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Sustainable Development of Maritime Transport Towards Net-Zero Emissions by 2050 Through a Feasible Fuel Transition Roadmap

Tran Huu Long, Phan Van Hung and Nguyen Xuan Long†

Vietnam Maritime University, Haiphong, Vietnam

†Corresponding author: Nguyen Xuan Long; nguyenxuanlong@vimaru.edu.vn

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ABSTRACT

With the 2023 International Maritime Organization (IMO) Greenhouse Gas (GHG) Strategy targeting net-zero ship emissions by 2050, shipowners and operators are seeking economically effective solutions to meet the latest emission requirements. The initial cost of changeover and use of new fuels can be too high, which is a major barrier for Vietnamese shipowners. Therefore, this article proposes a comprehensive fuel transition roadmap for Vietnam's maritime industry using the PLEETS multi-criteria decision analysis framework (Political, Legal, Economic, Environmental, Technological, and Social). Through a mixed-methods research design to evaluate Vietnamese fleet data, assess major port infrastructure, conduct surveys of 127 participants, and perform techno-economic modeling, seven alternative fuels were considered: compliant fuels, liquefied natural gas (LNG), methanol, ammonia, shore power, ethanol, and hydrogen. The analysis results indicate an optimal transition strategy comprising three phases: The immediate phase (2025–2030) focuses on building a basic foundation, such as deploying onshore power generation and providing and using appropriate fuels, to achieve a 15–20% emission reduction target with an estimated investment of USD 0.8–1.0 billion. The intermediate phase (2031–2040) involves using methanol and bio-LNG, aiming for a 40–50% reduction with an estimated investment of USD 1.8–2.2 billion. The final phase (2041–2050) will utilize green ammonia and e-methanol, aiming for net-zero emissions with an investment of approximately USD 2.8–3.4 billion. This roadmap provides evidence to support Vietnamese policymakers, shipowners, operators, and port authorities and contributes methodologically through the first-ever rigorous application of the PLEETS multi-criteria decision analysis framework integrated into a marine fuel transition strategy in the context of a developing nation.

1. INTRODUCTION

The maritime sector plays a pivotal role in the global economy, offering substantial advantages in terms of both the volume and distance of transportation. With the world's commercial fleet reaching about 108,789 vessels and a total capacity of approximately 2.4 billion deadweight tons, maritime transport remains the dominant mode of global trade, accounting for over 80% of world trade by volume (UNCTAD 2024). The maritime industry currently accounts for approximately 3% of total global greenhouse gas (GHG) emissions, contributing significantly to environmental pollution (Alamouch & Ölçer 2025, Lian et al. 2020). According to the IMO's Third Greenhouse Gas Study (Smith et al. 2014), CO₂ emissions from the international commercial shipping fleet increased from 848 million to 919 million metric tons between 2012 and 2018. As maritime trade is projected to continue growing, emissions from this fleet risk increasing by 50–250% by 2050.

Furthermore, ships are responsible for approximately 12% of global sulfur oxides (SO_x) and 13% of global nitrogen oxides (NO_x) emissions (Bolat 2026, Smith et al. 2014, IMO 2020, Perera & Soares 2017). In line with the goals of COP26, the 2023 IMO GHG Strategy was developed with the overarching goal of achieving carbon neutrality before 2050 (IMO 2018, IMO 2023). To implement this goal, the IMO issued tools and implementation guidelines such as the Energy Efficiency Design Index (EEDI), Energy Efficiency Existing Ship Index (EEXI), Energy Efficiency Operational Indicator (EEOI), and Carbon Intensity Indicator (CII), providing a solid foundation for countries to develop their own emission reduction strategies for their fleets.

Notably, in 2023, the IMO officially launched a new strategy for reducing greenhouse gas emissions from ships, with the core objective of achieving net-zero emissions by 2050, fully consistent with the commitments made at COP26 (IMO 2023). This strategy delineates specific objectives for the introduction of alternative green fuels and establishes indicative benchmarks for overall emission reduction. These benchmarks were designated for a 20–30% reduction by the year 2030 and a 70–80% reduction by the year 2040, respectively.

The 2023 IMO GHG Strategy requires shipowners and operators to plan for compliance with the emission reduction requirements of the CII, moving toward operating low- and zero-emission ships. There are several options (Cortez-Huerta et al. 2024, Premasarn et al. 2025, Wang & Iris 2025) for fuel suppliers and users, including heavy fuel oil (HFO) used with onboard exhaust gas cleaning systems (scrubbers); low-sulfur fuel oil (LSFO) and marine gas oil (MGO); liquefied natural gas (LNG) or compressed natural

gas (CNG); methanol; ethanol; biofuels such as bio-LNG, bio-MGO, e-LNG, and e-MGO; green fuels such as green hydrogen and green ammonia; and electricity from the grid. A ship's fuel consumption can account for more than 50% of its operating costs. With increasingly stringent requirements for the shipping industry, the incentives for shipowners/operators are not only environmental but also related to operational efficiency and ship economics. This paper considers options including fossil fuels combined with scrubbers, biofuels, green fuels, and electricity from the grid. The results of this study will help shipowners/operators make adaptation decisions in the short and long term. In particular, with 1,500 ships with a total tonnage of 13.7 million tons, the Vietnamese shipping fleet currently ranks 3rd in ASEAN and 22nd in the world. Notably, the average age of the Vietnamese shipping fleet is 15.5 years, 6 years younger than the world's fleet. The number of crew members also increased sharply from 39,400 people in 2018 to 62,000 people in 2023. A widely used indicator that provides insight into the capacity of a seaport is the volume of cargo handled by the port, which includes all types of cargo such as containers, liquids, and dry bulk, and can serve as a leading economic indicator. The volume of cargo through the Vietnamese seaport system in 2024 was 864.4 million tons, up 14% from the same period in 2023. Container cargo through the Vietnamese seaport system was estimated to be 29.9 million twenty-foot equivalent units (TEUs), up 21% from the same period in 2023, as shown in Fig. 1. An estimated 102.67 thousand ships were expected to sail through the ports in 2024, up 2% from the same period in 2023. An estimated 380.1 thousand inland waterway vessels were expected to pass through the harbor in 2024, an 8% increase over the same period in 2023.

