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Original Research

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

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ABSTRACT

With the International Maritime Organization (IMO) Strategy 2023 to reduce ship emissions to net zero 2050, ship owners or/and operators are looking for effective economic solutions to meet the latest emission requirements. The initial cost of changeover and using new fuels can be too high, which is a big 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 quantitative analysis of Vietnamese fleet data, assessment of major port infrastructure, surveys of 127 vessels, and economic-technical modeling, seven alternative fuels are considered: compliant fuels, 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 US$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 US$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 US$2.8-3.4 billion. This roadmap is based on evidence supporting 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 a developing nation context.

1. INTRODUCTION

The maritime sector assumes a pivotal position in the evolution of the global economy, offering substantial advantages concerning both the volume and distance of transportation. With the aggregate of the world's commercial fleet reaching 108,789 vessels and a total tonnage of 1.92 billion, specifically 2,353,899 thousand deadweight tons, maritime transport has emerged as the predominant mode of transportation, representing over 80% of global trade by volume, projected to be 12.3 million tons in 2024 (UNCTAD, 2024). The maritime industry currently accounts for approximately 3% of total global greenhouse gas (GHG) emissions, contributing significantly to environmental pollution (Alamoush and Ölçer, 2025; Lian et al., 2020). According to the IMO's Third Greenhouse Gas Study (Smith, T., et al., 2014), CO2 emissions from the international commercial shipping fleet increased from 848 million to 919 million tonnes 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 oxide (SOx) and 13% of global nitrogen oxide (NOx) emissions (Bolat, 2026; Smith, T., et al., 2014 ,IMO, 2020; Perera & Soares, 2017). In line with the goals of COP26, the IMO GHG Strategy 2023 was created with the overarching goal of achieving carbon neutrality before 2050 (IMO, 2018 and 2023). To implement this goal, the IMO issued tools and implementation guidelines such as EEDI, EEXI, EEOI, and 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 pertaining to the introduction of alternative green fuels as well as overall emission reduction, which is to say, the indicative benchmarks established. These benchmarks were designated for a 20–30% reduction by the year 2030 and a 70–80% reduction by the year 2040, respectively.

The IMO GHG 2023 requires shipowners and operators to plan for compliance with the emission reduction requirements of the Carbon Intensity Indicator (CII), moving towards operating low- and zero-emission ships. There are several options (Cortez-Huerta et al., 2024; Premsamarn et al., 2025; Wang and Iris, 2025) for fuel suppliers and users regarding compliant fuels such as using fossil fuels such as HFO and on-board exhaust gas cleaning systems/scrubbers, LSFO+MGO, liquefied natural gas (LNG, CNG), methanol, ethanol, or biofuels such as bio-LNG, bio-MGO, and e-LNG, e-MGO; or using green fuels such as green hydrogen, green ammonia; or electricity from the grid. A ship's fuel consumption can account for more than 50% of its operating costs. With increasingly strict requirements for the shipping industry, the incentives for ship owners/operators are not only environmental but also efficient operation and economic of the ship. This paper will consider the options, including fossil fuels combined scrubber, biofuels, green fuel, electricity from the grid. The results of this study will help ship owners/operators make adaptation decisions in the short-term 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 Vietnamese shipping fleet is 15.5 years old, 6 years younger than the world's fleet. The crew 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, which 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 is estimated to be 29.9 million TEUs, up 21% from the same period in 2023, according to Figure 1. An estimated 102.67 thousand ships are expected to sail through the ports in 2024, up 2% over the same time in 2023. An anticipated 380.1 thousand inland waterway vehicles will pass through the harbor in 2024, an 8% increase over the same period in 2023.

