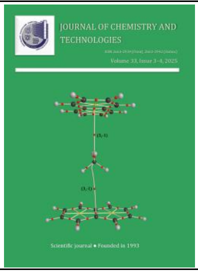
Journal of Chemistry and Technologies, 2025, *33*(4), 1216-1231

Journal of Chemistry and Technologies

pISSN 2663-2934 (Print), ISSN 2663-2942 (Online).

journal homepage: http://chemistry.dnu.dp.ua
editorial e-mail: chem.dnu@gmail.com



UDC 620.9:629.5

INTEGRATED MULTICRITERIA ANALYSIS OF HYDROGEN AND AMMONIA AS ALTERNATIVE MARINE FUELS IN THE MARITIME TRANSPORT DECARBONIZATION PROCESS

Oleksiy M. Melnyk[1*], Oleksandr M. Shumylo[1], Mykola P. Bulgakov[1], Serhii V. Voronenko[2], Oleg A. Onishchenko[3], Olena M. Korobkova[1], Inna O. Shapovalova[4], Olha S. Panteleieva[5]

[1]Odesa National Maritime University, 34, Mechnikova str., Odesa, 65029, Ukraine
[2]Kherson State Marine Academy, Ushakov, 20, Kherson, Ukraine
[3]National University "Odessa Maritime Academy", 8, Didrikhson str., Odesa, Ukraine
[4]Odessa State University of Internal Affairs, 1, Uspenska str., Odesa, Ukraine
Dnipro University of Technology, 49005 Dnipro, av. Dmytra Yavornytskoho, 19

Received 21 July 2025; accepted 11 November 2025; available online 25 December 2025

Abstract

In this work, a new method of fuel selection for ships is proposed, taking into account indicators of efficiency, environmental friendliness and safety. First, the characteristics of hydrogen and ammonia as potential substitutes for traditional fuels are analyzed in detail with an emphasis on cost, energy efficiency and technical features of their storage and transportation. Next, with the help of statistical models, the risks of emergency situations were assessed, taking into account random factors for the quantitative determination of the probability of failures under different operating conditions. The next step is to formulate the task of optimal choice of route and type of fuel, combining economic costs and safety requirements. A separate section is devoted to the analysis of the full life cycle of fuel, from production to final consumption, which makes it possible to compare the environmental impact of different options. Based on the obtained results, a generalized index was developed that allows shipowners and operators to make informed decisions during the transition to «green» technologies. Examples of real projects illustrate the practical suitability of the approach and its prospects for fleet modernization in the face of global emissions reduction requirements.

Keywords: maritime transport; ship operation; environmental safety; pollution prevention; NO_x emissions; technical systems; power plants; ammonia toxicity; fuel economy; marine environment protection; alternative fuels; energy efficiency; economic efficiency.

КОМПЛЕКСНИЙ БАГАТОКРИТЕРІАЛЬНИЙ АНАЛІЗ ВОДНЮ ТА АМІАКУ ЯК АЛЬТЕРНАТИВНИХ МОРСЬКИХ ПАЛИВ У ПРОЦЕСІ ДЕКАРБОНІЗАЦІЇ МОРСЬКОГО ТРАНСПОРТУ

Олексій М. Мельник[1], Олександр М. Шумило[1], Микола П. Булгаков[1], Сергій В. Вороненко[2], Олег А. Оніщенко[3], Олена М. Коробкова[1], Інна О. Шаповалова[4], Ольга С. Пантелеєва[5]

[1]Одеський національний морський університет, вул. Мечникова, 34, Одеса, 65029, Україна
[2]Херсонська державна морська академія, вул. Ушакова, 20, м. Херсон, Україна
[3]Національний університет «Одеська морська академія», вул. Дідріхсона, 8, м. Одеса, Україна
[4]Одеський державний університет внутрішніх справ, вул. Успенська, 1, м. Одеса, Україна
Національний технічний університет "Дніпровська політехніка", 49005 м. Дніпро, пр. Дмитра Яворницького, 19

Анотація

У данній роботі запропоновано новий метод вибору палива для суден з урахуванням показників ефективності, екологічності та безпеки. Спочатку детально проаналізовано характеристики водню та аміаку як потенційних замінників традиційних видів палива з акцентом на вартості, енергоефективності та технічних особливостях їх зберігання та транспортування. Далі за допомогою статистичних моделей оцінено ризики надзвичайних ситуацій з урахуванням випадкових факторів для кількісного визначення ймовірності відмов за різних умов експлуатації. Наступним кроком є формулювання завдання оптимального вибору маршруту та типу палива, що поєднує економічні витрати та вимоги безпеки. Окрема увага присвячена аналізу повного життєвого циклу палива, від виробництва до кінцевого споживання, що дозволяє порівняти вплив різних варіантів на навколишнє середовище. На основі отриманих результатів розроблено узагальнений індекс, який дозволяє судновласникам і операторам флоту приймати обґрунтовані рішення під час переходу на «зелені» технології. Приклади реальних проектів ілюструють практичну придатність підходу та його перспективи для модернізації флоту в умовах глобальних вимог щодо скорочення викидів.

Ключові слова: морський транспорт; експлуатація суден; екологічна безпека; запобігання забрудненню; викиди NO_x; технічні системи; енергетичні установки, токсичність аміаку; економія палива; захист морського середовища; альтернативні види палива; енергоефективність; економічна ефективність.

**Corresponding author:* m.onmu@ukr.net

 doi: 10.15421/jchemtech.v33i4.335825

Journal of Chemistry and Technologies, 2025, *33*(4), 1216-1231

Introduction

Climate change and the tightening of international environmental standards are creating new requirements for the shipping industry, which is currently one of the most significant sources of greenhouse gas emissions. In 2023, the International Maritime Organization (IMO) adopted a strategy that envisages the complete decarbonization of maritime transport by 2050 (International Maritime Organization, 2023). This requires a radical transformation of the fleet's energy systems and a transition to alternative, carbon-free fuels. Among the most discussed solutions are the use of hydrogen (H_2) and ammonia (NH_3), which do not produce CO_2 during combustion and have a high potential for sustainable development. At the same time, the practical implementation of these energy sources is associated with numerous challenges, both technical and economic.

Low-carbon ammonia is considered a promising marine fuel due to the absence of CO_2 emissions during combustion. In [1], laboratory tests of ammonia diesel engines were conducted and confirmed the possibility of achieving a 25% reduction in CO_2 emissions without significant power loss. Schreuder et al. [2] performed a feasibility study, showing that the capital costs of installing ammonia fuel systems can be recouped in 7–8 years at current ammonia prices. A review by Machaj et al. [3] systematized transportation, storage, and safety issues, suggesting ways to reduce the corrosive effects of ammonia on equipment.

Scientific papers [4; 5] explored the prospects for low-carbon liquid and gaseous fuels; ammonia and synthetic hydrocarbons and biofuels with a hydrogen component and papers [6; 7] detailed technical standards and regulations for hydrogen vessels, emphasizing gas storage pressure and temperature. At the same time, [15] looked at alternative fuels in the context of the UN Sustainable Development Goals, showing that a combination of bioenergy and CCUS could reduce total ship emissions by up to 50%. The authors in [12] formed an economic model of «green» shipping corridors, where the key factor is the balance between capital investment and operating costs. [18] provided a comparative LCA of different hydrogen supply methods between Australia and South Korea, finding that formulations using renewable sources have 20 % lower life cycle emissions than imports of hydrogen from hydrocarbon sources. In [11], the first commercial hydrogen passenger ferry, MV Sea Change, is described, where integrated fuel management and fuel cooling system are applied.

Further noteworthy are the following key publications: [8] undertakes a review of hydrogen compression and storage technologies for marine fuel cells; [9] analyses a variety of alternative fuels in the context of the United Nations Sustainable Development Goals; [10] introduces the notion of «green» hydrogen and ammonia and describes their capabilities and limitations; [13] outlines ways to introduce low-carbon fuels by 2050; [16] discloses approaches to energy management in maritime transport; [17] assesses the prospects for biofuels and their integration into ship systems; [18] conducts a life cycle-assessment of hydrogen supply methods between Australia and South Korea; [19] reviews low - and zero-carbon fuel technologies for ship decarbonisation; [20] analyses the development of hydrogen vessels over the past two decades.

The authors in [14] summarized the production technologies of «green» hydrogen and ammonia and described their combination with CCUS. Sources [21; 22] demonstrate configuration studies of hybrid power subsystems on different types of vessels, including a combination of fuel cells, turbines and battery packs. The authors' works [23–25] are based on experimental data and simulations that demonstrate the potential of integrating wind, solar, and CCUS to achieve up to 30 % fuel economy and a 40 % reduction in CO_2 emissions under real operating conditions.

Modern research on green fuels and decarbonization of maritime transport can be divided into two groups. The first group focuses on the production and use of alternative energy carriers: the economic efficiency of electric fuels is analyzed in [32], while [33] considers the use of ammonia in a large-scale energy cycle. At the same time, chemical processes for the purification of oil fractions are being advanced by AADES solvents [34].