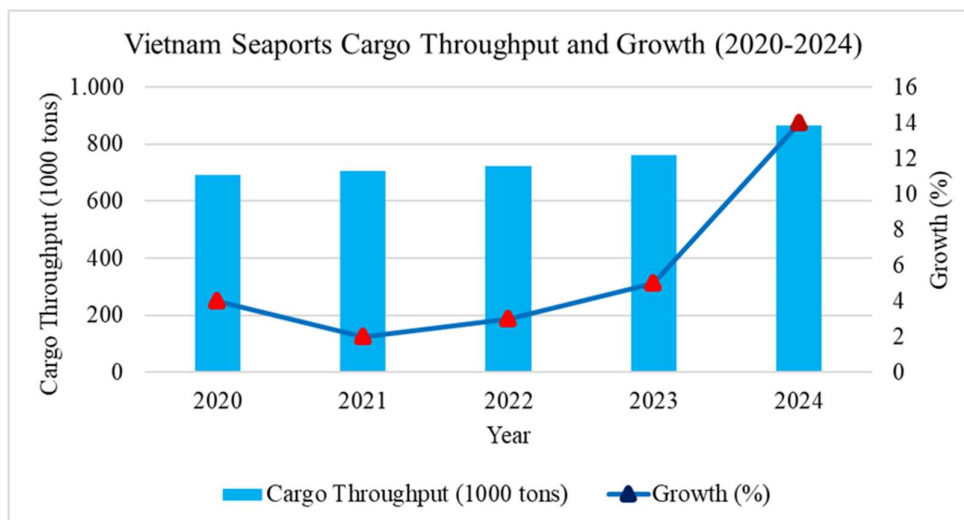


Fig. 1: Cargo throughput and growth of Vietnam seaports (Source: Vietnam Maritime and Waterway Administration 2025).

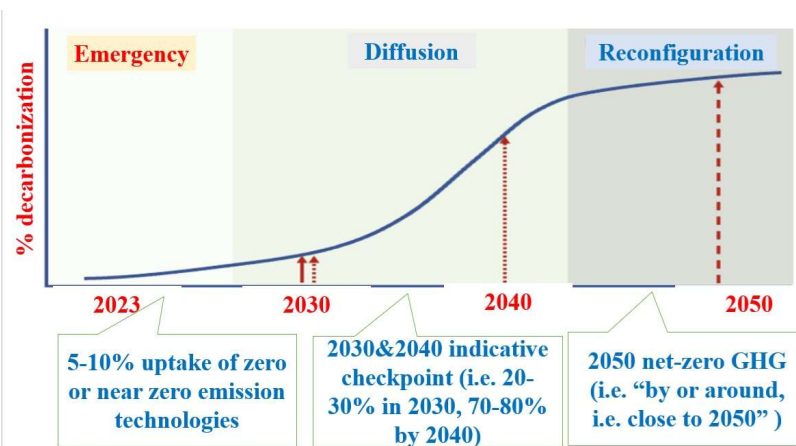


Fig. 2: The 2023 IMO GHG Strategy (IMO, 2023).

The world's largest container ship, with a deadweight tonnage (DWT) of 232,000, was successfully received at the Cai Be wharf area by the Vietnamese seaport system, which has established gateway ports along with international transit in the North and South areas. At the port of Lach Huyen, Cai Mep ships with a maximum capacity of 140,000 DWT head straight to the markets in Europe and America. Large-scale specialized ports connected to industrial parks, metallurgical complexes, petrochemical refineries, and coal-fired thermal power centers receive ships up to 200,000 DWT, liquid cargo up to 150,000 DWT (product export ships), and crude oil up to 320,000 DWT (at Nghi Son port buoy wharf).

Clearly, Vietnamese shipowners are struggling to make the right decision on the options for compliance with the emission reduction requirements of the 2023 IMO GHG Strategy for their existing vessels as well as their plans for operating new vessels. Therefore, it is necessary to analyze the advantages and disadvantages of the possible options for Vietnamese shipowners in this context.

2. MATERIALS AND METHODS

2.1. Literature Review

2.1.1. Regulatory Framework: Focusing on IMO Strategies and Vietnam's Legal Context

The IMO's revised 2023 GHG Strategy sets a target of net-zero emissions by around 2050, with interim goals of decreasing GHG emissions by 20–30% by 2030 and 70–80% by 2040, based on 2008 levels (Fig. 2). It also aims for a minimum 5% uptake of zero/near-zero emission fuels or technologies by 2030. The application of well-to-wake fuel emission control is a significant new step forward, contributing to a fair and equitable fuel transition. Industry- and vessel-specific emission reduction targets

are now primarily focused on greenhouse gas intensity per unit of transport. Specifically, each vessel is targeted to reduce emissions by 55–61% by 2030 and 86–91% by 2040 compared to 2008 baselines. This sends a very clear message to fuel producers and suppliers, strongly supporting a genuine green fuel transition; consequently, fossil fuel-based or environmentally unfriendly alternatives will no longer be encouraged.