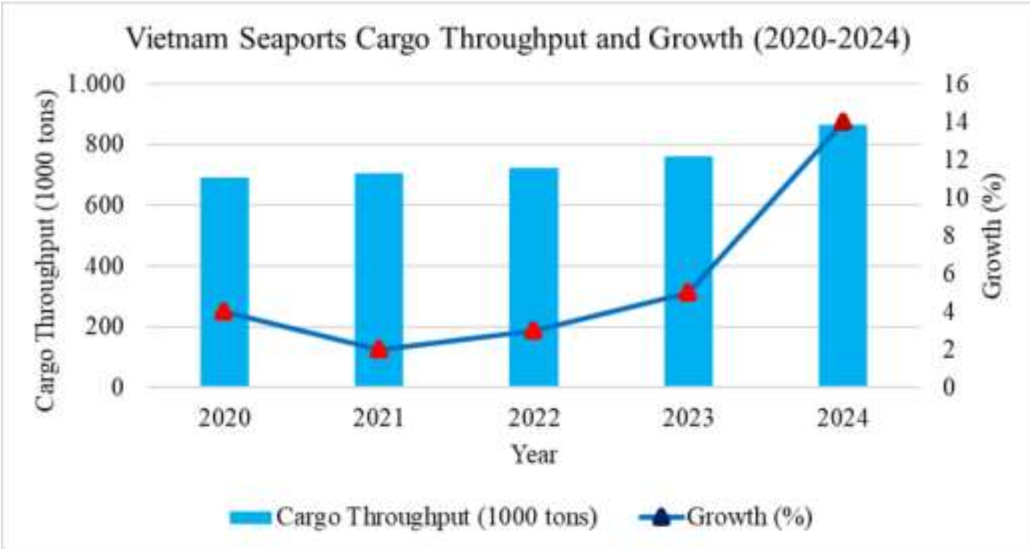

Fig.1 Cargo throughput and Growth of Vietnam seaports (Source: Vietnam Maritime and Waterway Administration (2025)).

The world's largest container ship, with a tonnage of 232,000 DWT, 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 com-pliance with the 2023 IMO GHG Strategy emission reduction regulation for their existing vessels as well as their plans for new vessels to operate. Therefore, it is necessary to analyze the advantages and disad-vantages 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 GHG strategy 2023 sets a target of net-zero emissions by around 2050, with in-terim goals of decreasing GHG emissions by 20–30% by 2030 and 70–80% by 2040, based on 2008 levels (see Figure 2). It also aims for a minimum 5% uptake of zero/near-zero emission fuels or tech-nologies by 2030. The appli-cation of well-to-wake fuel emission control is a significant new step for-ward, contributing to a fair and equi-table fuel transition. Industry- and vessel-specific emission reduc-tion 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 pro-ducers 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 towards technically viable green technologies (Barone et al. 2024, Balci et al., 2024; Cuong & Hung, 2020b; Nguyen, 2016).

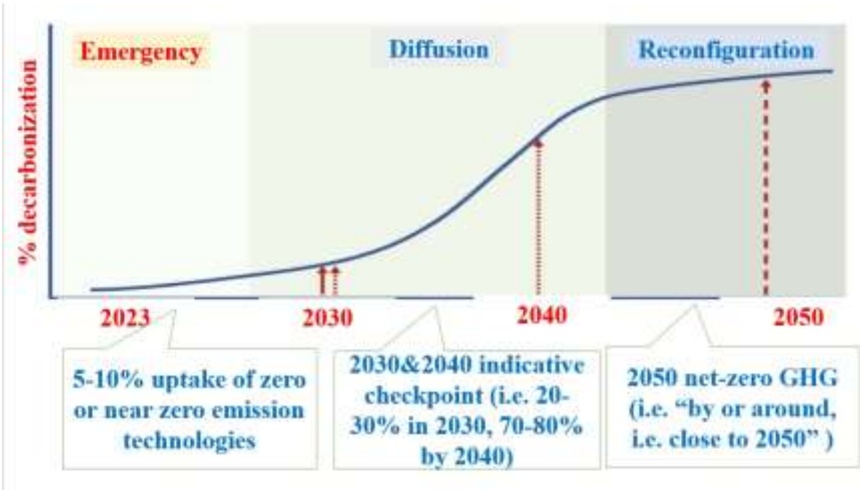

Fig. 2 The 2023 IMO GHG Strategy.

