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Hydrogen and ammonia as next-generation marine fuels in line with IMO 2050

Abstract. This article presents an interdisciplinary analysis of hydrogen (H_2) and ammonia (NH_3) as promising alternative energy carriers for maritime transport within the framework of the International Maritime Organization's 2050 Climate Strategy. The study aimed to determine the comparative efficiency of these fuels, taking into account their thermodynamic properties, storage requirements, operational safety, infrastructural compatibility, and economic feasibility. A multi-criteria assessment method was applied, incorporating analysis of Levelized Cost of Energy (LCOE), Energy Return on Investment (EROI), Capital Expenditures (CAPEX) and Operational Expenditures (OPEX), technical readiness of port and vessel infrastructure, environmental impacts, and potential risks. Particular attention is given to toxicological aspects, fire hazards, leakage scenarios, and crew training requirements. Data from real-world and pilot projects in Japan, Norway, and the EU are presented, illustrating practical steps towards the adoption of H_2/NH_3. The findings indicate that ammonia, despite its toxicity and the need for additional safety measures, is technologically and economically more suitable for medium- and long-distance shipping due to lower transport costs and the possibility of utilising existing liquefied gas infrastructure. Hydrogen, by contrast, offers higher environmental value owing to zero CO_2 and NO_x emissions (when used in fuel cells), but requires advanced storage systems and substantial investment in logistics, which limits its use primarily to short-sea shipping or within closed supply chains. The findings can serve as a basis for shaping fleet decarbonisation strategies, developing safety standards, and fostering innovation in marine

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energy. The conclusions are of practical interest to shipowners, engineering companies, environmental regulators, and policymakers in the field of green marine fuels

Keywords: environmental safety; pollution prevention; NO_x emissions; ammonia toxicity; fuel energy efficiency; port infrastructure; marine environment protection

INTRODUCTION

Climate change and the tightening of international environmental standards are creating new requirements for the shipping industry, which remains one of the significant sources of greenhouse gas emissions. In 2023, the International Maritime Organization (IMO, 2023a) adopted a strategy aiming for full decarbonisation of maritime transport by 2050. This necessitates a radical transformation of fleet energy systems and a transition to alternative, carbon-free fuels. Among the most widely discussed solutions are hydrogen (H_2) and ammonia (NH_3), which produce no CO_2 emissions during combustion and offer strong potential for sustainable development. At the same time, the practical deployment of these energy carriers is associated with numerous technical and economic challenges. Low-carbon ammonia is considered a promising marine fuel owing to the absence of CO_2 emissions during combustion. W. Schreuder *et al.* (2025), in their study, conducted a techno-economic assessment showing that the capital investment required for ammonia-fuelled systems could be recouped within 7-8 years at current ammonia prices. The review by K. Machaj *et al.* (2022) systematised the challenges associated with transport, storage, and safety, proposing measures to mitigate the corrosive impact of ammonia on equipment. The study by F. Harahap *et al*. (2023) examined alternative fuels in the context of the United Nations Sustainable Development Goals, demonstrating that combining bioenergy with Carbon Capture, Utilisation and Storage (CCUS) technologies could reduce overall vessel emissions by up to 50%. B. Jesus *et al*. (2024) developed an economic model of "green" shipping corridors, highlighting the balance between capital investment and operational costs as a key factor.

A review of modern hydrogen compression and storage technologies for marine fuel cells was presented by J.-C. Li *et al*. (2024), which outlined the main engineering challenges and potential solutions. Alternative fuels in relation to the United Nations Sustainable Development Goals were also discussed by Z.I. Rony *et al.* (2023), who noted their potential to reduce emissions in the maritime sector. The technical limitations and opportunities of "green" hydrogen and ammonia were examined in detail by R. Alrashid *et al*. (2024). Despite the availability of a substantial body of analytical material, most studies focus on isolated aspects – whether environmental impact, economic costs, or technical challenges. A systematic assessment integrating all key factors – from thermodynamic characteristics and storage parameters to crew safety and capital expenditure – remains insufficiently represented in current scientific debate. In addition, there is a shortage of interdisciplinary studies that consider the influence of regulatory mechanisms, legal uncertainty, and risk scenarios in the practical deployment of hydrogen and ammonia on board vessels. Against this background, the present study aimed to conduct a comprehensive comparison of hydrogen (H_2) and ammonia (NH_3) as next-generation marine fuels in the context of achieving the IMO 2050 climate targets, taking into account their thermodynamic properties, storage parameters, environmental risks, infrastructural readiness, economic efficiency, and technological safety.