A clear and systematic decarbonization roadmap will lead to a synchronized shift in investment toward technically viable green technologies (Barone et al. 2024, Balci et al. 2024, Cuong & Hung 2020b, Nguyen 2016) considerable challenges exist for green ammonia adoption as the future clean energy source in maritime transport. This study scrutinises the success factors of the industry-wide adoption of green ammonia. We examine the structural relationship between success factors to explore antecedents, illustrate the precedence relationships between success factors, and present a roadmap. We first determine success factors and then employ Interpretive Structural Modelling (ISM).

2.1.2. Empirical Evidence Regarding Fuel Adoption

The core objective of the maritime industry today is to achieve carbon neutrality through a fair and equitable fuel transition, in strict compliance with the IMO's 2023 Greenhouse Gas (GHG) Emission Reduction Strategy. This context also highlights the asymmetry in policy frameworks among developing countries due to varying levels of economic impact. Therefore, the adoption of a dual regulatory mechanism combining technical standards and a GHG pricing mechanism is crucial to bridging the cost gap between green and conventional fuels, while promoting the participation of developing countries in production and supply.

To assess the potential aspects of developing green fuels alongside improving energy efficiency, the maritime industry is witnessing a divergence in the trajectory of transition to alternative energy sources, such as liquefied natural gas (LNG) and biofuels (Ha et al. 2025, Park et al. 2021, DNV GL 2020). However, these low-emission transition fuels are projected to become unsuitable by 2040, posing a significant risk of wasted investment. Therefore, choosing an investment path toward large-scale zero-emission solutions focusing on green hydrogen, green ammonia, and green methanol that are supported by pilot projects will help create green corridors to mitigate risks for both the public and private sectors (Barone et al. 2024, Cuong & Hung 2020a, Achuo et al. 2022, Atilhan et al. 2021, DNV GL 2020, Karvounis & Theotokatos 2025).

In addition, integrated power generation solutions from seaports to completely eliminate port emissions also require extensive synchronization between port infrastructure and ships. Overall, the feasibility and suitability of each solution require stakeholders to carefully consider long-term asset use plans, ensuring compliance with stringent requirements in the roadmap toward near-zero emission technologies (Ortiz-Imedio et al. 2021, Sun et al. 2023).

2.1.3. Research Gaps

Although current research on maritime energy transition solutions is abundant, much of it is biased toward specific geographic regions and decarbonization strategies. Technologically advanced economies with high capital mobility, such as the EU, the US, China, and Japan, are often used as the standard reference point (Ha et al. 2025, Ortiz-Imedio et al. 2021, Wang & Iris 2025, Balci et al. 2024, Barone et al. 2024, Halpe et al. 2025, IMO 2018, IMO 2020, IMO 2023, Perera & Soares 2017, Al-Aboosi et al. 2021, Cameretti et al. 2025).

This research identifies three key gaps: (i) existing decision-support frameworks do not adequately address the essential sociopolitical and legal aspects for developing countries; (ii) studies on maritime decarbonization often focus on developed countries, without considering the characteristics faced by developing maritime nations such as infrastructure and finance; (iii) technological maturity over time, infrastructure development, and alternative fuel supply chains have not been fully integrated into transition plans. The new PLEETS decision-support framework developed in this study focuses on addressing these knowledge gaps.

2.2. Research Design and Data Collection

This study employed a sequential mixed-methods approach. The qualitative phase involves literature reviews and expert consultations to identify criteria and establish the AHP hierarchy model. The quantitative phase utilizes the AHP

method to compute criterion weights, applies the TCO model for cost evaluation, and conducts sensitivity analysis to validate the robustness of the decision-making model. Data across the following four areas were collected between January 2023 and December 2024.

Data for all commercial vessels, classified by vessel type (bulk carriers, container ships, oil tankers, general cargo ships, passenger ships, offshore support vessels), age distribution, engine type, and fuel consumption patterns, were collected from the Vietnam Maritime and Waterway Administration (VIMAWA). Emissions from vessels were calculated using the methodology of the Fourth IMO Greenhouse Gas Study (IMO 2020).

Surveys (assessing fuel preferences, infrastructure constraints, investment capacity, and policy priorities) were conducted with two distinct groups of participants: 27 domain experts who contributed to the AHP weighting process, and 127 participants in the validation survey, including 15 government agencies, 18 port authorities, 35 ship operators, 42 shipowners, and 17 maritime industry associations.

Assessments at six major ports (over 80% of the country's cargo throughput) in Vietnam (Hai Phong, Ho Chi Minh, Vung Tau, Da Nang, Nha Trang, Quy Nhon) considered existing refueling capacity, onshore power infrastructure, land area for fuel storage, and safety systems.

Techno-economic model: A specific total cost of ownership (TCO) model was developed using a 25-year life-cycle analysis with a 5% discount rate for each vessel and incorporating capital costs (vessel modifications and engine upgrades), fuel costs (current and projected), infrastructure costs (refueling, storage, and distribution), and operating costs (maintenance, training, and insurance).

2.3. PLEETS Framework Implementation

The PLEETS framework was implemented through a four-stage process:

Phase 1: Criterion Definition and Weighting

Nineteen evaluation criteria across six aspects of PLEETS were established (Tables 1 and 2).

Nineteen criteria were evaluated across six aspects of PLEETS (Tables 1–3). Based on the opinions of 27 maritime experts and analytic hierarchy process (AHP) analysis, the weights of the criteria were determined. A consistency ratio below 0.10 ensured the reliability of the evaluation method. Three sensitivity scenarios were analyzed to examine changes in weighting: environmental priority (environmental aspect weight increased by 50%), economic priority (economic aspect weight increased by 50%).

Table 1: PLEETS framework overview.