The second area covers the practical implementation and maintenance of systems on board ships: energy efficiency and emissions reduction are described in detail in [35; 36], and the role of biodiesel and green fuel blends in engines is studied in [37; 39]. This is complemented by port renewable solutions [38] and digital strategies for operation and maintenance management [40]. Papers [41] and [44] analyze the introduction of low-sulfur fuels and hydrogen as promising areas for decarbonizing the industry. The paper [42] assesses the efficiency of ship refrigeration systems and the potential for reducing energy consumption. Article [43] proposes a methodology for radar recognition of autonomous surface vessels in difficult conditions, which is important for the safety of maritime navigation. Studies [45] and [47] consider strategic approaches to maintaining the integrity of the ship's hull and improving lubricant cleaning systems. Works [46, 48, 49] analyzed the introduction of alternative technologies and measures to improve environmental safety and energy efficiency of ships.

Recent studies have developed system-based assessments of ship energy efficiency and environmental management, providing a methodological basis for multicriteria fuel evaluation [49–53]. These works highlight emission-reduction pathways and diagnostic methods essential for assessing hydrogen and ammonia transition scenarios in maritime transport decarbonization confirming the importance of an integrated approach to the innovative modernization of maritime transport.

While a wide assortment of analytical materials is available, the studied literature only examines some aspects, such as environmental impacts, economic costs, or various technical challenges. There is hardly any systematic assessment that considers all the relevant factors, from thermodynamic performance and storage parameters to crew safety and capital costs, in the present scientific discourse. Truly interdisciplinary scientific work that considers the regulatory mechanism, risk of regulatory uncertainty, and feasible risk scenarios as a whole in the practical realization of hydrogen and ammonia on board vessels is lacking. Bearing that in mind, this work therefore attempts to undertake a further comprehensive comparison of hydrogen and ammonia for next-generation marine fuels within the setting of the 2050 IMO climate goal, considering their thermodynamic properties, storage parameters, environmental risks, infrastructure readiness, economic efficiency, and technical safety.

The purpose of this study is to develop a comprehensive approach to the selection of alternative fuels for maritime transport, in particular hydrogen and ammonia, based on a combined analysis of thermodynamic, environmental, economic, infrastructure, and operational safety factors.

The scientific novelty of the work lies in the combination of several assessment methodologies, in particular, the analysis of hierarchies (AHP) method for technical and economic analysis, stochastic risk modeling based on the Ornstein-Uhlenbeck equation for reliability assessment, and life cycle analysis (LCA) for environmental impact. A distinctive feature of the proposed approach is its comprehensive consideration of all key aspects, from energy performance to infrastructure readiness and safety assessment, within a single decision support system.

To achieve this goal, the paper addresses the following tasks: developing a multi-criteria model that integrates economic, energy, environmental, and safety indicators to compare hydrogen and ammonia as alternative marine fuels, and modeling the dynamics of risks during real shipping operations. And to perform a comprehensive ranking and optimization of the choice of fuel type, taking into account economic feasibility, environmental safety, and the acceptable level of operational risks.

Materials and methods

In this study, the objects of comparative analysis are hydrogen (H_2) and ammonia (NH_3) as promising alternative marine fuels. The study was based on open technical and economic data from scientific publications (Scopus, Elsevier, MDPI), reports of international organizations (IEA, DNV, IRENA, IMO), as well as the results of pilot projects implemented in Norway, Japan, and the EU in 2020-2024:

1. IEA (International Energy Agency): analyzed the World Energy Outlook 2024 (October 2024), which contains a forecast of global energy consumption until 2050, including sections on international shipping and aviation [26];
2. DNV (Det Norske Veritas): the global Energy Transition Outlook 2025, which covers the period up to 2050 and forecasts the evolution of energy systems in all regions and sectors, including maritime transport, was considered [27];
3. IRENA (International Renewable Energy Agency): World Energy Transitions Outlook 2024: 1.5 °C pathway (November 2024), which analyzes the ways to achieve the 1.5 °C climate goal, as well as Renewable Energy Statistics 2024 (July 2024), which contains key data on the development of renewable energy in transport [28; 29];
4. IMO (International Maritime Organization): the 2023 IMO Strategy on Reduction of GHG Emissions from Ships (adopted July 2023), which sets the framework and targets for reducing emissions by 2050, as well as the Fourth IMO GHG Study 2020, which estimates maritime transport

Journal of Chemistry and Technologies, 2025, *33*(4), 1216-1231

emissions for 2018 and projections to 2050, were taken into account [30; 31].

Table 1 defines key economic and energy indicators commonly used in the assessment of energy systems. These parameters enable a comprehensive comparison of technologies in terms of both financial and energetic performance.

Table 1

Main economic and energy performance indicators

Indicator	Definition	Description
LCOE	Levelized Cost of Energy	Average cost per unit of electricity over a system's lifetime, including all costs.
EROI	Energy Return on Investment	Ratio of energy produced to energy used in production — higher is better.
CAPEX	Capital Expenditure	Upfront investment cost for building infrastructure or equipment.
OPEX	Operational Expenditure	Ongoing cost for operating and maintaining the system.

The use of these indicators facilitates the evaluation of both the economic efficiency and the sustainability of different energy technologies, supporting informed decision-making in energy planning and investment.

The study was conducted using analytical, comparative, and quantitative methods. First, scientific sources were systematized for the period 2019-2024, and then the main comparative parameters relevant to the maritime industry were identified:

- thermodynamic characteristics (lower calorific value, mass and volumetric energy content)

- storage conditions (temperature, pressure, shape);

- level of toxicity and risks (explosiveness, health effects, leakage scenarios);

- infrastructure readiness (technology maturity, availability of terminals);

- economic efficiency (LCOE, EROI, CAPEX, OPEX);

- environmental impacts (CO_2, NO_x, secondary impacts on ecosystems).

The comparison of alternative fuels in maritime transport was carried out according to six groups of criteria: thermodynamic characteristics (lower calorific value, mass and volumetric energy content), storage conditions (temperature, pressure, physical form), toxicity and risk level (explosiveness, health impact leakage scenarios), infrastructure readiness (technology maturity, availability of terminals and logistics chains), economic efficiency (LCOE, EROI, CAPEX, OPEX) and environmental impacts (CO_2, NO_x emissions, secondary impacts on ecosystems). According to each parameter, data was normalised and weighted by experts to obtain an essentially objective ranking of the fuel concerning its suitability for use in the ship's energy system.

Initially, an analytical hierarchy process (AHP) was applied to the economic evaluation of the levelized cost of electricity (LCOE). Four key criteria were identified - capital investment, fuel cost, operating cost and environmental cost - and their estimates were collected from ten leading experts in marine engineering and logistics. Based on this data, a vector of criteria weights was formed using the Saaty procedure (Saaty, 1980), which allowed us to rank hydrogen, ammonia, and traditional marine diesel by their LCOE, taking into account both economic and environmental indicators.

This multi-criteria evaluation of the technologies enabled us to bring out very clearly the strengths and weaknesses (e.g. high energy intensity for ammonia and difficult storage conditions, or inherently safe use of hydrogen but high compression investment) of each technology and combine these aspects into one integrated rating for strategic purposes. Thus, this led to recommendations for investors and regulators regarding priority infrastructure and safety standards, as well as a robust methodology for prioritizing the selection of alternative fuels for specific routes and vessel types in the decarbonization process.

To comprehensively assess the environmental and economic feasibility of alternative marine fuels, six key indicators were used in the study:

- LCOE (Levelized Cost of Energy) - allows comparing the total cost of 1 MWh of final energy, taking into account capital (CAPEX) and operating (OPEX) costs throughout the entire life cycle of the system;
- EROI (Energy Return on Investment) - the ratio of the total energy reproduced by the system to the energy spent on its creation and maintenance, which shows the "energy payback" of the technology;
- CAPEX – capital expenditures for the construction and installation of equipment, which determine the initial investment barriers;
- OPEX – operating costs for maintenance, fuel, and logistics, which affect the overall profitability in the long term;

Journal of Chemistry and Technologies, 2025, 33(4), 1216-1231

➢ CO_2-equivalent emissions – an estimate of direct greenhouse gas emissions adjusted for the life cycle of the fuel to compare the impact on global warming;

➢ NO_x, SO_x, $PM_{10}/_{2.5}$ – local pollutants that determine the environmental and social acceptability of a decision.

The use of this set of indicators provides a balanced assessment: economic (LCOE, CAPEX, OPEX), energy (EROI) and environmental (greenhouse gas emissions) components necessary for making an informed decision on the introduction of new technologies in ship energy.

Thus, LCOE (Levelized Cost of Energy) is the average cost per unit of energy over the life cycle, which was 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 - capital expenditures in year t, M_t - maintenance costs, F_t – fuel expenses, E_t - energy produced, r – discount rate, N – service life (we accept 20 years). Source data taken from DNV reports (2024).