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, 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 towards large-scale zero-emission solutions focusing on green hydrogen, green ammonia, and green methanol, 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, 2020; Achuo et al., 2022; Atilhan et al., 2021; Dnv, 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 towards 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 towards 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, 2020, 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 socio-political-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 and 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 will focus on addressing these knowledge gaps.

2.2. Research Design and Data Collection

This study employed a qualitative analysis method combined with expert consultation and infrastructure assessment. 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 VIMAWA. Emissions from vessels were calculated using the methodology of the Fourth IMO Greenhouse Gas Study (IMO, 2020).

Surveys (assessed fuel preferences, infrastructure constraints, investment capacity, and policy priorities) were conducted with 127 participants 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.

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

2.3. PLEETS Framework Implementation

This study 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 (Table 1, Table 2).

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	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
Sociological 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 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	SOx, NOx, 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	TRL level, 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
Sociological (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.

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.

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

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 bioethanol and electronic methanol production pathways), (4) ethanol (bioethanol), (5) ammonia (grey, 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, LCA data, and a Vietnam-specific feasibility assessment including differences in production 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).

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

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 Status as It Is (BAU), Moderate Transition, and Rapid Transition scenarios. The roadmap, in three phases (2030, 2040, 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

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.

As shown in Appendix A, 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 shown in parentheses; Scores normalized 0-1 scale (higher is better)

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

Legal Aspects: Compliant fuels have met IMO requirements and therefore have the highest weighting of 0.91. Second is LNG with a weighting 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 weightings of 0.72 and 0.68 respectively. Ammonia has a weighting of 0.65 and hydrogen 0.58, representing risks due to legal loopholes in production, storage, transportation, and bunkering.

Economics: First place goes to Compliant Fuels with a weight of 0.78, representing the lowest fuel cost. Second place goes to LNG with a weight 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 weights of 0.58 and 0.54 respectively. Finally, Ammonia and Hydrogen are ranked last, representing high fuel production investment costs, significant infrastructure and vehicle gaps, and high supply market risks, with weights of 0.52 and 0.41 respectively.

Environment: First place goes to onshore electricity with a weight of 0.89, followed by hydrogen with a weight of 0.86. These are two solutions with zero emissions when ships are docked in port. Third place goes to green ammonia, which can reduce greenhouse gas emissions by 95%, with a weight of 0.82. Methanol and bioethanol, developed in a bio-oriented direction, can reduce emissions by 60-80% (weights of 0.71 and 0.68 respectively). LNG (0.58) emits methane, so it only reduces emissions by 20-25%. Regulated fuel (with a weight of 0.42) meets minimum requirements.

Technology: The most mature technology belongs to Regulated Fuels, with a weight of 0.89. Fuels with readily available technology are LNG (0.74) and onshore electricity (0.72). Methanol-related technology can inherit from 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 and storage technology and ship fuel distribution systems for hydrogen give it the lowest weight (0.48).

Social: The port community strongly supports the use of onshore electricity, so this solution has the highest weight (0.71). Following closely are Compliant Fuels, LNG, methanol, and ethanol with medium impact. 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 (0.689) 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.

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

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 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

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 onshore power generation for ships (20%). Conduct Bio-LNG pilot projects at Hai Phong and Ho Chi Minh City ports. (Investment required: US$0.8 - US$1 billion).

Phase 2 (2031-2040) Fuel Diversification: Strong shift towards 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: US$1.8 - US$2.2 billion).

Phase 3 (2041-2050) Complete decarbonization: Complete transition to achieve Net-zero (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: US$2.8 - US$3.4 billion).