Framework Component	Description	Application in Maritime Fuel Selection	Data Sources
Political Dimension	Government policies, political stability, international cooperation	Assessment of policy support, regulatory certainty, geopolitical fuel security	Policy documents, stakeholder interviews, international agreements
Legal Dimension	Regulatory compliance, legal frameworks, liability	Evaluation of IMO compliance, national regulations, safety standards	IMO regulations, national maritime law, port regulations
Economic Dimension	Costs, financial viability, economic impacts	Total cost of ownership, infrastructure investment, operational economics	Fleet data, fuel prices, infrastructure cost estimates, TCO modeling
Environmental Dimension	GHG emissions, air quality, ecological impacts	Life-cycle emissions, air pollutants, water pollution, biodiversity	Life-cycle assessment (LCA) databases, emission factors, environmental impact assessments
Technological Dimension	Technology maturity, technical feasibility, safety	Technology readiness level, energy density, infrastructure maturity	Technical literature, manufacturer data, pilot projects
Social Dimension	Stakeholder acceptance, social impacts, equity	Workforce implications, public health, social acceptance, equity	Stakeholder surveys, health impact assessments, employment analysis

Source: Authors' framework development based on the PESTLE methodology

Table 2: PLEETS evaluation criteria and indicators.

Dimension	Criteria	Indicators	Weight	Data Source
Political (0.15)	Government support	Policy documents, funding commitments	0.06	Policy analysis
	Policy stability	Regulatory consistency, long-term planning	0.05	Expert assessment
	International cooperation	Regional agreements, technology transfer	0.04	International frameworks
Legal (0.12)	IMO compliance	Alignment with IMO 2030/2050 targets	0.05	Regulatory analysis
	National regulations	Domestic maritime law compatibility	0.04	Legal review
	Safety regulations	Handling, storage, bunkering standards	0.03	Safety assessments
Economic (0.25)	Capital costs	Vessel modifications, infrastructure investment	0.09	Cost modeling
	Fuel costs	Current and projected fuel prices	0.08	Market analysis
	Operational costs	Maintenance, training, insurance	0.05	Industry data
	Economic viability	Payback period, return on investment	0.03	Financial modeling
Environmental (0.28)	GHG emissions	Well-to-wake CO ₂ equivalent	0.12	LCA analysis
	Air quality	SO _x , NO _x , PM emissions	0.08	Emission modeling
	Water pollution	Ballast water, fuel spills	0.05	Environmental assessment
	Biodiversity impacts	Marine ecosystem effects	0.03	Ecological studies
Technological (0.13)	Technology readiness	Technology readiness level (TRL), commercial availability	0.05	Technology assessment
	Energy density	Volumetric and gravimetric density	0.04	Technical specifications
	Infrastructure maturity	Bunkering, storage, distribution	0.04	Infrastructure assessment
Social (0.07)	Stakeholder acceptance	Industry and public support	0.03	Survey data
	Workforce impacts	Training needs, employment effects	0.02	Labor analysis
	Health benefits	Air quality improvements	0.02	Health impact assessment

Dimension weights shown in parentheses; criteria weights sum to dimension weight. Source: Authors' AHP analysis with 27 expert participants.

Phase 2: Evaluation of Alternative Fuel Options

A systematic evaluation of seven typical alternative fuel options: (1) compliant low-sulfur fuel blends (VLSFO/MGO), (2) liquefied natural gas (LNG), (3) methanol (including production pathways), (4) ethanol (bioethanol), (5) ammonia (gray, blue, and green production pathways),

(6) hydrogen (compressed and liquid forms), and (7) onshore power for terminal operations.

Each fuel type was scored on a scale of 0 to 1 for each criterion based on a review of documentation, specifications, life-cycle assessment (LCA) data, and a Vietnam-specific feasibility assessment including differences in production

Table 3: Weight synthesis and sensitivity analysis.

Dimension	Base Case Weight	Environmental Priority Weight	Economic Priority Weight	Weight Range (Min–Max)	Coefficient of Variation
Political	0.15	0.12	0.13	0.12–0.18	0.14
Legal	0.12	0.10	0.11	0.09–0.15	0.18
Economic	0.25	0.20	0.375	0.20–0.38	0.25
Environmental	0.28	0.42	0.22	0.22–0.42	0.28
Technological	0.13	0.11	0.12	0.10–0.16	0.17
Sociological	0.07	0.05	0.06	0.05–0.09	0.21
Total	1.00	1.00	1.00	-	-
Consistency Ratio	0.08	0.09	0.07	-	-

Environmental priority: Environmental dimension weight increased 50%; Economic priority: Economic dimension weight increased 50%. Consistency ratio < 0.10 indicates acceptable judgment consistency. Source: Authors' AHP sensitivity analysis.

processes and technological maturity, cost projections, and infrastructure development.

Phase 3: Multi-criteria synthesis

This study uses a weighted synthesis method to calculate scores (Eq. 1).

$$S_f = \sum d = 16w_d \times \sum c = 16w_{d,c} \times s_{f,d,c} \quad \dots(1)$$

where S_f is the overall score for fuel f , w_d is the weight for dimension d , $w_{d,c}$ is the weight for criterion c within dimension d , and $s_{f,d,c}$ is the score for fuel f on criterion c of dimension d .

Phase 4: Scenario and sensitivity analysis

The study analyzes the business-as-usual (BAU), Moderate Transition, and Rapid Transition scenarios. The three-phase roadmap (2030, 2040, and 2050), developed after expert consultation, integrates the results of the PLEETS analysis, considering infrastructure constraints, investment financing capacity, and feasibility. Sensitivity analysis demonstrated stability against variations in weighting of technology maturity over time and the rate of fuel cost reduction.

3. RESULTS AND DISCUSSION

The 27 experts were selected based on their expertise

in maritime operations (10), energy policy (8), and environmental engineering (9). Pairwise comparisons were performed using Saaty's 9-point scale. The group consistency ratio (CR) was calculated as $0.076 < 0.1$, ensuring reliability. The 127 survey participants provided broader industry validation, with responses anonymized to comply with ethical standards.