The calculation is performed using the initial technical and economic parameters of the system (capital and operating costs, energy production, discount rate) in accordance with generally accepted methodologies in the field of energy analysis [link]. The parameters are taken from open data of technical documentation of projects or analytical reports of DNV, IEA, IRENA organizations.

EROI (Energy Return on Investment) - the ratio of energy produced by the system to the energy spent on its creation and maintenance:

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

where *Output Energy* – useful energy, *Input Energy* – total energy for production, storage and delivery. EROI values for H_2 and NH_3 were also taken from open sources.

The EROI value is determined based on the known technical characteristics of the system and data on energy costs for fuel production and logistics, according to the methods.

The study began with a review and systematization of sources (2019-2024) - IMO, IEA, DNV, IRENA reports, and key publications on hydrogen and ammonia - based on which six groups of comparative criteria were identified (thermodynamics, storage, safety, infrastructure, economics, and environment). Next, the technical, physical, and chemical characteristics of H_2 and NH_3 were collected, comparative tables were built, storage conditions and logistical readiness were assessed, and LCOE and EROI were calculated using data from Lazard, Trafikverket, and DNV. The normalized indicators were subjected to expert weighting (AHP), an integrated rating of alternative fuels was obtained, which was verified by comparing them with pilot projects (MV Sea Change, ammonia-diesel tests), and recommendations were made on the basis of this rating on priorities for infrastructure deployment and safety standards in maritime transport. The methods described above allowed us to obtain a generalized assessment of the effectiveness of hydrogen and ammonia in the context of decarbonizing shipping, taking into account both technological and practical aspects of their implementation.

In today's maritime transportation environment, ships face a number of interrelated challenges: rising fuel costs, the need to comply with strict environmental regulations, and maintaining a high level of operational safety. The development of a formalized and reproducible mathematical model that combines multi-criteria analysis of economic indicators (LCOE, logistics costs), stochastic accident risk assessment, and life cycle analysis (LCA) will allow:

- make informed decisions on the choice of the optimal fuel for each route segment, taking into account the simultaneous minimum of costs and risks;
- systematically evaluate the impact of technological and natural factors on shipping safety by modeling the evolution of risk using stochastic processes and Monte Carlo simulations;
- take into account environmental requirements and reduce greenhouse gas emissions using an integrated I-index that combines economic, environmental, and risk components;
- increase the reproducibility and transparency of the study, as all stages of the methodology - from normalization of criteria to optimization of route costs - are covered.

Thus, the proposed model serves as a tool for comprehensive analysis and strategic decision-making in the fuel supply of maritime transportation, taking into account economic efficiency, environmental safety, and operational risks.

Suppose we have n alternative fuels and m evaluation criteria (e.g., cost of electricity LCOE, energy return EROI, etc.). All evaluations are organized into a matrix A of size $n \times m$, where the element a_{ij} is the value of j of the j-th criterion for the i-th fuel.

Each criterion is assigned a weight w_j (j = 1,...,m), where

$$\sum_{j=1}^{m} w_j = 1 \quad (3)$$

where: w_j - weighting factor for the j-th criterion; m - number of criteria.

Weight vectors are determined by the AHP method based on expert surveys.

Before combining the indicators into a single rating, we normalize them depending on the direction of the criterion if "the more the merrier":

$$\frac{a_{ij} - \min_k a_{kj}}{\max_k a_{kj} - \min_k a_{kj}}, \quad (4)$$

where: a_{ij} – value of the jth criterion for the i-th fuel type; $\max(a_j)$ – maximum value of this criterion among all alternatives.

If "the smaller the better":

$$\frac{\max_k a_{kj} - a_{ij}}{\max_k a_{kj} - \min_k a_{kj}}, \quad (5)$$

where: $\min(a_j)$ – minimum value of the criterion among all alternatives.

The integral rating of each alternative i is calculated as a weighted sum:

$$R_i = \sum_{j=1}^{m} w_j \tilde{x}_{ij}, \quad (6)$$

where: R_i - integral rating of the ith alternative (fuel type).

To check the stability of the model, we perform a sensitivity analysis: each weight w_j is varied by ±10 % and a new rating R_i' is calculated. If the order of the alternatives remains almost unchanged, the model is considered robust to the subjectivity of expert judgment.

The stochastic Ornstein-Uhlenbeck process is used to model the risk of transportation delays. The value of the supply chain reaction speed X_t is given by the differential equation where X_t is a stochastic process representing the deviation of delay time from the long-term mean.

$$dX_t = \alpha(\mu - X_t)dt + \sigma dW_t, \quad (7)$$

where μ – long-term average value of the delay time (determined from historical AIS data for 2018–2023), α – rate of return to μ (estimated by the maximum likelihood method), σ – intensity of random fluctuations (calculated through the variance of real delays), W_t – standard Wiener process (Brownian motion).

Such a model allows to take into account both the trend component of delays (vessel inflow/outflow) and random fluctuations that directly generate additional costs and affect the optimization objective function.

The stochastic Ornstein-Uhlenbeck differential equation describes the risk for each fuel type:

$$dR(t) = \alpha \cdot (\beta - R(t))dt + \sigma dW_t, \quad (8)$$

where $dR(t)$ – the risk level at time t; α, β – deterministic parameters of risk growth (based on the data of emergency histograms); σ – intensity of random fluctuations.

The probability of exceeding the critical threshold risk level in the range [0; T], estimated by the Monte Carlo method:

$$P(R(t) > R_{\text{crit}}) = \frac{1}{N}\sum_{k=1}^{N} I\,(R_k(t) > R_{\text{crit}}), \quad (9)$$

where: $R_k(t)$ – risk value at k-th trajectory, R_{crit} – critical value of the risk, N – number of simulations, $I(\cdot)$ - indicator function (1 if the condition is met; 0 if not).

Using the Monte Carlo method, we simulate N trajectories $R_k(t)$, k = 1,...,N, and calculate the probability of exceeding the critical threshold R_{crit} in the interval [0, T] as

$$P\left(\max_{t\in[0,T]} R(t) > R_{\text{crit}}\right) \approx \frac{1}{N}\sum_{k=1}^{N} \mathbf{1}\left(\max_t R_k(t) > R_{\text{crit}}\right). \quad (10)$$

The task of minimizing the total cost, taking into account the risk, for the optimal choice of fuel on each route segment is formulated as follows:

$$min \sum_{l=1}^{L}\left(C_{it}^{\text{LCOE}} + C_{it}^{\text{log}}\right) \quad \text{provided that} \quad R_{il} \le R_{max}, \quad (11)$$

Let's assume that the route is divided into L segments. For each segment ℓ we choose the type of fuel i_ℓ. Problem statement:

$$\min_{\{i\}} C_{\text{total}} = \sum_{\ell=1}^{L}\left(C_{it}^{LCOE} + C_{it}^{log}\right), \quad \text{subject to } R_{i\ell}(t_\ell) \le R_{\max} \quad \forall \ell, \quad (12)$$

where C_i^{LCOE} – cost of energy for fuel i, C_i^{log} – logistics costs (compression, cooling), $R_{\max}$ – acceptable level of risk, L – number of route segments.

The problem is solved by integer linear programming (MILP) or metaheuristics (genetic algorithms, tabu search, etc.). The result is an optimal set of fuels for each route segment and a cost-risk curve.

Journal of Chemistry and Technologies, 2025, *33*(4), 1216-1231

Total greenhouse gas emissions at all stages of production and transportation are calculated as

$$\mathrm{GHG_{LCA}} = \sum_{k=1}^{K} E_k\, \theta_k, \qquad (13)$$

where E_k – energy consumption for k stage (production, transportation, storage), θ_k – CO_2-equivalent emission factor at the stage k.

An integral index is introduced for a combined assessment of economic, environmental and risk-based indicators:

$$I = \alpha_1 \cdot C_{\text{total}} + \alpha_2 \cdot CO_2^{\text{total}} + \alpha_3 \cdot R, \qquad (14)$$

where: C_{total} - total costs (LCOE + logistics); CO_2 total – total emissions; R – integral risk level; α_1, α_2, α_3 – weighting factors.

For a comprehensive assessment of economic, environmental and risk aspects, we introduce an index

$$I_i = \alpha_1 \frac{C_i^{\text{LCOE}}}{\max_i C_i^{\text{LCOE}}} + \alpha_2 \frac{\mathrm{GHG}_{\mathrm{LCA},i}}{\max_i \mathrm{GHG}_{\mathrm{LCA},i}} + \alpha_3 \frac{R_i}{\max_i R_i}, \quad \alpha_1 + \alpha_2 + \alpha_3 = 1, \qquad (15)$$

where α_1, α_2, α_3 – are weighting factors for the economic, environmental and risk components, respectively. All indicators were normalized relative to the base values of traditional marine diesel fuel (reference case).

