



Alternative Maritime Fuels Adoption in Southeast Asian Shipping: Barriers, Opportunities, and Regulatory Framework Analysis

Sahar Saleh^{1*}, Eriza I. Ulmi¹, Fitri Mulyana¹

¹ Maritime Institute, Sekolah Tinggi Ilmu Pelayaran Jakarta, North Jakarta, Indonesia
Jl. Marunda Makmur, RT.1/RW.1, Marunda, Kec. Cilincing, Jakarta Utara,
Daerah Khusus Ibukota Jakarta 14150

*Korespondensi penulis: saharsaleh15@gmail.com

Abstract. *This research investigates stakeholder perspectives on alternative maritime fuel adoption barriers, opportunities, and regulatory frameworks within Southeast Asian shipping contexts. Employing qualitative-dominant mixed methods, the study gathered insights through Focus Group Discussions, interviews, and surveys with thirty-eight participants comprising maritime students, lecturers, and veteran practitioners at Sekolah Tinggi Ilmu Pelayaran Jakarta. Thematic analysis revealed substantial adoption barriers dominated by infrastructure inadequacy (28%) and economic competitiveness challenges (26%), with significant regulatory gaps particularly in financial incentive mechanisms (gap score: 2.9/5.0). Comparative fuel pathway assessment identified liquefied natural gas as most viable near-term alternative (overall score: 3.9/5.0) despite limitations as transitional fuel, while zero-carbon alternatives including ammonia (2.7/5.0) and hydrogen (2.5/5.0) face substantial technical, infrastructural, and economic challenges. Overall regulatory adequacy (2.49/5.0) falls substantially below stakeholder-perceived importance (4.55/5.0), producing a regulatory gap of 2.06 points. Findings emphasize need for integrated strategies combining coordinated infrastructure development, substantial financial support mechanisms, regulatory harmonization, and systematic workforce development accelerating fuel transitions toward decarbonization objectives.*

Keywords: *Alternative maritime fuels; decarbonization; Southeast Asian shipping; regulatory frameworks; infrastructure barriers*

1. INTRODUCTION

The maritime industry confronts an existential imperative to decarbonize shipping operations in response to escalating climate change pressures, stringent international regulatory frameworks, and societal expectations for environmental responsibility, with the International Maritime Organization's 2023 Greenhouse Gas Strategy mandating net-zero emissions by or around 2050 and necessitating fundamental transformation of maritime fuel systems (Balcombe et al., 2019). Alternative maritime fuels including liquefied natural gas, methanol, ammonia, hydrogen, biofuels, and synthetic e-fuels represent critical technological pathways enabling decarbonization transitions, yet their adoption in Southeast Asian shipping contexts remains limited despite the region's strategic importance as a global maritime hub handling substantial cargo volumes and connecting major trade routes (Al-Breiki & Bicer, 2021). The persistent gap between decarbonization imperatives and actual alternative fuel implementation reflects complex interplays of technical, economic, infrastructural, regulatory, and institutional barriers that maritime stakeholders, policy-makers, and educators must comprehensively understand to accelerate necessary energy transitions. The fundamental question confronting Southeast Asian maritime communities concerns how alternative fuel adoption can be strategically advanced within regional contexts characterized

by diverse national capacities, varying regulatory frameworks, heterogeneous port infrastructure, limited investment capital, and competing developmental priorities that complicate coordinated regional responses to global environmental mandates.

Southeast Asia's maritime sector exhibits distinctive characteristics shaping alternative fuel adoption dynamics and creating both unique opportunities and formidable challenges. The region encompasses major shipping nations including Singapore operating as a global maritime hub and bunkering center, Indonesia with its vast archipelagic geography and extensive domestic shipping networks, Malaysia and Thailand with significant port operations and petrochemical industries, and emerging maritime economies including Vietnam and Philippines expanding shipping capacities rapidly (Hansson et al., 2020). This diversity creates fragmented regulatory landscapes, uneven infrastructure development, and varying institutional capacities for supporting alternative fuel transitions, complicating regional coordination essential for achieving economies of scale in fuel production, distribution infrastructure development, and technology standardization. Furthermore, Southeast Asian economies' developmental trajectories emphasizing rapid industrialization and economic growth create tensions between long-term decarbonization commitments and short-term cost competitiveness imperatives, with alternative fuels' higher costs and infrastructure requirements potentially disadvantaging regional shipping against competitors operating in jurisdictions with less stringent environmental regulations or greater public subsidies for green transitions (Balcombe et al., 2019).