While Compliant Fuels currently lead in aggregate scoring due to infrastructure maturity (T3, E4), their low Environmental scores (En1, En2) necessitate a transition to alternative fuels as carbon taxes and regulatory pressures increase toward 2050.

The PLEETS framework assessment (Table 4) reveals different performance characteristics among the seven alternative fuels. Reflecting immediate availability, regulatory compliance, and minimum infrastructure requirements, the compliant fuel blends achieved the highest overall score (0.712), but had limited emission reduction potential. Second place went to LNG (0.672), balancing moderate emission reduction with established technology and developing infrastructure. Methanol (0.658) and ammonia (0.643) showed strong long-term potential, particularly in environmental and technological aspects, but faced short-term economic and infrastructure hurdles.

Table 4: Comprehensive PLEETS evaluation scores.

Fuel Alternative	Political (0.15)	Legal (0.12)	Economic (0.25)	En. (0.28)	Tec. (0.13)	Soc. (0.07)	Overall Score	Rank
Compliant Fuels	0.82	0.91	0.78	0.42	0.89	0.76	0.712	1
LNG	0.71	0.78	0.72	0.58	0.74	0.68	0.672	2
Methanol	0.68	0.72	0.58	0.71	0.69	0.64	0.658	3
Ammonia	0.64	0.65	0.52	0.82	0.61	0.58	0.643	4
Shore Power	0.76	0.81	0.48	0.89	0.72	0.71	0.638	5
Ethanol	0.59	0.68	0.54	0.68	0.58	0.62	0.612	6
Hydrogen	0.52	0.58	0.41	0.86	0.48	0.54	0.571	7

Dimension weights are shown in parentheses; scores are normalized on a 0–1 scale (higher is better).

Policy: The compliant fuels score is 0.82 because there is a stable established legal framework, resulting in low risk. The LNG score is 0.71, indicating increasing government support and priority for developing national LNG infrastructure by 2030. The methanol score is 0.68, and the ammonia score is 0.64, showing unclear incentive policies for safe production and supply. The hydrogen score is the lowest (0.52) due to the lack of a roadmap.

Legal aspects: Compliant fuels meet IMO requirements and therefore have the highest score of 0.91. LNG ranks second with a score of 0.78, aligning with IMO 2030 targets, but methane emissions pose a risk. Next are methanol and ethanol, which still pose risks related to safety regulations and legal liability, with scores of 0.72 and 0.68, respectively. Ammonia has a score of 0.65 and hydrogen 0.58, representing risks due to legal gaps in production, storage, transportation, and bunkering.

Economics: Compliant fuels rank first with a score of 0.78, representing the lowest fuel cost. LNG ranks second with a score of 0.72, indicating low fuel costs but high infrastructure investment. Following are methanol and ethanol, which have moderate fixed capital costs but unpredictable fuel prices, with scores of 0.58 and 0.54, respectively. Finally, ammonia and hydrogen are ranked last, representing high fuel production investment costs, significant infrastructure and vessel gaps, and high supply market risks, with scores of 0.52 and 0.41, respectively.

Environment: Shore power ranks first with a score of 0.89, followed by hydrogen with a score of 0.86. These are two solutions with zero emissions when ships are docked in port. Green ammonia ranks third and can reduce greenhouse gas emissions by 95%, with a score of 0.82. Methanol and bioethanol, developed in a bio-oriented direction, can reduce emissions by 60–80% (scores of 0.71 and 0.68, respectively). LNG (0.58) emits methane, so it only reduces emissions by 20–25%. Compliant fuels (with a score of 0.42) meet minimum requirements.

Technology: The most mature technology is associated with compliant fuels, with a score of 0.89. Fuels with readily available technology are LNG (0.74) and shore power (0.72). Methanol-related technology can build on existing infrastructure (0.69), benefiting from existing chemical processing infrastructure. Technological barriers for ammonia (0.61) and ethanol (0.58) are moderate. Low energy density, storage technology, and ship fuel-distribution systems for hydrogen give it the lowest score (0.48).

Social: The port community strongly supports the use of shore power, so this solution has the highest score (0.71). Compliant fuels, LNG, methanol, and ethanol follow with moderate impacts. Finally, the new fuels, ammonia and hydrogen, still pose safety risks and widespread labor shortages.

Looking at Table 5, the sensitivity analysis ranking results for the fuels show that the overall ranking remains unchanged. However, there are slight changes in the environmental and economic aspects. The greenhouse gas emission reduction efficiency of ammonia (0.698) is higher than that of LNG (0.641). Compliant fuels (0.756) are the most economically efficient, while ammonia and hydrogen remain at the bottom due to high investment costs.

Although compliant fuels rank first in the static MCDA result, this reflects the current market maturity and economic feasibility. The proposed roadmap uses a dynamic transition approach, where the adoption of low-carbon fuels (methanol, ammonia) increases as their technological and economic scores improve through policy intervention and global supply chain development.

3.1. Fuel Transition Roadmap

Based on the PLEETS results, the existing infrastructure limitations, and consultations with stakeholders, the authors propose a fuel transition roadmap (Table 6) in three phases, consistent with the capacity of the Vietnamese maritime industry and the IMO timelines.

Table 5: Sensitivity analysis: fuel rankings under alternative weighting scenarios.

Fuel Alternative	Base Case Score	Base Rank	Environmental Priority Score	Env. Rank	Economic Priority Score	Econ. Rank	Ranking Stability
Compliant Fuels	0.712	1	0.658	1	0.756	1	Stable
LNG	0.672	2	0.641	4	0.698	2	Moderate
Methanol	0.658	3	0.687	3	0.632	3	Stable
Ammonia	0.643	4	0.698	2	0.601	5	Variable
Shore Power	0.638	5	0.672	5	0.589	6	Moderate
Ethanol	0.612	6	0.634	6	0.605	4	Moderate
Hydrogen	0.571	7	0.612	7	0.542	7	Stable

Table 6: Vietnam maritime fuel transition roadmap (2025–2050).

