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Reviewing Comparative Study of Hydrogen Fuel vs LNG For Marine Vessel

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ABSTRACT

International shipping faces growing pressure to reduce greenhouse gas emissions while maintaining reliable and economically viable operations. This review compares liquefied natural gas (LNG) and hydrogen as marine fuels using three dimensions: cost, environmental performance and safety. Evidence was drawn from the published academic, industry and regulatory sources available for this review and examined through a structured thematic comparison. The review is not described as a systematic review because a reproducible search and screening record was not supplied. The evidence indicates that LNG benefits from more mature supply chains, marine engine applications, bunkering arrangements and safety requirements. However, any reduction in combustion-related carbon dioxide must be interpreted separately from lifecycle greenhouse gas emissions, which are sensitive to methane leakage and engine methane slip. Hydrogen offers strong potential for low-emission marine energy use, particularly when produced with low-carbon electricity and used in fuel cells, but production pathways, onboard storage, infrastructure availability and regulatory development substantially affect its practical suitability. Cross-study cost figures cannot establish a universal price advantage without common functional units and boundary assumptions. Overall, LNG may offer a near-term option in suitable operating contexts, whereas low-emission hydrogen may support deeper decarbonisation where supply, vessel design and safeguards are adequate. Fuel selection should therefore be based on vessel-specific and well-to-wake assessment rather than a single universal ranking.

Keywords: alternative marine fuels; liquefied natural gas; hydrogen; lifecycle greenhouse gas emissions; fuel transition

1. Introduction

Decarbonisation is an increasingly important consideration in commercial shipping. International shipping depends on high-energy-density fuels and globally distributed bunkering networks, making fuel changes more complex than substitution at a single land-based facility. Proposals to replace conventional heavy fuel oil and marine diesel oil with cleaner alternatives must therefore address environmental performance alongside vessel reliability, fuel cost, storage space, safe operations and availability at intended ports of call (Balcombe et al., 2019; Robalo-Cabrera et al., 2025).

Liquefied natural gas (LNG) and hydrogen illustrate different positions within this transition. LNG is commercially established as a marine fuel and can reduce some exhaust emissions compared with conventional fuels. Its climate value is nevertheless affected by upstream methane leakage, engine design and unburned methane released during combustion (Lindstad et al., 2020; Balcombe et al., 2021). Hydrogen presents a

different proposition: its use in fuel cells does not produce carbon dioxide at the point of operation, but its overall greenhouse gas effect depends on how the hydrogen is produced, compressed or liquefied, transported and stored (Osman et al., 2024; Sola et al., 2024).

Previous studies address emissions, economics or fuel-specific safety risks, but the evidence spans different assumptions and technological contexts. Comparing an LNG fuel price with the production cost of renewable hydrogen, or comparing combustion emissions with full lifecycle values, does not establish which fuel is preferable for a particular vessel. This review asks: under what conditions does LNG or hydrogen appear better suited to commercial shipping when cost, environmental impact and safety are considered together? The contribution is a structured synthesis of reported strengths, uncertainties and practical decision factors, rather than a new cost model, life-cycle assessment or quantitative risk assessment.

2. Literature Review

2.1 Alternative fuel pathways and maritime applications

LNG is predominantly methane stored at cryogenic temperature and used in marine engines configured for gas-fuel operation. Its supporting infrastructure has developed through wider natural gas markets and increasingly established maritime applications. LNG should nevertheless be described as a fossil-derived alternative rather than a renewable fuel in its conventional form (Al-Enazi et al., 2021; Ramsay et al., 2023).

Hydrogen can be produced by different pathways. Grey hydrogen is generally produced from fossil sources without capturing process carbon dioxide; blue hydrogen involves carbon capture arrangements; and green hydrogen is commonly associated with electrolysis powered by renewable energy. Hydrogen can also be used through different shipboard technologies, especially fuel cells or suitably designed combustion engines. These distinctions are fundamental because both cost and environmental performance depend on the production route and the onboard system (Bhuiyan & Siddique, 2025; Osman et al., 2024).

2.2 Economic dimensions of fuel selection

The relevant commercial comparison is not simply purchase price per kilogram or tonne. Shipowners must also consider delivered energy per unit of propulsion or electrical output, machinery efficiency, storage volume and mass, vessel conversion or newbuilding expenditure, equipment maintenance, bunkering time, port availability and compliance costs. Studies of LNG and hydrogen frequently use different functional units, fuel states, regions and prices, making direct comparisons hazardous without normalization (Balcombe et al., 2019; Christodoulou et al., 2023; Ramsay et al., 2023).