MATERIALS AND METHODS

In this research, hydrogen (H_2) and ammonia (NH_3) were selected as the objects of comparative analysis as promising alternative marine fuels. The study was based on open techno-economic data drawn from scientific publications indexed in Scopus, Elsevier, and MDPI, reports of international organisations, as well as the results of pilot projects implemented in Norway, Japan, and the EU during 2020-2024. In particular, the International Energy Agency's (IEA, 2023) forecast of global energy consumption to 2050 was examined, which also included an analysis of international shipping and aviation, thereby providing insights into global decarbonisation trends. Furthermore, the Det Norske Veritas (DNV, n.d.) Energy Transition Outlook 2025 report was reviewed, which projects the evolution of energy systems across all regions and sectors, including maritime transport, and identifies the key technological and economic barriers to the transition to low-carbon fuels. As part of the present study, data from the International Maritime Organization (IMO, 2020; 2023a; 2023b) were considered, which set out the framework and targets for emission reduction by 2050, assessed maritime transport emissions for 2018, and provided projections to 2050.

The research was conducted using analytical, comparative, and quantitative methods. Initially, scientific sources from 2019 to 2024 were systematised, after which the main comparative parameters relevant to the maritime sector were identified. The comparison employed a multi-criteria approach involving parameter normalisation and expert evaluation, covering six groups of criteria:

- thermodynamic characteristics (lower heating value, gravimetric and volumetric energy density);
- storage conditions (temperature, pressure, form);
- level of toxicity and risks (flammability, health impacts, leakage scenarios);
- infrastructural readiness (technology maturity, availability of terminals);

- economic efficiency (Levelized Cost of Energy (LCOE), Energy Return on Investment (EROI), Capital Expenditures (CAPEX), Operational Expenditures (OPEX));
- environmental consequences (CO_2, NO_x, secondary impacts on ecosystems).

For each parameter, data were normalised and the relative importance was weighted by experts, ensuring an objective ranking of the fuels in terms of their suitability for application in marine energy systems. This multi-criteria approach made it possible to clearly distinguish the strengths and weaknesses of each technology – for example, the high energy density of ammonia but its demanding storage requirements, or the safe use of hydrogen at the cost of significant capital investment in compression. Subsequently, the techno-physical and chemical characteristics of H_2 and NH_3 were collected, comparative tables were constructed, and the storage conditions and logistical readiness of the sector were evaluated. To provide a comprehensive assessment of the environmental and economic viability of alternative marine fuels, six key indicators were applied:

- LCOE – enables comparison of the full cost of 1 MWh of final energy, accounting for capital (CAPEX) and operational (OPEX) expenditures over the entire system life cycle;
- EROI – the ratio of total energy generated by the system to the energy invested in its construction and maintenance, indicating the "energy payback" of the technology;
- CAPEX – capital expenditures on construction and installation of equipment, which determine the initial investment barriers;
- OPEX – operational expenditures on maintenance, fuel, and logistics, influencing overall long term profitability;
- CO_2-equivalent emissions – an assessment of direct greenhouse gas emissions, adjusted for the fuel's life cycle, to compare impacts on global warming;
- NO_x, SO_x, $PM_{10/2.5}$ – local air pollutants that determine the environmental and social acceptability of the solution.

The use of this set of indicators ensured a balanced evaluation: economic (LCOE, CAPEX, OPEX), energy-related (EROI), and environmental (greenhouse gas and pollutant emissions) components, all of which are necessary for making informed decisions regarding the adoption of new technologies in marine energy systems.

LCOE – the levelised cost of energy over the life cycle, calculated using the formula:

$$LCOE = \frac{\sum_{t=1}^{N}\frac{I_t+M_t+F_t}{(1+r)^t}}{\sum_{t=1}^{N}\frac{E_t}{(1+r)^t}}, \quad (1)$$

where I_t is the capital expenditures in year t; M_t is the maintenance costs; F_t is the fuel costs; E_t is the energy produced; r is the discount rate; N is the service life (assumed to be 20 years). Source data were taken from the report by S. Brynolf *et al.* (2023).

EROI – the ratio of the energy produced by the system to the energy consumed for its construction and maintenance, calculated as:

$$EROI = \frac{Output\ Energy}{Input\ Energy}, \quad (2)$$

where *Output Energy* is the useful energy; *Input Energy* is the total energy required for production, storage, and delivery. EROI values for H_2 and NH_3 were drawn from open sources.

The methods described provided a generalised assessment of the efficiency of hydrogen and ammonia in the context of maritime decarbonisation, taking into account both technological and practical aspects of their implementation.