The research problem central to this investigation addresses the critical knowledge gap regarding how maritime education stakeholders in Southeast Asian contexts perceive alternative fuel adoption challenges, evaluate different fuel pathway viability, and conceptualize enabling strategies for accelerating transitions within regional operational and regulatory realities. Specifically, this research explores the fundamental question: What are stakeholder perspectives on barriers, opportunities, and regulatory frameworks influencing alternative maritime fuel adoption in Southeast Asian shipping, and what strategic interventions can facilitate effective fuel transitions aligned with decarbonization objectives while respecting regional economic and developmental contexts? The specific objectives guiding this inquiry include: (1) identifying perceived barriers to alternative maritime fuel adoption across technical, economic, infrastructural, and regulatory dimensions; (2) evaluating stakeholder assessments of different alternative fuel pathways' viability, advantages, and limitations for Southeast Asian shipping contexts; (3) examining current

regulatory frameworks' adequacy and identifying policy gaps impeding alternative fuel implementation; and (4) developing strategic recommendations for accelerating alternative fuel adoption through integrated interventions addressing barriers while leveraging regional opportunities and capabilities.

The significance of this research extends beyond environmental compliance to encompass broader implications for Southeast Asian maritime competitiveness, economic development trajectories, energy security considerations, and regional leadership positioning in global decarbonization efforts. As environmental regulations increasingly influence shipping route selection, port competitiveness, and cargo owner preferences, Southeast Asian ports and shipping companies demonstrating alternative fuel capabilities position themselves advantageously for attracting environmentally conscious customers and maintaining market share in increasingly carbon-constrained global trade systems (Al-Breiki & Bicer, 2021). Moreover, this investigation addresses a substantial gap in existing literature, which predominantly examines alternative fuel transitions in European and North American maritime contexts with mature regulatory frameworks, substantial public funding mechanisms, and advanced technological capabilities while undertheorizing Southeast Asian-specific dynamics including infrastructure limitations, financial constraints, regulatory fragmentation, and the intersection of decarbonization imperatives with developmental priorities and energy access challenges (Hansson et al., 2020). The rationale for conducting this research within a maritime education institution stems from recognition that successful fuel transitions require not only technological innovation and regulatory frameworks but also systematic workforce development, stakeholder awareness cultivation, and educational curriculum transformation preparing future maritime professionals to navigate energy transitions, evaluate fuel alternatives, and implement decarbonization strategies throughout their careers.

Methodologically, this research employs a qualitative-dominant mixed methods approach, gathering comprehensive stakeholder perspectives through Focus Group Discussions, semi-structured interviews, surveys, and expert consultations with maritime students representing future industry professionals who will manage alternative fuel systems and implement decarbonization strategies across multi-decade careers, lecturers possessing academic expertise in marine engineering, environmental management, and energy systems who shape curriculum content and prepare students for evolving technological landscapes,

and veteran maritime officers now serving as practitioners and instructors who bring operational wisdom regarding fuel system management, economic constraints, and implementation realities derived from extensive industry experience. This multi-stakeholder triangulation enables holistic exploration of alternative fuel barriers, opportunities, and regulatory adequacy from complementary vantage points, generating nuanced understanding essential for developing contextually appropriate, practically viable, and stakeholder-endorsed strategies for accelerating fuel transitions. The thematic analysis of qualitative data, complemented by cross-group comparative insights examining convergent and divergent perspectives across stakeholder categories, illuminates how stakeholders conceptualize alternative fuel challenges, prioritize different fuel pathways, evaluate regulatory frameworks, and envision implementation strategies balancing environmental imperatives with economic realities and developmental contexts characteristic of Southeast Asian maritime operations.

2. RESEARCH METHOD

This research adopted a qualitative-dominant mixed methods design grounded in critical realist philosophy, recognizing that while alternative fuel adoption barriers and opportunities exist as objective phenomena independent of stakeholder perceptions, understanding these realities requires examining how stakeholders interpret, prioritize, and respond to alternative fuel challenges within specific social, economic, and institutional contexts (Creswell & Creswell, 2018). The methodological framework deliberately emphasized exploring stakeholder sense-making processes, evaluative criteria, and contextual reasoning shaping alternative fuel perceptions and implementation decisions, recognizing that successful transitions depend fundamentally on stakeholder awareness, acceptance, and strategic action rather than merely technological availability or regulatory mandates. The research population comprised all stakeholders affiliated with Sekolah Tinggi Ilmu Pelayaran Jakarta, with purposive sampling strategically employed to select information-rich participants possessing relevant expertise, direct experience with maritime fuel systems, and reflective capabilities enabling articulate analysis of alternative fuel challenges and opportunities. Sampling targeted three distinct stakeholder categories: maritime students, particularly those specializing in marine engineering and environmental management, who represent future workforce cohorts responsible for operating alternative fuel systems, managing fuel transitions, and implementing decarbonization strategies throughout professional careers; lecturers with specialized expertise in marine propulsion