Summarizing the above, we note that the proposed model combines several interrelated methods, which allows us to obtain a deep and comprehensive understanding of the process of selecting fuel for maritime transportation. First, a multi-criteria analysis provides a balanced comparison of alternative fuels, taking into account economic indicators (LCOE), energy return on investment (EROI) and other important criteria. Furthermore, stochastic risk modeling allows us to study the dynamics of emergency situations using the Ornstein-Uhlenbeck equations and Monte Carlo simulations, which increases the accuracy of forecasts and allows us to take into account unforeseen events.

Optimization of the route and fuel selection, implemented through integer linear programming or meta-heuristics, strikes a balance between minimizing fuel and logistics costs and limiting the acceptable level of risk on each route segment. At the same time, a fuel life cycle assessment (LCA) allows for a quantitative comparison of greenhouse gas emissions arising from the production, transportation, and storage stages of fuel. The integral environmental and economic index combines economic, environmental and risk indicators into one generalized value, which helps to make balanced and strategically sound decisions.

The practical application of this methodology allows shipowners to choose the best fuel options that provide both economic benefits and reduce environmental impact and maintain a high level of operational safety.

Results and discussion

According to the International Maritime Organization (IMO), both hydrogen and ammonia fuels have been accepted as candidates for marine fuels that can substitute conventional fuels, since the strategy aims for total zero GHG emissions by 2050. The selection between these options is mainly related to their physical state and chemical characteristics, as well as safety and environmental considerations. Only an objective comparison of these gases will enable their potential use in maritime transport to be realized. A comparison of some of the main physical and chemical parameters that are of fundamental importance from the standpoint of energy, safety, and operation on board ship is presented in Table 2. Based on this data, the assessment of parameters of interest to the recent carbon-free fuel industry will be discussed.

Table 2

Comparative table of hydrogen and ammonia characteristics

Criterion	Hydrogen	Ammonia
Chemical formula	H_2	NH_3
Molar mass (g/mol)	2.016	17.031
Aggregate state at 20 °C	Gas	Gas
Boiling point (°C)	–252.9	–33,3
Flash point (°C)	~560	~651
Explosive limits (vol. %)	4–75	15–28
Density in liquid state (kg/m^3)	~70,8	~681
Mass energy content (MJ/kg)	120	18.6
Volumetric energy content (MJ/l)	8.5	11.5
Odor	Low	High
Flame visibility during combustion	Invisible	Weakly yellow, visible

Journal of Chemistry and Technologies, 2025, *33*(4), 1216-1231

Continuation of Table 2

CO_2 emissions during combustion	Absent	Absent
NO_x emissions during combustion	Possible	High
State of the infrastructure	Limited	Partially visible
Production cost (approximate)	High	Medium

Both energy carriers can be produced using renewable energy sources, which is critical to achieving full carbon neutrality. Green hydrogen is produced by electrolysis of water, in which electrical energy from renewable sources (sun, wind, hydroelectric power plants) decomposes H_2O molecules into molecular hydrogen and oxygen. The most common method is PEM electrolysis (Proton Exchange Membrane), which is characterized by high current density, fast start-up and the ability to work with unstable energy flows, but requires an expensive platinum catalyst system and fine water treatment. The efficiency of modern PEM electrolyzers reaches 60–70 %, and the main losses are associated with overvoltages on the electrodes and membrane resistance. Only after hydrogen has been purified to ≥ 99.9 % can it be supplied to fuel cells or compressed to 350–700 bar for storage and transportation, which adds about 10–15 % to the final energy consumption.

Green ammonia is synthesized by the Haber-Bosch process from green hydrogen and nitrogen separated from the air through PSA adsorption pumps. The synthesis itself takes place under high pressure (150–300 bar) and temperature (400–500 °C) using an iron catalyst, so about 25–30 % of the hydrogen produced is consumed in the form of thermal and mechanical energy. However, the resulting ammonia at standard pressure and temperature can be easily liquefied (–33 °C) and stored in standard low-pressure tanks, which minimizes energy consumption for compression compared to hydrogen. The overall efficiency of the electric power → hydrogen → ammonia chain is about 50–55 %, but the lack of high-pressure storage makes this scheme more suitable for marine logistics [32; 33] – basic reaction: $2H_2O \rightarrow 2H_2 + O_2$. Green ammonia is synthesized through the Haber-Bosch reaction, where hydrogen comes from a "green" source and nitrogen from the air.

Figure 1 presents a flow chart of green ammonia production using water, air, and renewable energy as feedstocks. The process includes electrolysis of water to generate hydrogen, separation of air to produce nitrogen, and the synthesis of NH_3 in an appropriate reactor. It also covers product recovery, buffering, and cooling. The scheme accounts for recycling flows and the utilization of excess gas.

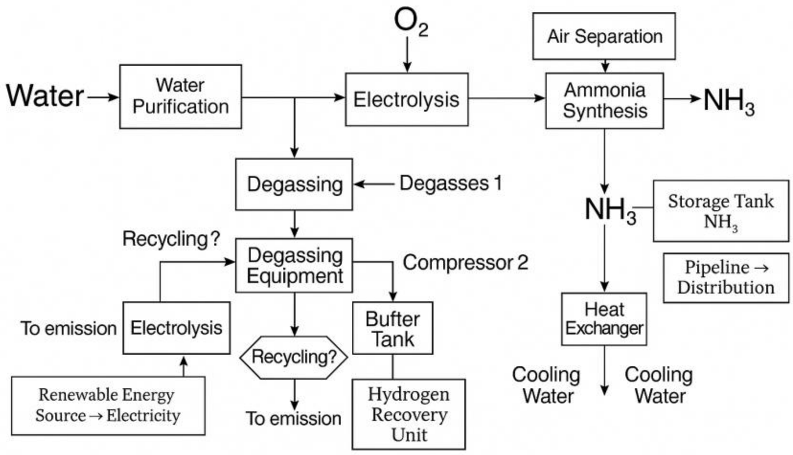


Fig. 1. Flowchart of green ammonia (NH_3) production: water purification - electrolysis - degassing - buffering - synthesis of ammonia from N_2 (via air separation), followed by cooling and storage of the product

Choosing between hydrogen and ammonia for future maritime transport fuels will depend largely on their physical and chemical properties, environmental safety, production costs, and existing infrastructure needs. From an energy density and mass viewpoint, hydrogen has a clear advantage, but its use faces technical difficulties due to low bulk density and extremely low storage temperature. Ammonia in contrast, is more integrated with the existing infrastructure and thus easier to get stored; however, it poses serious environmental and safety concerns owing to its high toxicity and NO_X emissions.

Thermodynamic properties

In mass terms, hydrogen lower heating value (LHV ~ 120 MJ/kg) is almost 6 times the energy density of ammonia (LHV ~ 20 MJ/kg), but due to the low density of liquid hydrogen (~71 kg/m^3), its volumetric energy density (~ 8.5 MJ/l) is much lower than that of ammonia (~ 11.5 MJ/l at 681 kg/m^3). This trade-off between the high mass energy content of hydrogen and the smaller volume of ammonia determines the choice of fuel depending on the available space on board and the need to ensure sufficient energy for long voyages.

Hydrogen is a highly explosive gas with a narrow range of mixtures with air (4–75 % by volume) and a low flash point (~560 °C), which increases the risk of spontaneous combustion in case of accidental leaks. Ammonia is less explosive, but toxic at concentrations above 300 ppm, can cause corrosion of equipment and harm health on contact; at the same time, in the event of a leak, its odor leads to early evacuation.

For hydrogen, high-pressure (350–700 bar) or deep-cooled (–253 °C) storage facilities are required, which require special cylinders and compensation for leaks due to diffusion. Ammonia can be stored in a liquefied state at –33 °C at relatively low pressure (~10 bar), which significantly simplifies its integration into existing terminals and fuel corridors. The ammonia infrastructure is currently partially available in key ports, while hydrogen requires substantial investments in new compressor modules and refrigeration units.

Assessment of thermodynamic properties is key to determining the efficiency of fuels in marine power. The most critical parameters are the mass and volumetric heat of combustion (LHV), which determine the amount of energy that can be obtained in real operating conditions. Hydrogen has an exceptionally high mass energy content, which is almost 6.5 times higher than that of ammonia. However, due to its low density in the liquid state (about 71 kg/m^3 versus 681 kg/m^3 for NH_3), its volumetric energy content is only 8.5 MJ/l, while for ammonia it reaches 11.5 MJ/l. This means that in conditions of limited space on board a ship, ammonia provides more energy per unit volume, which is a critical factor in practical applications. In addition, ammonia has a higher flash point (651 °C versus ~560 °C for hydrogen), which reduces the risk of spontaneous combustion in emergency conditions.

Safety, toxicity, and operational risks

The use of alternative fuels in maritime transport is not possible without a comprehensive consideration of issues related to technological safety. Although hydrogen and ammonia are seen as a promising way to decarbonize the fleet due to their carbon-free nature, their implementation is accompanied by significant risks that affect the ship's architecture, storage systems, maintenance organization, and even the crew training structure.