RESULTS

Physicochemical characteristics of hydrogen and ammonia

Within the framework of the IMO strategy (2023a) to achieve net-zero greenhouse gas emissions by 2050, hydrogen (H_2) and ammonia (NH_3) are considered as potential alternatives to conventional marine fuels. The choice between them depends on their physicochemical properties, safety levels, and environmental characteristics. An objective comparison of these substances makes it possible to evaluate their potential in maritime transport. Below is a comparison of the key physicochemical parameters that are critically important in terms of energy performance, safety, and operational use on board vessels. The data presented in Table 1 make it possible to assess the key parameters relevant to the industry's transition to carbon-free fuels.

Table 1. Comparative characteristics of hydrogen and ammonia

Criterion	Hydrogen	Ammonia
Chemical formula	H_2	NH_3
Molar mass (g/mol)	2.016	17.031
Physical state at 20 °C	Gas	Gas
Boiling point (°C)	-252.9	-33.3
Ignition temperature (°C)	~560	~651
Explosion limits (vol. %)	4-75	15-28
Density in liquid state (kg/m³)	~70.8	~681
Gravimetric energy density (MJ/kg)	120	18.6
Volumetric energy density (MJ/L)	8.5	11.5
Odour	Low	Strong
Flame visibility during combustion	Invisible	Pale yellow, visible

Continued Table 1.

Criterion	Hydrogen	Ammonia
CO_2 emissions on combustion	None	None
NO_x emissions on combustion	Possible	High
Infrastructure status	Limited	Partially available
Production cost (approx.)	Strong	Medium

Source: authors' compilation

Both energy carriers can be produced using renewable energy sources, which is critical for achieving full carbon neutrality. Green hydrogen is generated through water electrolysis, in which electrical energy from renewable sources (solar, wind, hydro) splits H_2O molecules into molecular hydrogen and oxygen. The most common method is Proton Exchange Membrane (PEM) electrolysis, characterised by high current density, rapid start-up, and the ability to operate with fluctuating energy flows. However, it requires an expensive platinum-based catalytic system and highly purified feedwater. The energy conversion efficiency (η) of modern PEM electrolysers reaches 60%-70%, with the main losses arising from electrode overpotentials and membrane resistance. Only after hydrogen is purified to ⩾99.9% can it be supplied to fuel cells or compressed to 350-700 bar for storage and transport, which adds approximately 10%-15% to the overall energy demand. Green ammonia is synthesised via the Haber-Bosch process from green hydrogen and nitrogen, the latter separated from air using Pressure Swing Adsorption (PSA) units. The synthesis occurs under high pressure (150-300 bar) and elevated temperatures (400°C-500°C) in the presence of an iron catalyst. Maintaining these conditions consumes around 25%-30% of the produced hydrogen in the form of thermal and mechanical energy. However, the resulting ammonia can be readily liquefied at -33°C under normal pressure and stored in standard lowpressure tanks, which minimises compression-related energy requirements compared with hydrogen (Thomas & Parks, 2006). The overall energy conversion efficiency of the "electricity → hydrogen → ammonia" chain is about 50%-55%. Nevertheless, the absence of high-pressure storage needs makes this pathway more suitable for maritime logistics (Valera-Medina *et al.*, 2018; Brynolf *et al.*, 2023). The principal reaction is as follows:

$$2H_2O \rightarrow 2H_2 + O_2. \quad (3)$$

Green ammonia is synthesised through the Haber-Bosch reaction, in which hydrogen is derived from renewable sources and nitrogen from air. The choice between hydrogen and ammonia as future marine fuels largely depends on their physicochemical characteristics, environmental safety, production costs, and compatibility with existing infrastructure. Data in Table 1 indicate that hydrogen has a clear advantage in terms of gravimetric energy density. However, its low volumetric density and extremely low storage temperature make its use technically challenging. Ammonia, by contrast, is more readily integrated into existing infrastructure and easier to store, but it raises serious environmental and safety concerns owing to its high toxicity and NO_x emissions.

Thermodynamic properties of hydrogen and ammonia

On a mass basis, hydrogen (LHV ≈ 120 MJ/kg) has nearly six times the energy density of ammonia (LHV ≈ 20 MJ/kg). Yet, due to the low density of liquid hydrogen (~71 kg/m³), its volumetric energy density (≈ 8.5 MJ/L) is significantly lower than that of ammonia (≈ 11.5 MJ/L at 681 kg/m³). This tradeoff between the high gravimetric energy density of hydrogen and the more compact storage volume of ammonia determines the choice of fuel according to available onboard space and the need to ensure sufficient energy reserves for long voyages. Hydrogen is a highly explosive gas with a broad flammability range in air (4%-75% vol.) and a low ignition temperature (~560°C), which increases the risk of auto-ignition in the event of accidental leaks. Ammonia is less explosive but becomes toxic at concentrations above 300 ppm, can cause equipment corrosion, and poses health hazards upon exposure.