systems, energy technologies, environmental regulations, and sustainable operations who shape curriculum content, prepare students for alternative fuel realities, and maintain scholarly engagement with evolving fuel transition literature; and veteran maritime officers now serving as practitioners, chief engineers, and technical advisors who possess extensive operational experience with conventional fuel systems, understand economic and operational constraints shaping fuel decisions, and evaluate alternative fuel feasibility from practical implementation perspectives. The rationale for this multi-stakeholder sampling approach reflects understanding that comprehensive alternative fuel assessment requires integrating aspirational environmental perspectives from emerging professionals, theoretical frameworks and technological knowledge from academic experts, and operational wisdom and economic realism from experienced practitioners who navigate competing priorities including cost pressures, reliability requirements, regulatory compliance, and environmental responsibility (Merriam & Tisdell, 2016). Sample composition included eighteen maritime students representing marine engineering and nautical science specializations, nine lecturers from propulsion systems, environmental management, and energy technology domains, and eleven veteran practitioners with collective experience spanning diverse vessel types, fuel systems, and operational contexts, totaling thirty-eight participants whose aggregated knowledge, experiences, and analytical perspectives provide comprehensive coverage of alternative maritime fuel adoption phenomena and strategic implementation imperatives.

The research instruments were meticulously designed to elicit detailed, contextually grounded perspectives on specific alternative fuel barriers, fuel pathway viability assessments, regulatory framework adequacy, and strategic recommendations while enabling systematic comparison across stakeholder categories and fuel alternatives. The primary instrument consisted of semi-structured interview protocols organized around dependent variables including perceived alternative fuel viability, adoption barrier severity, and regulatory framework adequacy, while independent variables encompassed stakeholder category, marine engineering expertise, environmental knowledge levels, and exposure to alternative fuel technologies. Specific indicators operationalizing these constructs included identification and prioritization of alternative fuel adoption barriers across multiple dimensions including technical readiness and maturity levels, infrastructure availability for production, storage, and bunkering, economic competitiveness relative to conventional fuels, safety considerations and risk management requirements, regulatory clarity and policy support, workforce competency and training requirements, and supply chain reliability and

fuel availability assurance, comparative evaluation of specific alternative fuel pathways including liquefied natural gas as transitional fuel, methanol offering handling advantages and infrastructure compatibility, ammonia providing zero-carbon combustion potential, hydrogen enabling complete decarbonization with storage challenges, biofuels offering drop-in compatibility with sustainability concerns, and synthetic e-fuels representing long-term carbon-neutral solutions with production cost challenges, assessment of current regulatory frameworks including IMO regulations, national policies, port state requirements, and regional coordination mechanisms, identification of regulatory gaps, policy inconsistencies, and support mechanism inadequacies impeding alternative fuel implementation, and articulation of strategic recommendations spanning infrastructure development priorities, policy interventions, financial incentive mechanisms, workforce development programs, and industry collaboration models. Supporting instruments included structured survey questionnaires administering Likert-scale items measuring alternative fuel awareness levels, barrier severity perceptions, fuel pathway preference rankings, and regulatory adequacy assessments, Focus Group Discussion protocols enabling collaborative exploration of alternative fuel challenges, comparative fuel evaluation, and consensus-building around implementation priorities, and documentary analysis examining IMO regulations, national maritime policies, alternative fuel technical reports, and regional shipping industry publications to contextualize stakeholder perspectives within broader regulatory and industry discourse landscapes (Kumar, 2019).

Data collection proceeded through systematic, ethically grounded procedures beginning with institutional research approval and participant recruitment emphasizing voluntary participation, confidentiality assurances, and informed consent protocols clearly explaining research purposes and participant rights. Baseline surveys were administered establishing participants' demographic characteristics, marine engineering backgrounds, alternative fuel knowledge levels, and environmental awareness, providing contextual grounding for subsequent qualitative data collection and enabling sample description. Semi-structured individual interviews averaging seventy-five to one hundred minutes were conducted with lecturer and practitioner participants, employing open-ended questioning strategies encouraging detailed elaboration on alternative fuel assessments, barrier perceptions, regulatory evaluations, and strategic recommendations while maintaining sufficient structure ensuring systematic coverage of key fuel alternatives and thematic domains across interviews. Focus Group Discussions involving student participants

