reviewed studies originates from Northern Europe and East Asia. Consequently, the findings on social acceptance and infrastructure readiness may not reflect the realities of the Global South, where a significant portion of the world's maritime refueling takes place. Furthermore, the geographic bias inherent in the synthesized literature—which predominantly reflects European and East Asian regulatory frameworks (e.g., the EU ETS)—masks a critical geopolitical vulnerability in the maritime transition. By focusing heavily on localized 'Green Corridors' in the Global North, current research largely ignores the operational realities of the Global South, where a significant volume of global bunkering occurs. This oversight risks the emergence of a 'two-tier' shipping industry. Without globally uniform enforcement mechanisms, stringent regional regulations may inadvertently incentivize a 'shadow fleet'—older, highly polluting vessels operating on conventional HFO in less-regulated developing waters, thereby undermining global net-zero targets. However, the implications for the Global South are not solely defined by regulatory risk; they also present an unprecedented strategic opportunity. The literature frequently frames developing nations merely as passive consumers of maritime fuels or potential compliance loopholes. Yet, regions such as Africa, South America, and Southeast Asia possess immense, untapped renewable energy potential. By strategically developing the infrastructure for scalable zero-emission fuels, these developing economies are uniquely positioned to transition from their historical role as fossil-fuel importers to dominant global

producers and exporters of e-ammonia and e-methanol, fundamentally redrawing the geopolitical map of maritime energy.

Given the identified gaps, future academic inquiry should pivot from general techno-economic comparisons to specific implementation challenges. Second, there is an urgent need for empirical quantitative risk assessments regarding the toxicity and dispersion of liquid ammonia in densely populated port environments. Moreover, future scholarship must expand beyond Eurocentric regulatory models to empirically quantify the economic potential of developing nations to serve as primary e-fuel producers, thereby transforming the global maritime energy landscape. Further investigation is required to evaluate the impact of these fuel transitions on developing nations. Specifically, can the Global South leverage its renewable energy potential to become producers of green hydrogen or ammonia, or will the green premium simply increase their import costs? In short, the technology to decarbonize the shipping industry exists, but the market architecture to deploy it does not. Methodologically, this requires three specific adjustments:

(a) ***Financial Modeling Calibration:*** Researchers should replace generic global discount rates with country-specific weighted-average costs of capital (WACCs) that accurately reflect localized inflation, currency volatility, and geopolitical risk premiums.
(b) ***Lifecycle Emissions Adjustments:*** Well-to-Wake models must incorporate the actual, empirical carbon intensity of local electrical grids in developing regions rather than assuming zero-carbon renewable inputs from day one, accounting for the transitional phase in which local bunkering hubs may still rely on fossil-heavy grids.
(c) ***Infrastructure Constraint Mapping:*** Models must integrate empirical brownfield data from actual ports in the Global South, explicitly accounting for localized draft limitations, storage capacity restrictions, and lower initial automation efficiencies.

Embedding these three empirical layers into future TEA frameworks will prevent distorted viability projections and provide global policymakers with a scientifically accurate roadmap for a globally equitable maritime transition.

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Abbreviations

Abbreviation	Description
AHP	Analytic Hierarchy Process
ANOVA	Analysis of Variance
ASLET	Australia–Singapore Initiative on Low Emissions Technologies for Maritime and Port Operations
BWM	Best–Worst Method
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CII	Carbon Intensity Indicator
CO_2	Carbon Dioxide
CSMO	Centre for Seafaring and Maritime Operations
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DC	Direct Current
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
ETS	Emissions Trading System (EU ETS)
FAME	Fatty Acid Methyl Ester
GFI	GHG Fuel Intensity (standard)
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
HPDF	High-Pressure Dual-Fuel (engine)
HR	Human Resources
HVO	Hydrotreated Vegetable Oil
IGF Code	International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels
ILUC	Indirect Land Use Change
IMO	International Maritime Organization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LH_2	Liquid Hydrogen
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MBM	Market-Based Measure
MCDM	Multi-Criteria Decision Making
MCDA	Multi-Criteria Decision Analysis
MSFC	Multi-Stack Fuel Cell
NIMBY	Not In My Back Yard
NPV	Net Present Value
OPEX	Operating Expenditure
OHS	Occupational Health and Safety
PEM	Proton Exchange Membrane (fuel cell)
PM	Particulate Matter
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
Q1, Q2	First/second quartile journal rankings (Journal Citation Reports/ Scopus categories)
SLR	Systematic Literature Review
SPEEK	Sulfonated Polyether Ether Ketone
SOLAS	International Convention for the Safety of Life at Sea
STCW	International Convention on Standards of Training, Certification and Watchkeeping for Seafarers
TEA	Techno-Economic Analysis
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution

TtW	Tank-to-Wake
VLSFO	Very Low Sulphur Fuel Oil
WACC	Weighted Average Cost of Capital
WtT	Well-to-Tank
WtW	Well-to-Wake

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