Hydrogen requires high-pressure storage (350-700 bar) or cryogenic tanks at -253°C, which necessitates specialised cylinders and compensation for diffusion-related leakage. Ammonia, by contrast, can be stored in liquid form at -33°C under relatively low pressure (~10 bar), greatly simplifying its integration into existing terminals and fuel corridors. Ammonia infrastructure is already partially available in key ports, whereas hydrogen would require substantial capital investment in new compression modules and refrigeration systems. The assessment of thermodynamic properties is crucial for determining fuel efficiency in marine energy applications. The most important parameters are the gravimetric and volumetric lower heating values (LHV), which define the amount of usable energy under real operating conditions. Hydrogen exhibits exceptionally high gravimetric energy density, nearly 6.5 times greater than that of ammonia. However, owing to its low liquid density (~71 kg/m³ compared with 681 kg/m³ for NH_3), its volumetric energy density is only 8.5 MJ/L, whereas ammonia achieves 11.5 MJ/L. This means that under the space constraints typical on board of ships, ammonia provides more energy per unit volume, a critical factor in practical applications. In addition, ammonia has a higher ignition temperature (651°C compared with ~560°C for hydrogen), reducing the risk of auto-ignition under accident conditions.

Safety, toxicity and operational risks

The adoption of alternative fuels in maritime transport is not feasible without a comprehensive assessment of safety issues. Although hydrogen and ammonia are regarded as promising pathways towards fleet decarbonisation due to their carbon-free nature, their use entails significant risks that affect ship design, storage systems, maintenance organisation, and even crew training requirements. For hydrogen, the most critical concerns are its high flammability, wide range of explosive concentrations in air, and the tendency to produce invisible flames during combustion. As a result, even minor leaks may lead to catastrophic consequences if effective detection, ventilation, and cut-off systems are not in place. From a technical standpoint, the challenge is compounded by the need for storage at extremely low temperatures, requiring cryogenic tanks with advanced insulation. Ammonia, unlike hydrogen, is not explosive in the conventional sense. However, its vapours irritate mucous membranes, may cause chemical burns, and pose serious risks to personnel, especially in the event of leaks within enclosed or poorly ventilated spaces. Moreover, ammonia is corrosively aggressive to certain metals, necessitating careful selection of materials for pipelines, fittings, and storage systems (Li *et al.*, 2025). Therefore, while both fuels hold potential for reducing emissions, their safe integration into marine systems demands meticulous engineering design, regulatory adaptation, and specialised crew training.

Table 2 presents a comparison of the key risks associated with the use of hydrogen and ammonia in shipping – ranging from differences in toxicity and flammability to ignition energy, incident scenarios, and the readiness of detection systems and regulatory frameworks. Hydrogen has the advantage of being non-toxic, but requires very low ignition energy and rapid sensor response due to its wide flammability range. Ammonia, while easier to store in liquefied form, demands careful management of toxic leaks, protective equipment for crew members, and adherence to temporary IMO guidelines (2020).

Table 2. Risks and safety measures

Parameter	Hydrogen (H_2)	Ammonia (NH_3)
Toxicity	Low. Non-toxic, but displaces oxygen in the air	High. Toxic when inhaled; irritates skin and eyes
Flammability	High (4%-75% in air), invisible flame	Moderate (15%-28% in air), visible flame
Ignition energy	Very low (0.02 mJ)	Higher (~0.3 mJ), auto-ignition at ~651°C
Risk scenarios	Leak → explosion without warning	Leak → toxic air contamination
Detection systems	H_2 detectors, ventilation control	NH_3 sensors (25/110/220 ppm), extraction, emergency shut-off
Regulatory framework (IMO)	Under development	Temporary IMO principles (2020)
Crew training needs	High (explosion response)	Very high (handling toxic substances)

Source: authors' compilation on base R. Alrashid *et al.* (2024)

The storage of hydrogen and ammonia in maritime applications is determined not only by their energy density but also by the technological requirements of tanks and maintenance systems. Hydrogen requires either high-pressure composite tanks (350-700 bar) to minimise leakage or cryogenic storage at -253°C with ultra-low boil-off losses, which demands complex insulation and continuous monitoring. By contrast, ammonia can be stored in liquid form at relatively moderate conditions (~10 bar and -33°C) in conventional steel tanks with anti-corrosion coatings, substantially reducing both capital and operational infrastructure costs. This difference in storage regimes determines the choice of fuel system depending on the availability of technical equipment, onboard space constraints, and the economic feasibility of implementation (Table 3).