facilitated collective exploration of alternative fuel learning needs, career preparation concerns, and future industry expectations through peer interaction and collaborative dialogue, with discussions explicitly comparing different fuel pathways to elicit comparative assessments and preference justifications. All interviews and focus group sessions were audio-recorded with explicit participant consent and professionally transcribed verbatim to preserve narrative detail and enable rigorous analytical procedures. Comprehensive field notes documenting technical discussions, particularly emphatic statements regarding specific barriers or opportunities, expressions of uncertainty or knowledge limitations, and contextual observations complemented transcribed data, capturing nuances potentially lost in verbal transcription alone. The collection process emphasized creating intellectually safe environments enabling candid discussion of knowledge limitations, uncertainties regarding fuel pathway viability, and honest assessments of regulatory inadequacies without defensive institutional reactions, recognizing that meaningful strategy development requires acknowledging current limitations alongside identifying future possibilities.

Data analysis followed systematic thematic analysis procedures involving initial familiarization through repeated reading of transcripts and immersive engagement with participant narratives, systematic coding identifying meaningful units within data including specific barrier mentions, fuel pathway evaluations, regulatory assessments, and strategic recommendations, and iterative theme development organizing codes into coherent conceptual categories aligned with research objectives and emergent patterns. The analytical process specifically focused on categorizing insights into alternative fuel adoption barrier taxonomies organized by technical, economic, infrastructural, regulatory, and workforce dimensions, comparative fuel pathway viability assessments examining advantages, limitations, and contextual appropriateness of different alternatives, regulatory framework adequacy evaluations identifying policy gaps and support mechanism inadequacies, and strategic recommendations spanning infrastructure development, policy intervention, financial incentive, workforce development, and collaborative governance domains. Cross-group comparisons systematically examined convergences and divergences among student, lecturer, and practitioner perspectives, identifying areas of consensus regarding critical barriers and regulatory inadequacies while highlighting contrasting fuel pathway preferences and implementation priority emphases reflecting different experiential backgrounds, knowledge bases, and stakeholder interests. Narrative synthesis integrated findings across individual cases, stakeholder groups, fuel alternatives, and thematic domains, developing

comprehensive explanatory accounts illuminating what barriers most significantly impede alternative fuel adoption, how different fuel pathways compare regarding viability and appropriateness for Southeast Asian contexts, what regulatory frameworks require strengthening, and what strategic interventions promise greatest effectiveness for accelerating fuel transitions. Methodological rigor was enhanced through data triangulation across multiple sources and stakeholder perspectives, expert validation consulting with marine engineering faculty regarding technical interpretations, and audit trail documentation systematically recording analytical decisions, interpretive reasoning, and theme development processes throughout the investigation.

3. RESULTS AND DISCUSSION

Results and Analysis

The qualitative analysis of stakeholder perspectives revealed complex and multifaceted challenges surrounding alternative maritime fuel adoption in Southeast Asian contexts, with participants demonstrating variable awareness of different fuel alternatives but converging on recognition that substantial technical, economic, infrastructural, and regulatory barriers impede transitions despite environmental imperatives and regulatory pressures. Thematic analysis identified six primary barrier categories structuring stakeholder understanding: infrastructure inadequacy and development costs, economic competitiveness and fuel price premiums, technical readiness and operational challenges, regulatory fragmentation and policy gaps, workforce competency and training requirements, and supply chain reliability and fuel availability concerns.

Regarding overall alternative fuel awareness and knowledge levels, results indicated significant variation across stakeholder groups with concerning knowledge gaps particularly regarding emerging fuel alternatives. Lecturer participants demonstrated the highest alternative fuel familiarity (Mean Awareness Score: 3.9/5.0), articulating detailed understanding of different fuel pathways' technical characteristics, environmental benefits, and implementation challenges, though several acknowledged that rapidly evolving fuel technologies required continuous professional development. Veteran practitioners exhibited moderate awareness levels (Mean Score: 3.4/5.0), typically demonstrating operational understanding of liquefied natural gas as increasingly common alternative while expressing limited familiarity with ammonia, hydrogen, and synthetic e-fuels representing longer-term decarbonization pathways. Student participants showed emerging but incomplete awareness (Mean Score: 2.9/5.0), with most recognizing general decarbonization imperatives and LNG

as alternative fuel while lacking detailed knowledge of technical characteristics, infrastructure requirements, or comparative advantages across fuel alternatives.