In the case of hydrogen, the most critical aspect is its high flammability, wide range of explosive concentrations in the air, and tendency to produce invisible flames in case of fire. In view of this, even minor leaks can have catastrophic consequences if effective detection, ventilation, and shut-off systems are not implemented. On the technical side, the need for storage at ultra-low temperatures, which requires cryogenic tanks with sophisticated insulation, also complicates the situation.

Ammonia, unlike hydrogen, is not explosive in the classical sense, but its vapors irritate mucous membranes, can cause chemical burns, and pose a danger to personnel, especially in cases of leaks in closed or poorly ventilated spaces. In addition, ammonia is corrosive to some metals, requiring special selection of materials for pipelines, fittings, and storage systems.

Thus, while both fuel options have potential in terms of emissions reduction, their safe integration into ship systems requires careful engineering design, regulatory adaptation, and specialized crew training.

Table 3 shows a comparison of the key risks of hydrogen and ammonia in ship operations, from the difference in toxicity and explosiveness to the specifics of ignition energy, incident scenarios, and the readiness of detection systems and regulatory support; hydrogen wins in terms of non-toxicity, but requires minimal ignition energy and fast sensor response due to its wide flammability range, while ammonia, although easier to store in liquefied form, requires attention to toxic leaks, crew personal protection and application of IMO interim recommendations (IEC 60079 and MSC.1/Circ.1687).

The storage of hydrogen and ammonia in maritime shipping is determined not only by their energy density but also by the technological requirements for tanks and maintenance systems. Hydrogen requires either high-pressure tanks (350-700 bar) made of composite materials to minimize leakage or cryogenic storage at -253 °C, which necessitates sophisticated insulation and constant monitoring to achieve ultra-low evaporation losses.

Journal of Chemistry and Technologies, 2025, *33*(4), 1216-1231

Table 3

Risks and safety measures

Parameter	Hydrogen (H_2)	Ammonia (NH_3)
Toxicity	Low. Non-toxic, but displaces oxygen in the air	High. Toxic by inhalation, irritating to skin and eyes
Flammability	High (4–75 % in air), invisible flame	Moderate (15–28 % in air), visible on combustion
Ignition energy	Very low (0.02 mJ)	High (~0.3 mJ), spontaneous combustion at ~651 °C
Risk scenarios	Leakage → explosion without warning	Leakage → toxic air contamination
Detection systems	H_2 detectors, ventilation control	NH_3 sensors (25/110/220 ppm), exhaust hood, emergency shutdown
Regulatory framework (IMO)	Under development	Interim principles (MSC.1/Circ.1687)
Crew training needs	High (for explosion response)	Very high (handling of toxic substances)

Instead, ammonia can be stored in a liquefied state at a relatively moderate pressure (~10 bar) and temperature of –33 °C in conventional steel tanks with a corrosion-resistant coating, which significantly reduces capital and operating costs for infrastructure. This difference in storage modes determines the choice of fuel system depending on the availability of technical means, space limitations on board, and economic criteria for implementation (Table 4).

Table 4

Comparative analysis of hydrogen and ammonia storage parameters

Parameter	Hydrogen (H_2)	Ammonia (NH_3)
Form of storage	Liquid (cryogenic) / Compressed gas	Liquid / Pressurized
Storage temperature (°C)	–253	–33
Gas storage pressure (bar)	~350–700	~10–20
Volume per 1 MJ of energy	High (low density)	Lower (higher density)
Volatility	Very high	High
Leakage potential	Significant	Moderate
Requirements for tanks	Double-walled, with vacuum insulation	Similar to LPG infrastructure

The table shows that storing liquid hydrogen is technically challenging, as a temperature of –253 °C is required, which is close to absolute zero. Such conditions require high-tech tanks with multi-level insulation. Compressed hydrogen is an alternative, but it requires pressures of up to 700 bar, which also makes it difficult to use safely. Whereas ammonia is stored under moderate conditions, making it suitable for existing LPG terminals and simplifying adaptation on ships.

Infrastructure requirements and economic aspects

One of the key factors for the introduction of alternative marine fuels is the availability and scalability of infrastructure. In this context, ammonia has a significant advantage over hydrogen: there is already a global network for its production, storage, and transportation. More than 180 million tons of NH_3 are produced globally each year, and supply chains cover most major ports, especially in Asia, Europe, and the Middle East. However, the infrastructure for hydrogen, especially liquid or compressed hydrogen, is still in its infancy. It requires high-tech terminals, cryogenic storage facilities, and high-pressure pipelines, which significantly increases the cost and time of implementation (Table 5).

Table 5

Comparative table: infrastructure requirements

Aspect	Hydrogen (H_2)	Ammonia (NH_3)
Production maturity level	Under development (green H_2 through electrolysis)	Installed (green NH_3 at the test stage)
Storage infrastructure	Cryogenic tanks / high pressure tanks	Existing LPG-like tanks
Transportation logistics	Limited: pipelines + vehicles (pilot scale)	Global network: by sea, rail and pipeline
Port readiness (2025)	Several demonstration projects	More than 120 terminals with NH_3 compatibility
Compatibility with existing systems	Low (new designs required)	Medium-high (can be adapted to LPG systems)
Capital expenditures for scaling	Very high	Medium-high

Ammonia is more suitable for rapid adaptation in ports and on ships, as it can use part of the existing LPG infrastructure. At the same time, "green" ammonia, like "green" hydrogen, requires

Journal of Chemistry and Technologies, 2025, *33*(4), 1216-1231

massive electrolysis based on cheap renewable energy. This creates competition for resources and requires coordination with the energy policies of countries and the EU. The diagram (Figure 2) provides a comparative overview of the most important characteristics of hydrogen and ammonia as alternative energy carriers for shipping.

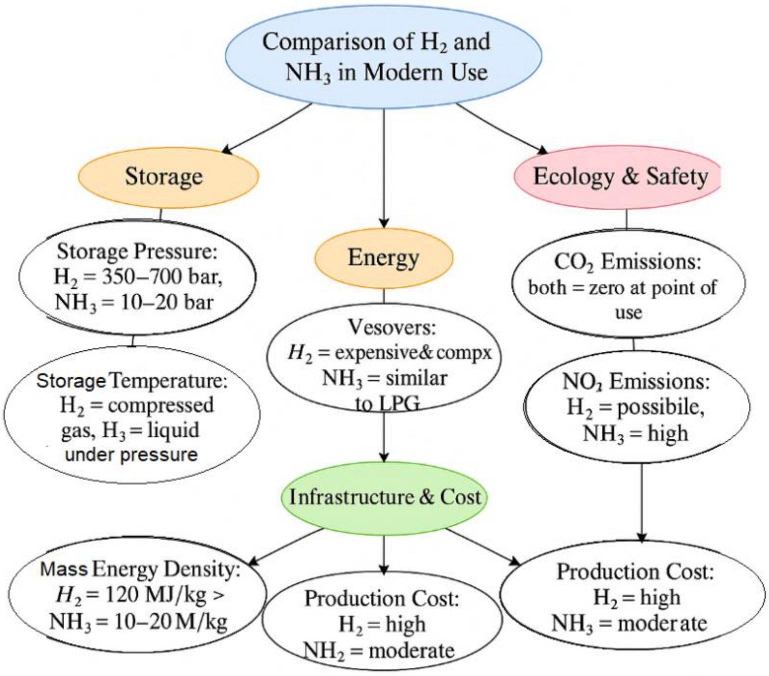


Fig. 2. The structure of hydrogen (H_2) and ammonia (NH_3) use as energy carriers in shipping

As a result, when using hydrogen, the main challenge is explosion control, which requires careful monitoring of tightness, ventilation, and leak detectors. In the case of ammonia, biomedical risks come to the fore: even small leaks can be life-threatening for the crew. Both options require a high level of personnel training and modernization of safety systems on board.

Experimental and commercial projects

In line with global objectives for decarbonizing shipping by 2050, several companies and international bodies have initiated projects to introduce alternative fuels, such as hydrogen and ammonia (Table 6).

Table 6

Key implemented ammonia fuel projects

Project / Initiative	Participants & Country	Fuel Type	Route / Tests	Terminals / Infrastructure	Expected Effectiveness	Emergency Incidents
Fortescue Green Pioneer	Fortescue (Australia); MPA, Seatrium, Vopak, A*STAR's IHPC, NTU, DNV (Singapore)	Liquid ammonia (NH_3)	Trials in Singapore; voyage to the Persian Gulf during COP28	Vopak terminals; HAZID/HAZOP system; drones, land-based control	Significant CO_2 reduction anticipated; "Gas Fueled Ammonia" certification	None recorded
Dutch Ammonia Tanker	C-Job Naval Architects, Proton Ventures, Enviu; Province of Zuid-Holland (Netherlands)	Ammonia (NH_3)	Laboratory models & preliminary trials; sea trials pending	Integration with LPG infrastructure at Dutch ports	~44 % higher energy efficiency compared to hydrogen	None recorded
CAMPFIRE "Ammonia Sherpa"	ENERTRAG, sunfire, KIT, University of Rostock, ZBT (Germany)	Ammonia (NH_3)	Yacht "Ammonia Sherpa" tests (2023); barge "Odin" planned for 2026	Bunkering system installed at Rostock port	~350 kW power generation; targeted at small vessels	None recorded

These initiatives range from demonstration vessels to green corridors for carbon-free transportation. Present emphasis is still placed on the infrastructure for clean fuels in main ports, on safety standards for handling ammonia, and on storing and power-testing solutions for next-generation marine power plants. In addition, intergovernmental partnerships are being

Journal of Chemistry and Technologies, 2025, *33*(4), 1216-1231

actively formed to fund life-cycle studies of such fuels, as well as subsidy mechanisms for operators to switch to environmentally neutral technologies.