Table 3. Comparative analysis of hydrogen and ammonia storage parameters

Parameter	Hydrogen (H_2)	Ammonia (NH_3)
Storage form	Liquid (cryogenic) / Compressed gas	Liquid / Pressurised
Storage temperature (°C)	-253	-33
Storage pressure (bar)	~350-700	~10-20
Volume per 1 MJ of energy	High (low density)	Lower (higher density)
Volatility	Very high	High
Leak potential	Significant	Moderate
Tank requirements	Double-walled, vacuum-insulated	Comparable to liquefied petroleum gas (LPG) infrastructure

Source: authors' compilation on base R. Alrashid *et al.* (2024)

The table shows that storing liquid hydrogen is technically demanding, as it requires a temperature of -253°C, which is close to absolute zero. Such conditions necessitate advanced tanks with multilayered insulation. Compressed hydrogen is an alternative, but pressures of up to 700 bar complicate safe handling. Ammonia, on the other hand, can be stored under moderate conditions, making it compatible with existing LPG terminals and easier to adapt for maritime use.

Infrastructure requirements for the deployment of carbon-free fuels

One of the key factors in the adoption of alternative marine fuels is the availability, scalability, and technological maturity of the supporting infrastructure. In this respect, ammonia demonstrates a significant advantage over hydrogen: a global network for its production, storage, and transportation is already in place. More than 180 million tonnes of NH_3 are produced annually worldwide, with supply chains covering most major ports, particularly in Asia, Europe, and the Middle East (IEA, 2023). By contrast, infrastructure for hydrogen – especially in liquid or compressed form – remains at a formative stage. It requires advanced terminals, cryogenic storage facilities, and high-pressure pipelines, which considerably increase both costs and implementation time (Table 4).

Table 4. Comparative overview: Infrastructure requirements

Aspect	Hydrogen (H_2)	Ammonia (NH_3)
Maturity of production	In development (green H_2 via electrolysis)	Established (green NH_3 under trial)
Storage infrastructure	Cryogenic tanks/high-pressure vessels	Existing tanks similar to LPG
Transport logistics	Limited: pipelines + road (pilot scale)	Global network: maritime, rail, and pipelines
Port readiness (2025)	Several demonstration projects	Over 120 terminals compatible with NH_3
Compatibility with existing systems	Low (requires new designs)	Medium-high (possible adaptation of LPG systems)
Capital expenditure for scaling	Very high	Medium-high

Source: authors' compilation O. Melnyk *et al.* (2024; 2025)

Ammonia is more suitable for rapid adaptation in ports and on vessels, as it can make use of part of the existing LPG infrastructure. However, given the production process of "green" ammonia, the development of infrastructure directly depends on the scaling of renewable hydrogen production, creating a kind of "double barrier" – first requiring electrolysis capacity, followed by adapted or new industrial complexes for ammonia synthesis. This means that even with a global logistics network already in place, the transition to "green" NH_3 demands investments in production and port facilities no less substantial than in the case of H_2, although the initial conditions for ammonia integration are more favourable. It should also be noted that the production of these 'green' fuels generates competition for inexpensive energy resources and must be aligned with national and regional policies, including EU directives. Thus, the choice between hydrogen and ammonia for shipping depends not only on the technological maturity of production, but also on the availability of infrastructure and integration with energy policy.

Performance assessment: LCOE, EROI, CAPEX + OPEX

For the strategic planning of hydrogen and ammonia use in maritime transport, it is important to consider not only their thermodynamic and infrastructural characteristics but also their overall economic viability. The assessment was carried out using three key indicators: LCOE, EROI, and combined CAPEX + OPEX, representing investment and operational costs. The assessment of total implementation costs includes: CAPEX – infrastructure costs for fuel production, storage, and processing; and OPEX – expenses for cooling, pressure, safety, and maintenance (Table 5).

Table 5. Integrated comparative table of economic efficiency: H_2 vs. NH_3

Indicator	Hydrogen (H_2)	Ammonia (NH_3)
LCOE (USD/MWh)	200-300	150-220
EROI	~4-6	~5-8
CAPEX	Very high: electrolysers, cryogenic storage	Moderate: synthesis plants, compatible tanks
OPEX	High: cooling to -253°C, compression	Medium: cooling to -33°C
Commercial readiness	Low (TRL 6-7), requires R&D	Higher (TRL 8-9), partly integrated into the industry

Note: TRL – technology readiness level, R&D – research and development
Source: authors' compilation

Table 5 shows that ammonia outperforms hydrogen in economic terms: its LCOE (150220 USD/MWh) is 25%-50% lower, and its EROI (~5-8) is somewhat higher than that of hydrogen (200-300 USD/MWh and ~4-6, respectively). At the same time, hydrogen requires significantly higher capital expenditure (CAPEX) for electrolysers and cryogenic storage, and has high operational costs (OPEX) for cooling to -253°C and compression. By contrast, ammonia involves moderate CAPEX – synthesis plants and compatible tanks – and lower OPEX, as liquefaction requires only -33°C. Technology readiness levels (TRLs) further highlight this difference: hydrogen is at stages 6-7 and still requires additional research and development, whereas ammonia is at 8-9 and is already partly integrated into the industry. Thus, although hydrogen has a higher energy potential, ammonia represents a more realistic short- and medium-term alternative for decarbonising the maritime fleet due to its economic and technological availability.