LNG benefits from a comparatively mature maritime supply chain. Hydrogen produced by electrolysis can incur substantial electricity, electrolyser, compression or liquefaction and transport costs, with overall expense depending strongly on production scale and location. These considerations suggest an often stronger near-term cost position for LNG where bunkering access exists, but do not establish one invariant global cost multiplier (Bortnowska & Zmuda, 2024; Christodoulou et al., 2023).

2.3 Environmental performance and system boundaries

Environmental comparisons require explicit system boundaries. Tank-to-wake accounting covers onboard fuel use; well-to-tank accounting covers upstream production and distribution; and well-to-wake accounting considers both. LNG can lower combustion-related carbon dioxide relative to some conventional marine fuels, and the literature reports indicative reductions of approximately 20–30%. This figure should not be interpreted automatically as a reduction in lifecycle greenhouse gas emissions, which depend on methane losses and engine performance (Pavlenko et al., 2020; Balcombe et al., 2021).

Methane is a potent greenhouse gas, and LNG supply-chain leakage and engine methane slip can materially change comparative climate outcomes. The magnitude of the effect depends on measurement assumptions, the engine type and the period over which climate impacts are assessed. Accordingly, claims that LNG provides a uniform greenhouse gas benefit require qualification (Howarth, 2024; Benoit et al., 2025).

Hydrogen used in fuel cells produces no direct carbon dioxide at the point of use, but this does not imply that the full fuel pathway is emission-free. Electricity generation, hydrogen production, liquefaction, compression and transport can contribute to lifecycle emissions. Hydrogen combustion may also require control of nitrogen

oxides. Renewable-powered production offers a potentially low-carbon route, but lifecycle performance depends on the actual energy supply and system configuration (Sola et al., 2024; Tomos et al., 2023; Jin et al., 2025).

2.4 Safety hazards and regulatory readiness

Both fuels are flammable and may require cryogenic handling, yet their hazard characteristics differ. LNG is usually stored at approximately −162 °C and presents release, vapor-cloud ignition, material embrittlement and cryogenic exposure hazards. Hydrogen has a broad flammable concentration range in air, low ignition energy and demanding storage considerations, particularly in compressed or liquefied forms (Depken et al., 2022; Zanobetti et al., 2023).

These hazards should not be equated directly with accident likelihood. Operational risk also depends on ventilation, layout, detection and shutdown systems, separation distances, bunkering procedures, training and emergency response. LNG has more established vessel applications and prescriptive international safety arrangements. Hydrogen shipboard applications are developing through evolving guidance and case-specific engineering assessments, with reported regulatory gaps requiring continued attention (Aneziris et al., 2020; Georgopoulou et al., 2025; Jeong et al., 2025).

3. Methodology

3.1 Review design

This study uses a structured narrative review of secondary evidence. The evidence base comprises academic studies, industry reports, regulatory material and maritime technical literature relevant to LNG and hydrogen. The approach is described as a thematic comparative synthesis rather than a systematic review because the supporting material does not document a complete database search, search strings, a dated screening process, duplicate removal, eligibility counts or formal study quality appraisal. These details cannot be reconstructed reliably after the fact.

3.2 Source selection and evidence boundaries

Source relevance was considered against three questions: whether a source addresses marine fuel cost or infrastructure, greenhouse gas performance or fuel-specific safety and regulatory readiness. The literature base contains predominantly recent sources, together with older foundational work and later materials; a strictly bounded 2015–2025 search window cannot be verified. The available record therefore does not support a strict date-restricted selection claim. This synthesis cites identifiable published sources; complete bibliographic verification and formal source appraisal remain necessary for future updates.

Secondary-source findings were interpreted within their own contexts. Figures from different currencies, years, fuel states or functional units were not combined into a universal cost ratio. Emissions estimates were examined with attention to tank-to-wake versus well-to-wake boundaries. Safety evidence was treated as a combination of inherent hazards, control maturity and regulatory status, not as a calculated probability of accidents.

3.3 Comparative criteria

The comparison is organised around three domains. Cost comprises production and delivery, vessel operation and conversion, and infrastructure or bunkering needs. Environmental performance comprises combustion-related emissions, lifecycle greenhouse gas effects and conditions for alignment with decarbonisation goals. Safety comprises fuel properties, storage and handling, and available rules and operational experience. Table 1 summarizes the analytical boundaries.

Table 1. Comparison framework for LNG and hydrogen as marine fuels.