As part of the global strategy to decarbonize maritime transport by 2050, a number of important demonstration and commercial projects are being implemented to use green fuels. Firstly, MV Sea Change (Norway-UK) is the world's first commercial hydrogen fuel cell ferry designed by Mitsubishi FCH Energy and certified by DNV, currently operating between the ferry terminals of Stavanger and London; its efficiency was 65% (energy penetration into the fuel cell), infrastructure – 350 bar onshore fueling stations, and no accidents. Secondly, Yara Birkeland (Norway) is an autonomous carbon-free fertilizer ship developed by Kongsberg and Yara International, which is being tested in the Oslo fjords, and has demonstrated an 80% reduction in CO_2 emissions compared to diesel counterparts; ammonia refueling is organized in the ports of Oslo and Narvik, and no leaks or accidents have been reported so far. The third is the HySTRA project (Japan), a consortium of JERA, Kawasaki Heavy Industries, and UBE, which has been testing an ammonia and hydrogen fuel ship on the Yokohama-Tokyo route since 2023; preliminary data indicate a stable efficiency of 50 % and the need to modernize terminal gasifiers. In addition, the Green Corridor initiative (Singapore-Rotterdam), supported by the Global Maritime Forum and ABS, envisages the construction of port infrastructure for ammonia and hydrogen from 2025, with a planned loading of up to 10,000 tons of green fuel per voyage, and includes ISO 23875 safety standards and MSC.1/Circ.1687 emergency protocols. All projects prove the commercial viability and technical reliability of green technologies without significant incidents, forming a template for large-scale implementation in global shipping.

Evaluation of effectiveness: LCOE, EROI, CAPEX + OPEX

For the strategic planning of hydrogen and ammonia use in maritime transport, it is important to take into account not only their thermodynamic and infrastructure properties, but also their full economic feasibility. The assessment was based on three key indicators: LCOE (life cycle energy cost), EROI (energy return on investment), and total CAPEX + OPEX (capital and operating costs).

Investment and operating costs. Estimation of the total cost of implementation includes: CAPEX (Capital Expenditures): the cost of infrastructure for fuel production, storage, and processing, and OPEX (Operational Expenditures): costs for cooling, pressure, safety, and maintenance (Table 7).

Table 7

Integrated comparative table of economic efficiency of 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: electrolyzers, cryogenic storage	Moderate: synthesis plants, compatible tanks
OPEX	High: cooling to –253 °C, compression	Medium: cooling down to –33 °C
State of commercial readiness	Low (TRL 6–7), requires R&D	Higher (TRL 8–9), partially integrated into the industry

Notes: TRL – Technology Readiness Level, R&D – Research and Development

Table 7 shows that ammonia is ahead of hydrogen in terms of economic indicators: its LCOE (150-220 USD/MWh) is 25–50 % lower, and its EROI (~5–8) is slightly higher than that of hydrogen (200–300 USD/MWh and ~4–6, respectively). At the same time, hydrogen requires significantly higher capital expenditures (CAPEX) for electrolyzers and cryogenic storage, and has high operating costs (OPEX) for cooling to –253 °C and compression. In contrast, ammonia has moderate CAPEX for synthesis units and compatible tanks, and lower OPEX due to liquefaction at –33 °C. Technology Readiness Levels (TRLs) reflect this difference: hydrogen is at TRL 6–7 with additional R&D required, and ammonia is at TRL 8–9 with time to integrate into the industry. Thus, although hydrogen has a higher energy potential, ammonia is a more realistic short- and medium-term alternative for decarbonizing the maritime fleet in terms of economic and technological availability.

To demonstrate the impact of strategic priorities on fuel choice, a scenario analysis was conducted with varying weights for economic costs, environmental impact, and risk. The table 8 demonstrates the recommended fuel choice depending on the shipowner's priorities (cost, environmental impact, safety).

Journal of Chemistry and Technologies, 2025, *33*(4), 1216-1231

Table 8

Scenario analysis of fuel choice

Scenario	Priority of expenses	Priority of the environment	Security priority	Recommended fuel
1. Minimizing costs	High (0.6)	Low (0.2)	Low (0.2)	Ammonia (NH_3)
2. Environmental	Low (0.2)	High (0.6)	Medium (0.2)	Hydrogen (H_2)
3. Safety priority	Low (0.2)	Medium (0.3)	High (0.5)	Hydrogen (H_2)
4. Balanced	Medium (0.4)	Medium (0.3)	Medium (0.3)	Ammonia or hydrogen (as appropriate)

The results demonstrate that ammonia is the most cost-effective option due to its well-developed infrastructure and lower investment costs. At the same time, hydrogen, which is characterized by zero emissions and lower toxicity, should be preferred in terms of environmental performance and risk-based safety. In balanced scenarios, the choice depends on specific operating conditions and geographical factors.

The comparative analysis reveals that both hydrogen and ammonia can play major roles in the decarbonization of maritime transport. The efficacy of their use is not necessarily universal but depends on several factors, including types of vessels, route particulars, availability of infrastructure, and the level of technological maturity of the solutions in question. From the environmental perspective, hydrogen is almost perfect since it does not produce CO_2 or toxic nitrogen oxides when used in fuel cells. However, if one considers precisely the technological characteristics: low energy density per volume, the need for deep cooling or high pressure, and the lack of established logistics – currently sharply limit its widespread adoption, especially in long-distance transportation, and the cost of producing "green" hydrogen remains high, although it will decrease in the next decade [32].

Ammonia has proved to be a much more technological ship fuel, because the processes involved in its transport and storage can be carried out on existing infrastructure, for example, at port liquefied gas terminals, making it less expensive in the short and medium term. The given analysis showed that the environmental advantages of hydrogen lose their significance due to the high cost of logistics. At the same time, despite certain operational risks, ammonia seems to be a more realistic option for large-scale applications in the coming years. The main issue remains the reform of the infrastructure in the absence of public involvement, global specifications, and demonstration launches; neither H_2 nor NH_3 will move from a concept to a realistic commercial implementation. That is why the contribution of IMO, the European Commission and the government to defining the regulatory environment and financial incentives for the industry is essential.

The conducted comparative analysis showed that hydrogen and ammonia have significant differences in thermodynamic and logistical parameters. Hydrogen shows a significantly higher mass energy intensity – about 120 MJ/kg compared to ammonia, which has only 18.6 MJ/kg. But in volume, hydrogen is inferior: its volumetric energy intensity is about 8.5 MJ/L, while in ammonia it reaches 11.5 MJ/L, which gives it an advantage for applications on offshore vessels with a limited space. This finding confirms that under strict space constraints, ammonia provides more energy in a limited volume, while hydrogen – predominates in specific energy density. In terms of safety characteristics, hydrogen has a much wider explosive range (4–75 %), combustion flames are invisible, and ignition temperatures are around 560 °C. Ammonia in this aspect is less explosive (15–28 % of air concentrations), has a noticeable flame and almost 100 °C higher ignition temperature – this reduces the risks of self-ignition of hydroxides, but the toxic potential of ammonia (concentrations > 25 ppm) poses other threats. When stored, hydrogen requires a complex regime – either extremely low temperatures (–253 °C) or high pressures up to 700 bar, while ammonia is stored much easier at –33 °C or under a pressure of 10–20 bar in traditional LPG reservoirs. Thus, our work confirmed that hydrogen storage is much more difficult and expensive. We also described the production of green fuels – water electrolysis provided «green» hydrogen, and the Haber-Bosch process, which uses the same hydrogen and nitrogen from the air, to produce green ammonia. Both approaches demonstrate the potential to achieve complete carbon neutrality, provided that electricity from renewable energy sources is provided.

Journal of Chemistry and Technologies, 2025, *33*(4), 1216-1231

Conclusions

The study conducted a comprehensive systemic analysis on the alternative marine fuels of hydrogen and ammonia for technical, economic, environmental, and operational considerations. To ensure the objectivity of the assessment, a formalized methodology was developed, marrying together a multi-criteria analysis (AHP), stochastic risk modeling, and life cycle analysis. The results confirmed that from the economic point of view, in the short term, ammonia proves better than other options due to its low specific energy production cost (LCOE) and CAPEX.