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 7: Scenario Analysis Emission Reduction Trajectories (2025-2050)

Scenario	**2030 Emissions (Mt CO_2eq)**	**2030 Reduction vs. 2023**	**2040 Emissions (Mt CO_2eq)**	**2040 Reduction vs. 2023**	**2050 Emissions (Mt CO_2eq)**	**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

Detailed by three phases, 15 priority policy actions forming a comprehensive framework have been proposed in Table 8 according to Timeline, Responsible Agency, Key Performance Indicators, and Estimated Budget. Carbon pricing is a global trend being applied in stages up to 2030 (US$20-30/ton CO_2) and US$80-100/ton by 2050; developing and implementing a program to encourage green shipping with significant financial support for shipowners to switch; accelerating the construction of green ports, including policies such as mandatory use of onshore electricity, preferential port fees (30-50% reduction) for zero-emission vessels; strengthening ASEAN regional cooperation to harmonize fuel standards and cross-border refueling infrastructure.

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

4. DISCUSSION

4.1. 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 that are lacking in MCDA methodologies. The proposed framework five aspects with 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 which 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.

Table 9: Emission Calculation Parameters and Reduction Projections (Well-to-Wake boundary)

Fuel Type	Emission Factor (WtW) (gCO2e/gFuel)	Estimated Consumption 2030 (Mt)	Estimated Consumption 2050 (Mt)	WtW Reduction per Unit (%)
VLSFO/MGO (Baseline)	3.15 - 3.50	4.20	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%

The financial requirements for the transition are not merely asserted but are derived from a structural cost model. Table 10 provides a detailed breakdown of these estimates, categorizing investment needs across infrastructure, fleet adaptation, and capacity building.

Table 10: Estimated Investment Breakdown for Vietnam's Maritime Fuel Transition (2025–2050)

Investment Category	Estimated Cost (Billion USD)	Key Infrastructure & Unit Cost Assumptions	Primary Funding Sources

Port Infrastructure	1.2 – 1.5	- LNG bunkering hubs ($80-120M per port). - Shore power (OPS) systems ($2-5M per berth). - Ammonia/Methanol storage tanks.	Public-Private Partnership (PPP), Port Authorities
Vessel Retrofitting & Newbuilds	1.8 – 2.2	- Retrofitting engines for Dual-fuel ($2-4M/ship). - Premium for new green vessels (20-30% higher 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, FDI, Government Subsidies
R&D, Digitalization & Training	0.2 – 0.3	- Maritime ERP & 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	

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 onshore power generation for ships (20%). Conduct Bio-LNG pilot projects at Hai Phong and Ho Chi Minh City ports. (Investment required: US$0.8 - US$1 billion).

Phase 2 (2031-2040) Fuel Diversification: Strong shift towards 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: US$1.8 - US$2.2 billion).

Phase 3 (2041-2050) Complete decarbonization: Complete transition to achieve Net-zero (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: US$2.8 - US$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, thus 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.

4.2. 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 US$20-30/ton CO_2 by 2030 and US$80-100/ton by 2050). This will promote 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.

4.3. Limitations and Future Research

Although this study provides a very comprehensive fuel transition roadmap for the Vietnamese maritime industry, it still has some limitations. Firstly, the PLEETS framework for decision-making is inevitably subjective because the weighted results are based on expert surveys. Secondly, the dependence on fuel forecasts is highly uncertain, meaning the technical-economic model may change. Thirdly, the study only assesses representative infrastructure (the 6 largest ports) and does not evaluate the entire port system in general, 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, reducing costs.

The authors' next research directions will focus on: Developing specific roadmaps for each type of vessel due to differences in operational characteristics such as bulk carriers, container ships, and oil tankers. Assessing the production capacity and development of green fuel supply chains. Research on the application of AI, IoT, and Blockchain to optimize the fuel supply chain and monitor emissions.

5. 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 US$0.8-1.0 billion. During the period 2031-2040, Vietnam prioritizes the use of methanol and LNG biogas 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 electrochemical methanol (total investment of approximately US$2.8 to US$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. It 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.