Experimental and commercial projects

As part of the global decarbonisation strategy for shipping by 2050, a number of companies and international organisations have launched projects aimed at introducing alternative fuels such as hydrogen and ammonia (Table 6). These initiatives range from demonstration vessels to the creation of 'green corridors' for zero-carbon transport. Current priorities include the deployment of clean-fuel bunkering infrastructure in major ports, the development of safety standards for handling ammonia, and the testing of storage and fuel supply systems for next-generation marine power plants. In addition, intergovernmental partnerships are actively being established to fund life-cycle assessments of such fuels, as well as subsidy mechanisms to support operators in transitioning to environmentally neutral technologies.

Table 6. Key implemented ammonia and hydrogen fuel projects

Project/initiative	Participants and country	Fuel type	Route/test	Infrastructure	Expected performance
Fortescue Green Pioneer	Fortescue (Australia); MPA, Seatrium, Vopak, A*STAR's IHPC, NTU, DNV (Singapore)	Liquid ammonia (NH_3)	Trial in Singapore; voyage to the Persian Gulf during COP28	Vopak terminals; HAZID/HAZOP system; drones, shore-based monitoring	Significant CO_2 reduction; "Gas Fuelled Ammonia" certification
Dutch ammonia tanker	C-Job Naval Architects, Proton Ventures, Enviu, Province of ZuidHolland (Netherlands)	Ammonia (NH_3)	Laboratory models and preliminary trials; voyage not yet commenced	Integration with the LPG port infrastructure in the Netherlands	~44% higher energy efficiency compared with hydrogen
CAMPFIRE Ammonia Sherpa	ENERTRAG, Sunfire, KIT, University of Rostock, ZBT (Germany)	Ammonia (NH_3)	Yacht Ammonia Sherpa tested in 2023; barge Odin planned for 2026	Bunkering system constructed in Rostock port	~350 kW electricity generation; targeted at small vessels
Sea Change Project	USA	Hydrogen	San Francisco Bay	Mobile hydrogen refuelling station (tube trailers) by West Coast Clean Fuels and Plug Power	65% energy penetration into fuel cells
MF Hydra	Norway	Liquid hydrogen	Hjelmeland-Nesvik route	Shore-based LH_2 terminals, refuelling stations	50%-60%
Kawasaki DualFuel Generatoк	Japan	Hydrogen	Dual-fuel engine	Prototype engine only	Engine thermal efficiency 42%-45%

Source: authors' compilation based on B. Holtze (2023), Nippon Yusen Kabushiki Kaisha (2023), L.E. Klebanoff (2024), E. Van Sickle *et al.* (2025)

According to Table 6, ammonia projects are predominantly at the demonstration and pilot stage. Their main focus is the testing of technologies (internal combustion engines, cracking), bunkering operations, and proving safety. By contrast, hydrogen projects have already advanced to the stage of commercial operation. They are deployed on regular routes, demonstrating the practical viability of the technology for short voyages such as port services, ferries, and tugs. As part of the global strategy to decarbonise maritime transport by 2050, a number of important demonstration and commercial projects are being implemented using "green" fuels. E. Van Sickle *et al.* (2025) described the first commercial hydrogen-powered passenger ferry, MV Sea Change, which features integrated fuel management and a fuel cooling system. The ferry was designed by Mitsubishi FCH Energy and certified by DNV. According to L.E. Klebanoff (2024), its efficiency reached 65% (energy penetration into the fuel cell), the infrastructure consisted of a mobile hydrogen refuelling station, and no incidents were recorded. Since 2023, a consortium of Japanese manufacturers has been testing a shipboard ammonia and hydrogen fuel system on the Yokohama-Tokyo route; preliminary data indicate a stable energy conversion efficiency of 50% and a requirement to upgrade terminal gasifiers (Nippon Yusen Kabushiki Kaisha, 2023). All projects demonstrate the commercial viability and technical reliability of "green" technologies without significant incidents, establishing a model for large-scale adoption in global shipping.