In addition, the existing ammonia storage infrastructure is much more developed compared to hydrogen, which simplifies its implementation in maritime transport.. Hydrogen, in turn, demonstrates advantages in terms of environmental friendliness and operational safety due to the absence of toxic properties. However, its use requires substantial capital investments in cryogenic storage, transportation, and specialized infrastructure. The proposed integral fuel acceptability index allows for an objective assessment of the feasibility of choosing a particular type of fuel depending on the shipowner's strategic priorities - economic efficiency, environmental friendliness, or operational safety.

Thus, the work conceptualizes renewable circuits «electricality-hydrogen-ammonia», where ammonia is an intermediate link with an optimal balance of cost, safety, and available infrastructure. The obtained models and ratings are essential for operators and regulators: they allow to justify the priorities of investments in the development of liquefied gas terminals, adaptation of norms and standards (IEC 60079, MSC.1/Circ.1687) and deployment of «green corridors».

Prospective directions for further research are:

(1) development of hybrid fuel cores that combine hydrogen and ammonia in blends to reduce storage pressure;

(2) modeling the life cycle of infrastructure, taking into account regional conditions;

(3) integration of digital leak monitoring systems and corrective real-time control algorithms;

(4) analysis of the social and economic factors of the adoption of «green» technologies at the local level, which will help ensure a further transition from demonstration tests to large-scale commercial application without losing opportunities to achieve carbon neutrality in maritime shipping.

References

[1] Levikhin, A., Boryaev, A. (2025). Low-carbon ammonia-based fuel for maritime transport. *Results in Engineering*, *25*, 104175. https://doi.org/10.1016/j.rineng.2025.104175

[2] Schreuder, W., Slootweg, J. C., Van der Zwaan, B. (2025). Techno-economic assessment of low-carbon ammonia as fuel for the maritime sector. *Applications in Energy and Combustion Science*, *22*, 100330. https://doi.org/10.1016/j.jaecs.2025.100330

[3] Machaj, K., Kupecki, J., Malecha, Z., Morawski, A., Skrzypkiewicz, M., Stanclik, M., Chorowski, M. (2022). Ammonia as a potential marine fuel: A review. *Energy Strategy Reviews*, *44*, 100926. https://doi.org/10.1016/j.esr.2022.100926

[4] Li, Z., Wang, K., Liang, H., Wang, Y., Ma, R., Cao, J., Huang, L. (2025). Marine alternative fuels for shipping decarbonization: Technologies, applications and challenges. *Energy Conversion and Management*, *329*, 119641. https://doi.org/10.1016/j.enconman.2025.119641

[5] Dickson, U. J., Huang, C. (2025). 2050 UK shipping emissions of NO_x, SO_x, PM10, and PM2.5: What are the determining factors, is the zero pollution by 2050 feasible, and will the reduction rate for these pollutants be at the same pace? *Marine Pollution Bulletin*, *220*, 118371. https://doi.org/10.1016/j.marpolbul.2025.118371

[6] Jörissen, L. (2024). Fuels – Introduction | Hydrogen Industrial Use. *Encyclopedia of Electrochemical Power Sources (Second Edition)*, 161–170. https://doi.org/10.1016/B978-0-323-96022-9.00267-X

[7] Wang, Z., Li, M., Zhao, F., Ji, Y., Han, F. (2024). Status and prospects in technical standards of hydrogen-powered ships for advancing maritime zero-carbon transformation. *International Journal of Hydrogen Energy*, *62*, 925–946. https://doi.org/10.1016/j.ijhydene.2024.03.083

[8] Li, J., Xu, H., Zhou, K., Li, J. (2024). A review on the research progress and application of compressed hydrogen in the marine hydrogen fuel cell power system. *Heliyon*, *10*(3), e25304. https://doi.org/10.1016/j.heliyon.2024.e25304

[9] Islam Rony, Z., Mofijur, M., Hasan, M., Rasul, M., Jahirul, M., Forruque Ahmed, S., Kalam, M., Anjum Badruddin, I., Yunus Khan, T., Show, P. (2023). Alternative fuels to reduce greenhouse gas emissions from marine transport and promote UN sustainable development goals. *Fuel*, *338*, 127220. https://doi.org/10.1016/j.fuel.2022.127220

[10] Alrashid, R., Mahmoud, M., Alami, A. H. (2024). Introduction to Green Hydrogen and Green Ammonia. *Comprehensive Green Materials*, 256–271. https://doi.org/10.1016/B978-0-443-15738-7.00038-6

[11] Van Sickle, E., Ralli, P., Pratt, J., Klebanoff, L. (2025). MV Sea Change: The first commercial 100% hydrogen fuel cell passenger ferry in the world. *International Journal of Hydrogen Energy*, *105*, 389–404. https://doi.org/10.1016/j.ijhydene.2025.01.040

[12] Jesus, B., Ferreira, I. A., Carreira, A., Ove Erikstad, S., Godina, R. (2024). Economic framework for green shipping corridors: Evaluating cost-effective transition from fossil fuels towards hydrogen. *International Journal of Hydrogen Energy*, *83*, 1429–1447. https://doi.org/10.1016/j.ijhydene.2024.08.147

[13] Xing, H., Stuart, C., Spence, S., Chen, H. (2021). Alternative fuel options for low carbon maritime transportation: Pathways to 2050. *Journal of Cleaner Production*, *297*, 126651. https://doi.org/10.1016/j.jclepro.2021.126651

[14] Tasleem, S., Bongu, C. S., Krishnan, M. R., Alsharaeh, E. H. (2024). Navigating the hydrogen prospect: A comprehensive review of sustainable source-based production technologies, transport solutions, advanced storage mechanisms, and CCUS integration. *Journal of Energy Chemistry*, *97*, 166–215. https://doi.org/10.1016/j.jechem.2024.05.022

[15] Harahap, F., Nurdiawati, A., Conti, D., Leduc, S., Urban, F. (2023). Renewable marine fuel production for decarbonised maritime shipping: Pathways, policy measures and transition dynamics. *Journal of Cleaner Production*, *415*, 137906. https://doi.org/10.1016/j.jclepro.2023.137906

[16] Abbas, M., Abbas, Q., Khan, A., Tayyab, S. M., Mehdi Rizvi, S. H., Raza, A., Haider Zaidi, S. S., Razzaqi, A. A., Haider, S., Sarfraz, S. A. (2024). Energy management in marine transportation sector. *Reference Module in Earth Systems and Environmental Sciences*. https://doi.org/10.1016/B978-0-44-313219-3.00151-9

[17] Arias, A., Nika, C., Vasilaki, V., Feijoo, G., Moreira, M. T., & Katsou, E. (2024). Assessing the future prospects of emerging technologies for shipping and aviation biofuels: A critical review. *Renewable and Sustainable Energy Reviews*, *197*, 114427. https://doi.org/10.1016/j.rser.2024.114427

[18] Lee, G. N., Kim, J. M., Jung, K. H., Park, H. (2024). Comparative life cycle assessment of various hydrogen supply methods from Australia to the Republic of Korea in environmental and economic aspects. *Science of The Total Environment*, *947*, 174669. https://doi.org/10.1016/j.scitotenv.2024.174669

[19] Wang, Y., Cao, Q., Liu, L., Wu, Y., Liu, H., Gu, Z., Zhu, C. (2022). A review of low and zero carbon fuel technologies: Achieving ship carbon reduction targets. *Sustainable Energy Technologies and Assessments*, *54*, 102762. https://doi.org/10.1016/j.seta.2022.102762

[20] Fan, H., Abdussamie, N., Chen, P. S. L., Harris, A., Gray, E. M., Arzaghi, E., Bhaskar, P., Mehr, J. A., Penesis, I. (2025). Two decades of hydrogen-powered ships (2000–2024): Evolution, challenges, and future perspectives. *Renewable and Sustainable Energy Reviews*, *219*, 115878. https://doi.org/10.1016/j.rser.2025.115878

[21] Wang, Z., Dong, B., Li, M., Ji, Y., Han, F. (2024). Configuration of Low-Carbon fuels green marine power systems in diverse ship types and Applications. *Energy Conversion and Management*, *302*, 118139. https://doi.org/10.1016/j.enconman.2024.118139

[22] Hoang, A. T., Pandey, A., Martinez De Osés, F. J., Chen, W., Said, Z., Ng, K. H., Ağbulut, Ü., Tarełko, W., Ölçer, A. I., Nguyen, X. P. (2023). Technological solutions for boosting hydrogen role in decarbonization strategies and net-zero goals of world shipping: Challenges and perspectives. *Renewable and Sustainable Energy Reviews*, *188*, 113790. https://doi.org/10.1016/j.rser.2023.113790

[23] Melnyk, O., Onyshchenko, S., Onishchenko, O., Shumylo, O., Voloshyn, A., Ocheretna, V., & Fedorenko, O. (2024). Implementation Research of Alternative Fuels and Technologies in Maritime Transport. *Studies in Systems, Decision and Control*, 510, 13-31. https://doi.org/10.1007/978-3-031-44351-0_2