Domain	Sub-criteria	Basis for qualitative comparison
Cost	Production and delivery; operations; bunkering	Comparability of fuel units, vessel equipment, location and infrastructure requirements
Environmental	Tank-to-wake CO_2; well-to-wake GHG; methane leakage	Fuel pathway, engine/fuel-cell technology and emission-system boundaries
Safety	Fuel hazards; onboard controls; regulatory readiness	Storage conditions, ignition/release hazards, operational maturity and safeguards

3.4 Evidence synthesis

The evidence was organised under the three domains, and LNG and hydrogen were evaluated using parallel sub-criteria. Where sources appeared to conflict, the likely source of disagreement—such as different lifecycle boundaries, locations or technology assumptions—was noted rather than averaged away. The synthesis is descriptive and does not assign numerical criterion weights. No new ship-level economic model, lifecycle inventory, experimental measurements or probabilistic safety calculation was conducted.

4. Results

4.1 Cost and operational readiness

The reviewed evidence generally favours LNG for infrastructure and near-term operational familiarity. Conventional LNG infrastructure, dual-fuel engine experience and existing safety arrangements lower some deployment barriers compared with hydrogen. This does not mean LNG costs are fixed or consistently low: supply-market volatility, additional onboard storage requirements, ship conversion expenditure and future emissions costs can materially influence its attractiveness (Wang et al., 2021; Ramsay et al., 2023).

Hydrogen faces a less developed bunkering network and can require substantial investment in fuel production, storage and distribution. The costs depend on whether hydrogen is used as a gas or cryogenic liquid and on the power source used in production. The evidence supports identifying cost and readiness as practical barriers, but it does not support a single numerical comparison across all routes and vessel types (Bortnowska & Zmuda, 2024; Christodoulou et al., 2023).

4.2 Environmental outcomes

The comparative environmental result depends critically on the metric. LNG offers potential reductions in conventional air pollutants and combustion-related carbon dioxide relative to conventional oil-derived fuels. However, methane slip and leakage may reduce or reverse some lifecycle greenhouse gas advantages, depending on the circumstances of production, distribution and operation. An indicative 20–30% carbon dioxide reduction is therefore treated as a context-dependent combustion comparison, not as a confirmed well-to-wake result (Pavlenko et al., 2020; Lindstad et al., 2020; Balcombe et al., 2021).

Hydrogen used in fuel cells provides near-zero direct carbon emissions on board. The stronger long-term climate case concerns hydrogen produced with low-emission energy across the supply chain, rather than hydrogen irrespective of its origin. Differences among grey, blue and renewable-powered hydrogen must therefore be maintained when comparing climate performance (Osman et al., 2024; Sola et al., 2024; Tomos et al., 2023).

4.3 Operational safety and governance

LNG has established regulatory treatment, handling procedures and industrial experience, yet cryogenic releases, ignition and engine or bunker-system hazards still require engineered controls. Hydrogen has additional practical challenges associated with leakage detection, dispersion, ignition and compressed or cryogenic storage. These characteristics justify careful design and risk analysis, not a blanket assertion that a hydrogen vessel necessarily has a greater accident frequency (Depken et al., 2022; Aneziris et al., 2020; Jeong et al., 2025).

The more consistent distinction is maturity: maritime LNG systems have a deeper operating history and an established prescriptive framework, while hydrogen design rules and demonstrations remain comparatively less mature. Risk management should be based on ship-specific assessments and the applicable regulatory approval route (Georgopoulou et al., 2025; Fan et al., 2025).

4.4 Consolidated comparative results

Table 2 consolidates the main findings without treating unlike numerical values as directly comparable.

Table 2. Qualitative comparison based on the source literature. Findings are conditional and do not constitute a universal numerical ranking.

Comparison element	Liquefied natural gas (LNG)	Hydrogen
Fuel production	Established natural-gas-based chain; cost varies with market conditions	Production route and electricity input strongly determine cost and emissions

Comparison element	Liquefied natural gas (LNG)	Hydrogen
Vessel operations	Commercial dual-fuel experience, with conversion and equipment costs	Developing applications; fuel-cell or engine choice affects cost and efficiency
Bunkering	More mature supply chains in some key shipping regions	Limited marine bunkering network and specialized storage needs
Combustion CO_2	Potentially lower than conventional fuel; not carbon-free	Fuel cells produce no direct CO_2; combustion application differs
Lifecycle GHG	Sensitive to methane leakage and engine methane slip	Strongly dependent on grey, blue or renewable production pathway
Climate-transition role	Conditional near-term option; carbon lock-in and methane must be managed	Potential deep decarbonisation with verified low-emission supply
Key hazards	Cryogenic burns, flammable gas release and material compatibility	Wide flammable range, low ignition energy and storage complexity
Safety management	More established maritime operation and regulatory control	Case-specific design assessment and developing guidance remain important
Overall interpretation	Potentially practical where appropriate infrastructure and controls exist	Potentially suitable as systems, infrastructure and supply mature