Phase	Timeline	Primary Fuels	Supporting Infrastructure	Emission Reduction Target	Fleet Penetration	Cumulative Investment (USD billion)
Phase I: Foundation	2025–2030	Compliant fuels (70%), Shore power (20%), Bio-LNG pilot (10%)	Shore power at 6 major ports; LNG bunkering at 2 ports	15–20% vs. 2023 baseline	Shore power: 25% of port calls; LNG: 5% of fleet	0.8–1.0
Phase II: Transition	2031–2040	Methanol (35%), Bio-LNG (30%), Compliant fuels (25%), Shore power (10%)	Methanol bunkering at 4 ports; LNG network expansion; Pilot ammonia infrastructure	40–50% vs. 2023 baseline	Methanol: 30% of new builds; LNG: 25% of fleet	1.8–2.2
Phase III: Deep Decarbonization	2041–2050	Green ammonia (40%), E-methanol (30%), Bio-LNG (20%), Shore power (10%)	Ammonia bunkering network; Green fuel production facilities; Hydrogen pilot projects	90–100% vs. 2023 baseline (net-zero)	Ammonia: 35% of fleet; E-methanol: 25% of fleet	2.8–3.4

Table 7: Scenario analysis of emission reduction trajectories (2025–2050).

Scenario	2030 Emissions (Mt CO ₂ e)	2030 Reduction vs. 2023	2040 Emissions (Mt CO ₂ e)	2040 Reduction vs. 2023	2050 Emissions (Mt CO ₂ e)	2050 Reduction vs. 2023	Cumulative Investment (USD billion)
BAU	10.2	-14% (increase)	12.8	-43% (increase)	15.6	-74% (increase)	0.3–0.5
Moderate Transition	7.6	+15%	5.4	+40%	2.1	+77%	1.8–2.2
Accelerated Transition	7.2	+20%	4.5	+50%	0.9	+90%	2.8–3.4

Phase 1 (2025–2030) Foundation Building: Prioritize immediate emission reduction (15–20% reduction compared to 2023) through the use of low-sulfur fuels (meeting 70% of demand) and shore power for ships (20%). Conduct bio-LNG pilot projects at Hai Phong and Ho Chi Minh City ports. (Investment required: USD 0.8–1.0 billion).

Phase 2 (2031–2040) Fuel Diversification: Strong shift toward new fuels including methanol (35%) and bio-LNG (30%). Begin construction of methanol supply infrastructure at 4 major ports (Hai Phong, Ho Chi Minh City, Da Nang, Vung Tau), expand the LNG supply network to 6 ports, and pilot ammonia infrastructure in Ho Chi Minh City. Emissions will be reduced by 40–50% at this stage. (Cumulative investment: USD 1.8–2.2 billion).

Phase 3 (2041–2050) Complete decarbonization: Complete the transition to achieve net-zero emissions (90–100% reduction in emissions). The main fuel sources will be green ammonia (40%) and e-methanol (30%). This phase focuses on building large-scale green fuel production plants from offshore wind and renewable hydrogen, while also covering all major ports with ammonia supply stations (Cumulative investment: USD 2.8–3.4 billion). This USD 2.8–3.4 billion range represents direct maritime CAPEX specifically core port onshore power supply, bunkering infrastructure, and direct vessel retrofits.

Table 7 illustrates three emission reduction scenarios at three different policy levels. The BAU scenario, with conventional policies, sees the growth of maritime trade

leading to a faster increase in the number of ships than the improvement in ship efficiency, resulting in continued emissions growth of 74% by 2050. The Fuel Transition scenario, following the current policy roadmap, also fails to achieve zero emissions by 2050 (a 77% reduction). The Rapid Transition scenario, through comprehensive policy support and the adoption of alternative fuels, is expected to reduce emissions by over 90% by 2050, approaching net-zero emissions.

Table 8 presents 15 priority policy actions across the three phases, with the timeline, responsible agency, key performance indicators, and estimated budget. These actions include phased carbon pricing up to 2030 (USD 20–30/ton CO₂) and USD 80–100/ton by 2050; development and implementation of a green-shipping program with significant financial support for shipowners to transition; accelerated construction of green ports, including mandatory use of shore power and preferential port fees (30–50% reduction) for zero-emission vessels; and stronger ASEAN regional cooperation to harmonize fuel standards and cross-border refueling infrastructure.

3.2. Key Findings

The novelty of this study lies primarily in its methodology, integrated framework, and empirical approach in developing countries. Methodologically, the PLEETS framework is the first comprehensive multi-criteria assessment specifically designed for rapidly developing maritime nations like Vietnam by incorporating legal, political, and social aspects

Table 8: Policy implementation timeline and responsibility matrix.