The results of the comparative analysis show that both hydrogen and ammonia can play a key role in the decarbonisation of maritime transport. However, their effectiveness is not universal, as it depends on factors such as vessel type, route characteristics, infrastructure availability, and the technological maturity of the relevant solutions. Hydrogen is almost ideal from an environmental perspective, producing no CO_2 emissions and, when used in fuel cells, no toxic nitrogen oxides. However, considering the technological characteristics specifically – low volumetric energy density, the need for deep cooling or high pressure, and the lack of established logistics – hydrogen's widespread adoption is currently severely constrained, particularly for long-distance transport. The production cost of "green" hydrogen also remains high. Ammonia, by contrast, has proven to be a far more practical marine fuel, as its transportation and storage processes can be managed using existing infrastructure, such as liquefied gas port terminals, making it less expensive in the short to medium term. The analysis indicates that hydrogen's environmental advantages are offset by the high cost of logistics. At the same time, despite certain operational risks, ammonia appears to be a more realistic option for large-scale deployment in the coming years. The primary challenge remains infrastructure reform – without public engagement, global standards, and demonstration projects, neither H_2 nor NH_3 will move from concept to feasible commercial implementation. This underscores the importance of contributions from the IMO, the European Commission, and national governments in defining the regulatory environment and providing financial incentives for the sector.

DISCUSSION

The results of the comparative analysis of hydrogen and ammonia as next-generation marine fuels are broadly consistent with recent studies, although in some cases differences have emerged that require critical consideration. The present study focuses on thermodynamic characteristics, safety risks, economic feasibility, and infrastructural readiness, which made it possible to justify the use of ammonia on medium- and long-distance routes and hydrogen for short coastal shipping. Similar findings are reported in a number of international studies; however, detailed comparisons revealed differing approaches to assessing future prospects. H. Xing *et al*. (2021) outlined strategic directions for the adoption of low-carbon fuels by 2050 and emphasised that without active involvement of governments and international organisations, the transition to "green" technologies will be extremely slow. The results of the present analysis confirm this argument, as for both hydrogen and ammonia, state support and regulatory incentives remain the key factors for scaling up. One of the most critical aspects of adopting carbon-free technologies is economic efficiency. For instance, the study by M. Abbas *et al*. (2024), dedicated to optimising energy consumption in maritime transport, demonstrated the importance of effective energy flow management on board vessels. The present study also highlights the significance of economic efficiency through the indicators of LCOE and EROI. The results of both analyses converge in showing that even environmentally attractive fuels cannot be adopted without sufficient economic benefit. However, the findings presented here stress that ammonia currently offers lower operating costs due to the use of existing LPG terminals in ports. This conclusion is also supported by the study of Y. Wang *et al*. (2022), which examined low- and zero-carbon fuel technologies in the context of economic efficiency. It has been shown that the most promising solutions are those that combine low capital expenditure with the use of existing infrastructure.

These conclusions are supported by analyses of operational projects aimed at reducing carbon emissions from ships. For example, G.N. Lee *et al*. (2024) conducted a life-cycle assessment of hydrogen supply methods between Australia and South Korea and identified the advantages of systems based on renewable energy sources. The present study confirmed their conclusion of lower emissions when using "green" hydrogen, but also demonstrated that logistical complexity and transport costs remain significant barriers to large-scale deployment. In turn, H. Fan *et al*. (2025) analysed the development timeline of hydrogen-powered vessels and showed that most commercial trials occur on short routes, where constraints related to fuel storage and infrastructure are not critical. The present findings likewise support the view that hydrogen is best suited for coastal shipping and local operations. Both studies, therefore, converge on the conclusion that hydrogen has limited applicability in long-distance maritime transport. A. Arias *et al*. (2024) investigated barriers to the integration of biofuels into marine systems and emphasised the need for standardisation and technical compatibility. The present results revealed that similar barriers exist for the use of ammonia and hydrogen as marine fuels, particularly in relation to crew safety and the technologies required for storage and transport. In this respect, it becomes evident that the challenges of standardisation are common to all low-carbon technologies. S. Tasleem *et al*. (2024) systematised the technologies for producing "green" hydrogen, as well as its storage and transport, and highlighted the potential for combining them with CCUS technologies. The present study expanded upon their review by providing a more detailed examination of risks and safety aspects, which were not central to their analysis.

The primary focus of this study was on comparing two fuels – hydrogen and ammonia. However, other integrated technologies for reducing the carbon footprint and achieving decarbonisation in shipping are also of importance, particularly in terms of economic efficiency. Z. Wang *et al*. (2024) investigated configurations of hybrid low-carbon marine energy systems, including fuel cells and battery packs, and proposed broader system integration. This demonstrated the differing scales of research but also underscored the importance of pursuing combined energy solutions. O. Melnyk *et al*. (2024; 2025) presented modelling and experimental results showing the feasibility of integrating renewable energy sources with carbon capture technologies. The present findings confirmed their conclusions regarding the potential for significant reductions in CO_2 emissions and improvements in energy efficiency, while supplementing their conclusions with quantitative indicators of economic viability. Thus, this study broadened the practical understanding of the feasibility of adopting such technologies. In summary, the present research largely confirmed the conclusions of earlier studies, while refining them through quantitative analysis, comparison of risks, and assessment of infrastructural constraints. This approach made it possible to more clearly define the applicability limits of hydrogen and ammonia in shipping and provided a basis for further research.