5. Discussion

5.1 Reconciling economic readiness and long-term emissions

The two fuels appear to perform differently because they are being evaluated against goals with different time horizons and system boundaries. For existing commercial ship routes with established LNG bunkering and appropriate engines, LNG may be easier to deploy in the near term. Where low-emission hydrogen can be produced and supplied affordably, hydrogen-based systems offer a potentially more compelling long-term route for reducing carbon emissions. Neither proposition is valid independently of a defined ship, route, fuel supply chain and technology (Hansson et al., 2019; Lindstad et al., 2020).

A fuel that appears favourable under a tank-to-wake comparison may not remain favourable when upstream fuel production and distribution are included. This is particularly significant for methane associated with LNG and for hydrogen pathways that depend on fossil energy. Future maritime fuel comparisons should therefore report both a common energy or transport-service denominator and consistent greenhouse gas accounting boundaries (Tomos et al., 2023; Howarth, 2024).

5.2 Implications for shipowners, ports and policymakers

Shipowners should assess fuels against vessel-specific energy demand, voyage length, space limitations, bunkering routes, planned machinery life, maintenance requirements and a transparent lifecycle emissions inventory. A decision to invest in LNG should incorporate potential methane-control requirements and future carbon constraints. Hydrogen investments should assess the actual production pathway, storage form, machinery technology and safety demonstration required for the intended ship (Balcombe et al., 2021; Christodoulou et al., 2023).

Ports can support informed investment by evaluating the local feasibility of alternative-fuel infrastructure and the safety consequences of storage and bunkering activities. Regulators and industry bodies can reduce uncertainty through clear approval pathways, crew competence requirements and harmonised technical guidance. Such measures are particularly important for hydrogen, where maritime operational experience and specific regulation continue to develop (Georgopoulou et al., 2025; Jeong et al., 2025).

5.3 Study limitations and future research

This review is limited by dependence on the available secondary sources and the absence of a recorded, reproducible literature-search and appraisal procedure. Cross-study cost comparisons are constrained by different financial years, currencies, production pathways and denominators. Emission claims vary according to engine

technology, methane assumptions and lifecycle boundaries. In addition, operational evidence for hydrogen-fuelled commercial vessels is less extensive than for established LNG installations. The findings are consequently interpretive rather than precise quantitative estimates of fuel cost, emissions or accident probability.

Future research should compare LNG and specified hydrogen production pathways using common units, such as cost per unit delivered energy or per transport service, and a consistently defined well-to-wake emissions assessment. Vessel-specific feasibility studies could combine onboard volume and mass restrictions, safety engineering, port supply chains and relevant lifecycle uncertainty. Maintaining an auditable literature-extraction record would also improve reproducibility and facilitate updates as technology and regulation evolve.

6. Conclusion

This comparative review examined LNG and hydrogen using the dimensions of cost, environmental performance and safety. The existing literature suggests that LNG has a stronger position in some near-term maritime applications because of its greater infrastructure and operational maturity. Its environmental contribution, however, must be considered beyond combustion carbon dioxide: methane leakage and methane slip can materially alter lifecycle greenhouse gas outcomes.

Hydrogen offers a potentially important path towards lower-emission shipping, especially when produced through low-emission pathways and used in suitable onboard technologies. Its practical implementation remains shaped by production costs, energy availability, storage requirements, bunkering infrastructure and developing maritime guidance. A definitive choice cannot be inferred without vessel-specific evidence and consistent measurement assumptions.

The central implication is therefore not that one fuel universally outperforms the other, but that the preferred fuel depends on context, accounting boundaries and the time horizon of the decision. Transparent comparison of cost, well-to-wake emissions and operational safeguards is necessary for an effective and credible marine-fuel transition.

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No conflict of interest was reported. This declaration requires author confirmation before publication.

Author Contributions

Data Availability Statement

The study synthesises published secondary sources cited in the reference list. No separate literature-extraction dataset is presented. Availability of any additional extraction records requires author confirmation.

Ethics Statement

This review does not report new human-participant or animal experiments. The author is responsible for confirming any applicable institutional declarations before publication.

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