Policy Action	Phase	Timeline	Responsible Agency	Key Performance Indicators	Estimated Budget (USD million)
1. Shore power mandate for major ports	I	2024–2026	Ministry of Construction; Port authorities	60 berths equipped by 2026	180–220
2. LNG bunkering infrastructure development	I	2025–2028	Vietnam National Oil & Gas Group; Port authorities	2 LNG bunkering facilities operational	240–280
3. Green shipping incentive program	I	2024–2030	Ministry of Finance; Maritime Administration	20% of fleet participating by 2030	150–200
4. Carbon pricing mechanism for shipping	I	2026–2030	Ministry of Finance; Ministry of Natural Resources	Carbon price: USD 20–30/ton CO ₂ by 2030	50–80 (admin)
5. Maritime workforce training program	I	2024–2030	Ministry of Construction; Maritime universities	5,000 personnel trained in alternative fuels	30–45
6. Methanol bunkering network establishment	II	2028–2035	Port authorities; Private sector	4 methanol bunkering facilities operational	320–380
7. Alternative fuel vessel subsidy program	II	2030–2040	Ministry of Finance; Development banks	30% of new builds alternative-fuel capable	400–500
8. Ammonia safety regulation framework	II	2030–2033	Maritime Administration; Ministry of Industry and Trade	Comprehensive ammonia handling regulations	15–25
9. Green fuel production incentives	II	2031–2040	Ministry of Industry and Trade; Ministry of Finance	500,000 tons/year green ammonia capacity	800–1,000
10. ASEAN maritime decarbonization cooperation	II	2030–2040	Ministry of Foreign Affairs; ASEAN Secretariat	Regional fuel standards harmonization	20–30
11. Ammonia bunkering infrastructure	III	2038–2045	Port authorities; Energy companies	6 ammonia bunkering facilities operational	650–800
12. E-methanol production facilities	III	2040–2048	Renewable energy companies; Chemical industry	300,000 tons/year e-methanol capacity	600–750
13. Zero-emission shipping zones	III	2042–2050	Ministry of Construction; Port authorities	3 zero-emission port zones established	100–150
14. Green hydrogen infrastructure pilot	III	2043–2050	Energy companies; Research institutions	50,000 tons/year green hydrogen capacity	400–500
15. Net-zero compliance verification system	III	2045–2050	Maritime Administration; Third-party verifiers	100% fleet emissions verified annually	40–60

that are lacking in multi-criteria decision analysis (MCDA) methodologies. The proposed framework incorporates six aspects and 19 criteria to comprehensively assess seven typical alternative fuels, while still considering the characteristic barriers of developing countries such as lack of investment capital, poor infrastructure, and weak governance capacity. Empirically, the proposed transition roadmap follows three stages to give developing countries a gradual approach, different from developed countries that immediately adopt hydrogen and ammonia fuels (Hansson et al. 2020, Gray et al. 2021).

To ensure the transparency of the roadmap's effectiveness, Table 9 details the emission factors and fuel consumption assumptions used to calculate the projected GHG reductions. Unlike previous studies that focused on Tank-to-Wake (TtW), this research adopts a Well-to-Wake (WtW) perspective to account for the carbon intensity of fuel production and supply

chains, aligning with the latest IMO MEPC 80 guidelines. Note that the estimated fuel consumption figures in Table 9 represent gross sector energy throughput; specific operational load factors, vessel activity scaling, and shore-power offsets are applied to derive the net scenario emissions presented in Table 7.

The financial requirements for the transition are derived from a comprehensive structural cost model. While Table 6 and Table 7 focus strictly on direct maritime CAPEX (USD 2.8–3.4 billion), Table 10 expands the system boundary to cover the total ecosystem investment (USD 3.85–4.90 billion) by incorporating upstream alternative fuel production facilities (USD 0.6–0.8 billion), soft infrastructure, R&D, digitalization, and policy implementation. This broader ecosystem scope aligns with the total aggregated policy-action budgets presented in Table 8 (USD 4.00–5.02 billion).

Phase 1 (2025–2030) Foundation Building: Prioritize immediate emission reduction (15–20% reduction compared to 2023) through the use of low-sulfur fuels (meeting 70% of demand) and shore power for ships (20%). Conduct bio-LNG pilot projects at Hai Phong and Ho Chi Minh City ports. (Investment required: USD 0.8–1.0 billion).

Phase 2 (2031–2040) Fuel Diversification: Strong shift toward new fuels including methanol (35%) and bio-LNG (30%). Begin construction of methanol supply infrastructure at 4 major ports (Hai Phong, Ho Chi Minh City, Da Nang, Vung Tau), expand the LNG supply network to 6 ports, and pilot ammonia infrastructure in Ho Chi Minh City. Emissions will be reduced by 40–50% at this stage. (Cumulative investment: USD 1.8–2.2 billion).

Phase 3 (2041–2050) Complete decarbonization: Complete the transition to achieve net-zero emissions (90–100% reduction in emissions). The main fuel sources will be green ammonia (40%) and e-methanol (30%). This phase focuses on building large-scale green fuel

production plants from offshore wind and renewable hydrogen, while also covering all major ports with ammonia supply stations. (Cumulative investment: USD 2.8–3.4 billion).

Given the unique characteristics of a rapidly developing country like Vietnam, the 2025–2030 period requires policies and actions to support the rapid development of infrastructure and improve the quality of the shipping fleet. The choice of methanol over LNG is consistent with existing energy security and infrastructure. Meanwhile, hydrogen still carries many technological risks, and its price is still subject to market fluctuations; therefore, its adoption is postponed to the 2041–2050 period. According to the proposed roadmap, the necessary investment capital accounts for approximately 0.7–0.9% of Vietnam's projected GDP for the 2024–2050 period. This investment level falls within the decarbonization investment limits for the maritime sector in developed countries (0.6–1.2%) (OECD 2022). This demonstrates political will, showing that despite financial and infrastructure limitations, with the support of the international community, this is entirely feasible.

Table 9: Emission calculation parameters and reduction projections (well-to-wake boundary).

Fuel Type	Emission Factor (WtW) (g CO _{2e} g ⁻¹ fuel)	Estimated Consumption 2030 (Mt)	Estimated Consumption 2050 (Mt)	WtW Reduction per Unit (%)
VLSFO/MGO (Baseline)	3.15–3.50	2.50–3.00	0.45	0%
LNG (Fossil)	2.70–2.90	0.85	0.20	15–20%
Bio-LNG	0.50–1.20	0.15	1.10	70–85%
E-Methanol	0.20–0.80	0.10	1.50	80–95%
Green Ammonia	0.10–0.50	0.02	2.10	90–100%
Green Hydrogen	0.05–0.40	0.01	0.80	95–100%

Table 10: Estimated investment breakdown for Vietnam's maritime fuel transition (2025–2050).