6. PATENTS

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REFERENCES

1. Achuo, E.D., Miamo, C.W., Nchofoung, T.N., 2022. Energy consumption and environmental sustainability: What lessons for posterity? Energy Rep. 8, 12491–12502. https://doi.org/10.1016/j.egyr.2022.09.033
2. Al-Aboosi, F.Y., El-Halwagi, M.M., Moore, M., Nielsen, R.B., 2021. Renewable ammonia as an alternative fuel for the shipping industry. Curr. Opin. Chem. Eng. 31, 100670. https://doi.org/10.1016/j.coche.2021.100670
3. Alamoush, A.S., Ölçer, A.I., 2025. Harnessing cutting-edge technologies for sustainable future shipping: An overview of innovations, drivers, barriers, and opportunities. Marit. Technol. Res. 7, 277313–277313. https://doi.org/10.33175/mtr.2025.277313
4. Atilhan, S., Park, S., El-Halwagi, M.M., Atilhan, M., Moore, M., Nielsen, R.B., 2021. Green hydrogen as an alternative fuel for the shipping industry. Curr. Opin. Chem. Eng. 31, 100668. https://doi.org/10.1016/j.coche.2020.100668
5. Balci, G., Phan, T.T.N., Surucu-Balci, E., Iris, Ç., 2024. A roadmap to alternative fuels for decarbonising shipping: The case of green ammonia. Res. Transp. Bus. Manag. 53, 101100. https://doi.org/10.1016/j.rtbm.2024.101100
6. Barone, G., Buonomano, A., Del Papa, G., Maka, R., Palombo, A., 2024. Approaching zero emissions in ports: implementation of batteries and supercapacitors with smart energy management in hybrid ships. Energy Convers. Manag. 314, 118446. https://doi.org/10.1016/j.enconman.2024.118446