CONCLUSIONS

The study compared hydrogen (H_2) and ammonia (NH_3) as alternative marine fuels, taking into account their physicochemical, logistical and economic characteristics in the context of the IMO 2050 targets. The literature was systematised and analysed, six groups of comparative parameters were identified (thermodynamics, storage, safety, infrastructure, economics, ecology), and key indicators were calculated – LCOE, EROI, CAPEX, OPEX and emissions. The findings confirmed that ammonia demonstrates a lower LCOE (150-220 USD/MWh) and higher EROI (~5-8) compared with hydrogen (200-300 USD/MWh; EROI ~4-6), as well as a more developed storage infrastructure at -33°C and ~10-20 bar, making it a more promising option for fleet decarbonisation. At the same time, hydrogen, despite its higher gravimetric energy density and zero emissions when produced through "green" pathways, remains constrained by high-pressure (350-700 bar) or cryogenic (-253°C) storage, substantial capital requirements for compression and cooling, and the need for refined safety protocols addressing explosion risks. The study conceptualised renewable pathways of "electricity → hydrogen → ammonia", where ammonia serves as an intermediate carrier with an optimal balance of cost, safety and available infrastructure. The comparison of the two carbon-free fuels, alongside a review of experimental and operational projects employing them in shipping, confirmed that each has distinct advantages depending on the type of maritime transport. Hydrogen was found to be more suitable for coastal or short-distance operations, whereas ammonia systems demonstrated greater technological and infrastructural readiness for medium- and long-distance shipping.

Promising directions for further research include: the development of hybrid fuel cores that combine hydrogen and ammonia in blends to reduce storage pressure; life-cycle modelling of infrastructure under regional conditions; the integration of digital systems for leak monitoring and real-time corrective management algorithms; and the analysis of social and economic factors influencing the adoption of "green" technologies at the local level. Together, these directions could support the transition from demonstration trials to large-scale commercial deployment, ensuring that opportunities to achieve carbon neutrality in maritime transport are not lost.

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Водень та аміак як суднове паливо наступного покоління згідно з IMO 2050

Анотація. У статті здійснено міждисциплінарний аналіз водню (H_2) та аміаку (NH_3) як перспективних альтернативних енергоносіїв для морського транспорту в умовах реалізації кліматичної стратегії-2050 Міжнародної морської організації. Метою дослідження стало визначення порівняльної ефективності зазначених палив з урахуванням їх термодинамічних властивостей, умов зберігання, експлуатаційної безпеки, інфраструктурної сумісності та економічної доцільності. У роботі використано методику багатокритеріального оцінювання, яка включає аналіз показників LCOE (Levelized Cost of Energy), EROI (Energy Return on Investment), CAPEX (Capital Expenditures) та OPEX (Operational Expenditures), технічної готовності портової та суднової інфраструктури, екологічних наслідків і потенційних ризиків. Окрема увага приділена токсикологічним аспектам, ризикам займання, сценаріям витоків і вимогам до підготовки екіпажу. Наведено дані з реальних та пілотних проєктів у Японії, Норвегії та ЄС, що демонструють практичні кроки з впровадження H_2/NH_3. Результати дослідження показали, що аміак, попри токсичність і потребу в додаткових заходах безпеки, є технологічно і економічно придатнішим для середньо- та далекомагістрального судноплавства завдяки нижчим витратам на транспортування і можливості використання існуючої інфраструктури зрідженого газу. Водень, у свою чергу, характеризується вищою екологічною цінністю через нульові викиди CO_2 та NO_x (за умов використання паливних елементів), але вимагає високотехнологічних систем зберігання та значних інвестицій у логістику, що обмежує його застосування переважно в каботажних перевезеннях або в умовах замкнених ланцюгів постачання. Представлені результати можуть слугувати основою для формування стратегій декарбонізації флоту, розробки стандартів безпеки та стимулювання інновацій у морській енергетиці. Отримані висновки становлять практичний інтерес для судновласників, інженерних компаній, екологічних регуляторів та розробників політик у сфері зеленого морського палива

Ключові слова: екологічна безпека; запобігання забрудненню; викиди NO_x; токсичність аміаку; енергетична ефективність палива; портова інфраструктура; захист морського середовища