[24] Melnyk, O., Onishchenko, O., Onyshchenko, S. (2023). Renewable Energy Concept Development and Application in Shipping Industry. *Lex Portus, 9*(6), 15–24. https://doi.org/10.26886/2524-101X.9.6.2023.2

[25] Melnyk, O., Bulgakov, M., Fomin, O., Onyshchenko, S., Onishchenko, O., Pulyaev, I. (2025). Sustainable development of renewable energy in shipping: technological and environmental prospects. *Scientific Journal of Silesian University of Technology. Series Transport, 127*, 165–188. https://doi.org/10.20858/sjsutst.2025.127.10

[26] International Energy Agency. (2024). *World Energy Outlook 2024*. https://www.iea.org/reports/world-energy-outlook-2024

[27] Det Norske Veritas. (2025). *Energy Transition Outlook 2025*. https://www.dnv.com/energy-transition-outlook/

[28] International Renewable Energy Agency. (2024a). *World Energy Transitions Outlook 2024: 1.5 °C pathway*. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Nov/IRENA_World_energy_transitions_outlook_2024.pdf

[29] International Renewable Energy Agency. (2024b). *Renewable Energy Statistics 2024*. https://www.irena.org/-media/Files/IRENA/Agency/Publication/2024/Jul/IRENA_Renewable_Energy_Statistics_2024.pdf

[30] International Maritime Organization. (2023). *2023 IMO strategy on reduction of GHG emissions from ships*. Доступно: https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx

[31] International Maritime Organization. (2020). *Fourth IMO GHG study 2020*. Доступно: https://www.imo.org/en/Publications/Pages/Fourth-IMO-GHG-Study-2020.aspx

[32] Brynolf, S., Taljegard, M., Grahn, M., Hansson, J. (2017). Electrofuels for the transport sector: A review of production costs. *Renewable and Sustainable Energy Reviews*, *81*, 1887–1905. https://doi.org/10.1016/j.rser.2017.05.288

[33] Valera-Medina, A., Xiao, H., Owen-Jones, M., David, W., Bowen, P. (2018). Ammonia for power. *Progress in Energy and Combustion Science*, *69*, 63–102. https://doi.org/10.1016/j.pecs.2018.07.001

[34] Ishak, M. I., Masri, A. N., Rasol, A. A. A., Ibrahim, I. M., & Hasbullah, H. (2025). Amino acid deep eutectic solvents (AADES) in oil purification: An overview of properties, applications, and future directions. *Journal of Ionic Liquids, 5*(1), 100143. https://doi.org/10.1016/j.jil.2025.100143

[35] Shumylo, O., Yarovenko, V., Malaksiano, M., & Melnyk, O. (2023). Comprehensive assessment of hull geometry influence of a modernized ship on maneuvering performance and propulsion system parameters. *Pomorstvo*, 37(2), 314–325. https://doi.org/10.31217/p.37.2.13

[36] Anantharaman, M., Sardar, A., Islam, R. (2025). Decarbonization of shipping and progressing towards reducing greenhouse gas emissions to net zero: A bibliometric analysis. *Sustainability*, *17*(7), 2936. https://doi.org/10.3390/su17072936

[37] Sagin, S., Haichenia, O., Karianskyi, S., Kuropyatnyk, O., Razinkin, R., Sagin, A., Volkov, O. (2025). Improving green shipping by using alternative fuels in ship diesel engines. *Journal of Marine Science and Engineering, 13*(3), 589. https://doi.org/10.3390/jmse13030589

[38] Petrychenko, O., Levinskyi, M., Goolak, S., Lukoševičius, V. (2025). Prospects of solar energy in the context of greening maritime transport. *Sustainability*, *17*(5), 2141. https://doi.org/10.3390/su17052141

[39] Christopher Selvam, D., Raja, T., Nagappan, B., Upadhye, V. J., Guntaj, J., Devarajan, Y., & Mishra, R. (2025). The role of biodiesel in marine decarbonization: Technological innovations and ocean engineering challenges. *Results in Engineering, 25*, Article 103974. https://doi.org/10.1016/j.rineng.2025.103974

[40] Kalafatelis, A. S., Nomikos, N., Giannopoulos, A., Alexandridis, G., Karditsa, A., & Trakadas, P. (2025). Towards predictive maintenance in the maritime industry: A component-based overview. *Journal of Marine Science and Engineering, 13*(3), 425. https://doi.org/10.3390/jmse13030425

[41] Melnyk, O. M., Onishchenko, O. A., Shyshkin, O. V., Volkov, O. M., Volyanskyy, S. M., Maulevych, V. O., Kreitser, K. O. (2024). Enhancing shipboard technical facility performance through the utilization of low-sulfur marine fuel grades. *Journal of Chemistry and Technologies, 32*(1), 233–245. https://doi.org/10.15421/jchemtech.v32i1.297916

[42] Onishchenko, O., Bukaros, A., Melnyk, O., Yarovenko, V., Voloshyn, A., Lohinov, O. (2023). Ship refrigeration system operating cycle efficiency assessment and identification of ways to reduce energy consumption of maritime transport. In *Studies in Systems, Decision and Control,* 481, 641–652). Springer. https://doi.org/10.1007/978-3-031-35088-7_36

[43] Korban, D., Melnyk, O., Onishchenko, O., Kurdiuk, S., Shevchenko, V., Obniavko, T. (2024). Radar-based detection and recognition methodology of autonomous surface vehicles in challenging marine environment. *Scientific Journal of Silesian University of Technology. Series Transport, 122*, 111–127. https://doi.org/10.20858/sjsutst.2024.122.7

[44] Melnyk, O., Onishchenko, O., Onyshchenko, S., Yaremenko, N., Maliuha, E., Honcharuk, I., Shamov, O. (2024). Innovative technologies for the maritime industry: Hydrogen fuel as a promising direction. In *Studies in Systems, Decision and Control, 510*, 23–34). Springer. https://doi.org/10.1007/978-3-031-44351-0_3

[45] Melnyk, O., Onyshchenko, S., Onishchenko, O., Shibaev, O., Volyanskaya, Y. (2024). A comprehensive approach to structural integrity analysis and maintenance strategy for ship's hull. *Journal of Maritime Research, 21*(1), 36–44.

[46] Melnyk, O., Onyshchenko, S., Onishchenko, O., Shumylo, O., Voloshyn, A., Ocheretna, V., Fedorenko, O. (2024). Implementation research of alternative fuels and technologies in maritime transport. In *Studies in Systems, Decision and Control*, *510*, 13–21. Springer. https://doi.org/10.1007/978-3-031-44351-0_2

[47] Onishchenko, O. A., Melnyk, O. M., Yarovenko, V. A., Aleksandrovska, N. I., Kurdiuk, S. V., Parmenova, D. G., Storchak, O. O. (2023). Study of efficiency and advancement of marine engine oil purification and filtration technologies. *Journal of Chemistry and Technologies, 31*(4), 762–774. https://doi.org/10.15421/jchemtech.v31i4.285643

[48] Onyshchenko, S., Bychkovsky, Y., Melnyk, O., Onishchenko, O., Jurkovič, M., Rubskyi, V., Liashenko, K. (2024). A model for assessing shipping safety within project-orientated risk management based on human element. *Scientific Journal of Silesian University of Technology. Series Transport, 123*, 319–334. https://doi.org/10.20858/sjsutst.2024.123.16

[49] Melnyk, O., Onishchenko, O., Onyshchenko, S., Voloshyn, A., Ocheretna, V. (2023). Comprehensive study and evaluation of ship energy efficiency and environmental safety management measures. In *Studies in Systems, Decision and Control*, *481*, 665–679. Springer. https://doi.org/10.1007/978-3-031-35088-7_38

[50] Sagin, S., Chymshyr, V., Karianskyi, S., Kuropyatnyk, O., Madey, V., Rusnak, D. (2025). Using ultrasonic fuel treatment technology to reduce sulfur oxide emissions from marine diesel exhaust gases. *Energies*, *18*(17), 4756. https://doi.org/10.3390/en18174756

[51] Minchev, D. S., Varbanets, R. A., Alexandrovskaya, N. I., Pisintsaly, L. V. (2021). Marine diesel engines operating cycle simulation for diagnostics issues. Acta *Polytechnica, 61*(3), 428–440. https://doi.org/10.14311/ap.2021.61.0435

[52] Varbanets, R., Minchev, D., Kucherenko, Y., Zalozh, V., Kyrylash, O., Tarasenko, T. (2024). Methods of real-time parametric diagnostics for marine diesel engines. *Polish Maritime Research*, *31*(3), 71–84. https://doi.org/10.2478/pomr-2024-0037

[53] Onyshchenko, S., Bondar, A., Andrievska, V., Sudnyk, N., Lohinov, O. (2019). Constructing and exploring the model to form the road map of enterprise development. *Eastern-European Journal of Enterprise Technologies,* *5*(3-101), 33–42. https://doi.org/10.15587/1729-4061.2019.179185