Investment Category	Estimated Cost (USD billion)	Key Infrastructure & Unit Cost Assumptions	Primary Funding Sources
Port Infrastructure	1.2–1.5	- LNG bunkering hubs (USD 80–120 million per port). - Shore power (OPS) systems (USD 2–5 million per berth). - Ammonia/Methanol storage tanks.	Public-Private Partnership (PPP), Port Authorities
Vessel Retrofitting & Newbuilds	1.8–2.2	- Retrofitting engines for Dual-fuel (USD 2–4 million per ship). - Premium for new green vessels (20–30% higher capital expenditure (CAPEX)). - Scrubbers & Energy Saving Devices (ESD).	Shipowners, Green Credit, Commercial Banks
Fuel Supply Chain & Production	0.6–0.8	- Pilot green hydrogen/ammonia production plants. - Supply chain logistics and distribution fleet.	Energy companies, foreign direct investment (FDI), government subsidies
R&D, Digitalization & Training	0.2–0.3	- Maritime enterprise resource planning (ERP) and artificial intelligence (AI) for route optimization. - Seafarer training for hazardous fuel handling. - Living Lab models at major ports.	State Budget, University Research Grants
Policy & Regulatory Framework	0.05–0.1	- Development of safety standards and carbon tax systems. - International consultancy and certification.	Official Development Assistance (ODA), State Budget
Total Estimated	3.85–4.9	Cumulative investment through 2050	

3.3. Policy Implications

Based on the analysis results, five key policy priorities are proposed as follows:

First, establish a carbon pricing mechanism aligned with the general trend of the maritime industry (carbon price at USD 20–30/ton CO₂ by 2030 and USD 80–100/ton by 2050). This will promote the green transition as the cost of traditional fuels will gradually increase while the cost of green fuels will gradually decrease.

Second, implement green port standards nationwide, tailored to each specific port over time. Prioritize the construction of deep-sea ports according to global green standards.

Third, there is a shortage of approximately 5,000–7,000 maritime workers in the fields of green fuel bunkering, safety management, and operation of ships and green ports. Vietnam needs to enact policies to support the development of green maritime training programs at all levels.

Fourth, Vietnam needs to strengthen cooperation with neighboring countries and the ASEAN region in the production and distribution of alternative fuels under a program aimed at harmonizing fuel standards, fuel production, and a common green fuel supply chain for the ASEAN region.

Fifth, engage in extensive international advocacy and cooperation to mobilize financing for Vietnam's maritime decarbonization program. It is necessary to prepare key projects, enhance institutional capacity and monitoring frameworks to access resources such as climate change programs aligned with the Sustainable Development Goals (SDGs 7, 9, 13, 14), support from COP, the Asian Development Bank, the Green Climate Fund, etc.

3.4. Limitations and Future Research

Although this study provides a very comprehensive fuel transition roadmap for the Vietnamese maritime industry, it still has some limitations. First, the PLEETS framework for decision-making is inevitably subjective because the weighted results are based on expert surveys. Second, the dependence on fuel forecasts is highly uncertain, meaning the techno-economic model may change. Third, the study only assesses representative infrastructure (the 6 largest ports) and does not evaluate the entire port system, including auxiliary ports and regional connections. Finally, the proposed roadmap is based on the assumption of continuous progress in green fuel technology and supply-chain development, with associated cost reductions.

The authors' next research directions will focus on developing specific roadmaps for each vessel type because of

differences in operational characteristics among bulk carriers, container ships, and oil tankers; assessing the production capacity and development of green fuel supply chains; and researching the application of artificial intelligence (AI), the Internet of Things (IoT), and blockchain to optimize the fuel supply chain and monitor emissions.

4. CONCLUSIONS

Through the systematic application of the PLEETS framework to support data-driven decision-making in Vietnam's maritime industry and consultation with 127 experts, the study proposes a fuel transition roadmap for Vietnam's maritime industry by 2050, aligned with IMO targets. Accordingly, Vietnam could achieve a reduction of over 90% in emissions by 2050 in three phases.

The immediate phase (2025–2030) focuses on building a basic foundation, such as deploying onshore power generation and providing and using appropriate fuels, to achieve a 15–20% emission reduction target with an estimated investment of USD 0.8–1.0 billion. During the period 2031–2040, Vietnam prioritizes the use of methanol and bio-LNG to achieve a 40–50% reduction in emissions. In the final phase (2041–2050), aiming for net-zero emissions, Vietnam will utilize green ammonia and e-methanol (total investment of approximately USD 2.8–3.4 billion).

To achieve the net emission reduction target by 2050, Vietnam needs to enact specific policies and action plans for each stage regarding carbon pricing for ships and ports, encourage the conversion of low- and zero-emission vessels, build green maritime infrastructure along with new and supplementary training for maritime personnel with green and digital skills, and foster extensive cooperation on the production and bunkering of green marine fuels within the ASEAN region. Vietnam should proactively explore access to green international financing through the Sustainable Development Goals (SDGs 7, 9, 13, 14), support from countries committed at COP, the Asian Development Bank, and the Green Climate Fund.

The proposed roadmap serves as a foundation for implementing Vietnam's strong commitments at COP26 and fulfilling its obligations as a member state under Annex VI, MARPOL 73/78. The findings of this study can be replicated and used as a foundation for developing fuel transition roadmaps for the maritime industry in countries with similar conditions.

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