7. Bolat, F., 2026. Time series modeling of greenhouse gas emissions: A case study for a chemical tanker ship. Marit. Technol. Res. 8, 278949–278949. https://doi.org/10.33175/mtr.2026.278949
8. Cameretti, M.C., De Robbio, R., Palomba, M., Zucareli de Souza, T., 2025. Strategies to improve ammonia combustion in a dual fuel marine engine by using CFD. Fuel 381, 133440. https://doi.org/10.1016/j.fuel.2024.133440
9. Cortez-Huerta, M., Sosa Echeverría, R., Fuentes García, G., Antonio Durán, R.E., Ramírez-Macías, J.I., Kahl, J.DW., 2024. High-resolution atmospheric emissions estimate from dredging activities during port expansion in Veracruz, Mexico. Ocean Eng. 310, 118621. https://doi.org/10.1016/j.oceaneng.2024.118621
10. Cuong, N.M., Hung, P.V., 2020a. Sea navigation-based Thai Canal implication: an analysis of its effect on the Vietnamese maritime industry. Aust. J. Marit. Ocean Aff. 12, 83–94. https://doi.org/10.1080/18366503.2020.1764174
11. Cuong, N.M., Hung, P.V., 2020b. An analysis of available solutions for commercial vessels to comply with IMO strategy on low sulphur. J. Int. Marit. Saf. Environ. Aff. Shipp. 4, 40–47. https://doi.org/10.1080/25725084.2020.1784080
12. Dnv, G.L., 2020. Energy transition outlook 2020: maritime forecast to 2050. Available Here Httpseto Dnvgl Com2020index Html Footer Accessed 5, 2021.
13. Ha, S., Park, C., Jang, H., Jeong, B., Hwang, I., 2025. Developing a framework for effective accounting GHG emissions from international shipping for sustainable marine fuel and onboard carbon capture: Case study of methanol. Sustain. Prod. Consum. 56, 263–283. https://doi.org/10.1016/j.spc.2025.03.024
14. Halpe, P., Adams, M., Walker, T.R., 2025. Challenges and opportunities for ports in achieving net-zero emissions in maritime transport. Transp. Res. Interdiscip. Perspect. 30, 101379. https://doi.org/10.1016/j.trip.2025.101379
15. IMO, 2023. Status of conventions. Available from: http://www.imo.org/en/About/C onventions/StatusOfConventions/Pages/Default.aspx.
16. IMO, 2020. Fourth Greenhouse Gas Study 2020 [WWW Document]. URL https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx (accessed 7.26.21).
17. IMO, 2018. Initial IMO GHG Strategy [WWW Document]. URL https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx (accessed 7.26.21).
18. Karvounis, P., Theotokatos, G., 2025. Performance improvement and emissions reduction of methanol fuelled marine dual-fuel engine with variable compression ratio. Fuel Process. Technol. 272, 108208. https://doi.org/10.1016/j.fuproc.2025.108208
19. Lian, F., He, Y., Yang, Z., 2020. Competitiveness of the China-Europe Railway Express and liner shipping under the enforced sulfur emission control convention. Transp. Res. Part E Logist. Transp. Rev. 135, 101861. https://doi.org/10.1016/j.tre.2020.101861
20. Nguyen, T.T., 2016. An Investigation of the Vietnamese Shipping Industry and Policy Recommendations for Profound Participation into ASEAN Integration. Asian J. Shipp. Logist. 32, 81–88. https://doi.org/10.1016/j.ajsl.2016.05.001
21. Ortiz-Imedio, R., Caglayan, D.G., Ortiz, A., Heinrichs, H., Robinius, M., Stolten, D., Ortiz, I., 2021. Power-to-Ships: Future electricity and hydrogen demands for shipping on the Atlantic coast of Europe in 2050. Energy 228, 120660. https://doi.org/10.1016/j.energy.2021.120660
22. Park, T., So, S., Jeong, B., Zhou, P., Lee, J., 2021. Life cycle assessment for enhanced Re-liquefaction systems applied to LNG carriers; effectiveness of partial Re-liquefaction system. J. Clean. Prod. 285, 124832. https://doi.org/10.1016/j.jclepro.2020.124832

23. Perera, L.P., Soares, C.G., 2017. Weather routing and safe ship handling in the future of shipping. Ocean Eng. 130, 684–695. https://doi.org/10.1016/j.oceaneng.2016.09.007
24. Premsamarn, P., Win, T.K., Watanabe, D., 2025. Assessing the impact of emission control areas policy on ship emissions in the Gulf of Thailand using AIS data. Marit. Technol. Res. 7, 275311–275311. https://doi.org/10.33175/mtr.2025.275311
25. Smith, T., nderson, B., Corbett, J., Faber, J., Hanayama, S., O'Keefe, E., Parker, S., Johansson, L., Aldous, L., Raucci, C., Traut, M., Ettinger, S., Nelissen, D., Lee, D., Ng, S., Agarwal, A., Winebrake, J., Hoen, M.,, Chesworth, S., et al., 2014. Third IMO GHG Study 2014 [WWW Document]. URL https://www.imo.org/en/OurWork/Environment/Pages/Greenhouse-Gas-Studies-2014.aspx (accessed 7.28.21).
26. Sun, L., Zhang, Y., Ma, F., Ji, F., Xiong, Y., 2023. Energy and speed optimization of inland battery-powered ship with considering the dynamic electricity price and complex navigational environment. Energy Rep., 2022 The 3rd International Conference on Power Engineering 9, 293–304. https://doi.org/10.1016/j.egyr.2023.04.267
27. UNCTAD, 2024. Statistics | Unctad [WWW Document]. URL https://unctad.org/statistics (accessed 7.27.21).
28. Wang, Y., Iris, Ç., 2025. Transition to near-zero emission shipping fleet powered by alternative fuels under uncertainty. Transp. Res. Part Transp. Environ. 142, 104689. https://doi.org/10.1016/j.trd.2025.104689