Table 1: Alternative Fuel Pathway Viability Assessment and Adoption Barriers

Alternative Fuel Type	Technical Viability (1-5)	Economic Viability (1-5)	Infrastructure Readiness (1-5)	Overall Adoption Potential (1-5)	Primary Barriers Identified
Liquefied Natural Gas (LNG)	4.3	3.6	3.8	3.9	Infrastructure costs, methane slip, limited carbon reduction
Methanol	3.8	3.2	2.9	3.3	Production capacity, bunkering infrastructure, toxicity concerns
Ammonia	3.4	2.7	2.1	2.7	Toxicity risks, engine technology, infrastructure absence, storage challenges
Hydrogen	3.2	2.4	1.8	2.5	Storage technology, energy density, infrastructure costs, safety concerns
Biofuels	3.9	2.9	3.4	3.4	Sustainability certification, feedstock availability, production scale, cost premiums
Synthetic E-fuels	3.1	2.2	2.0	2.4	Production costs, renewable energy requirements, infrastructure needs, technology maturity

Note: All scores based on 5-point scale (1=Very Low/Poor, 5=Very High/Excellent)

The comparative fuel pathway viability assessment revealed LNG as the most viable near-term alternative (Overall Score: 3.9/5.0) given existing infrastructure in major Southeast Asian ports, established engine technology, and regulatory frameworks supporting LNG bunkering, though stakeholders acknowledged LNG's limitations as transitional fuel providing only modest carbon reduction compared to conventional marine fuels. Biofuels and methanol exhibited moderate viability (3.4 and 3.3 respectively), offering advantages including compatibility with existing or adapted engine systems and potential for leveraging regional agricultural or industrial feedstocks, though concerns regarding sustainability, production scale, and infrastructure requirements limited enthusiasm. Hydrogen, ammonia,

and synthetic e-fuels demonstrated lower current viability assessments (2.5, 2.7, and 2.4 respectively), reflecting stakeholder recognition of these fuels' long-term decarbonization potential balanced against substantial technical challenges, infrastructure deficiencies, safety concerns, and economic barriers requiring resolution before widespread adoption becomes feasible.

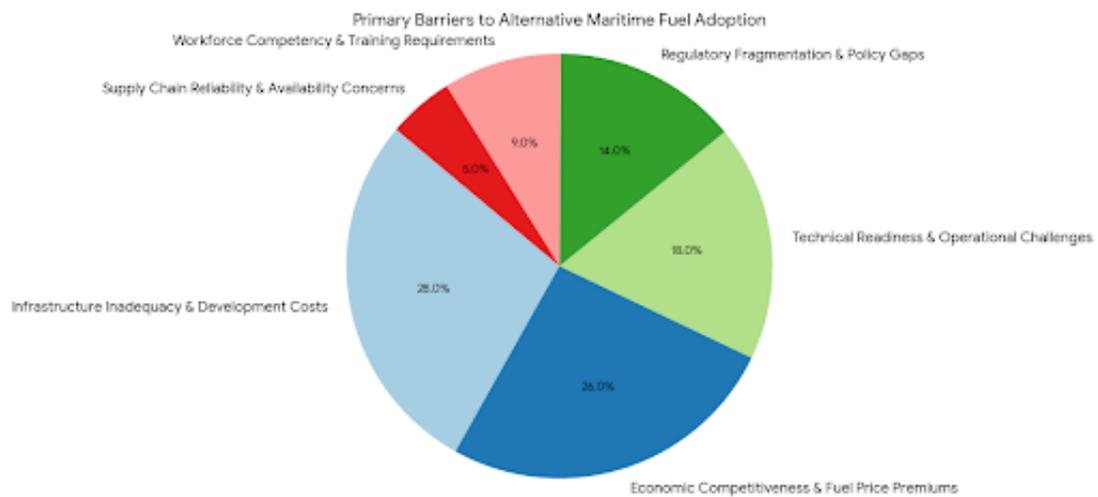


Figure 1: Primary Barriers to Alternative Maritime Fuel Adoption

Analysis of adoption barriers revealed infrastructure inadequacy and associated development costs as the dominant impediment (28%), encompassing absence of bunkering facilities for most alternative fuels beyond LNG in select major ports, inadequate storage infrastructure, limited production capacity within Southeast Asian region, and massive capital investment requirements for developing comprehensive alternative fuel supply chains. Economic competitiveness and fuel price premiums represented nearly equal concern (26%), with participants emphasizing that alternative fuels' higher costs compared to conventional heavy fuel oil or marine gas oil create substantial competitive disadvantages for shipping companies operating in cost-sensitive markets, particularly absent carbon pricing mechanisms or financial incentives offsetting green fuel premiums.

Qualitative narratives provided rich contextual depth illuminating stakeholder reasoning and implementation concerns. A veteran practitioner serving as Chief Engineer with twenty-six years of experience across various vessel types articulated: "Everyone talks about decarbonization and alternative fuels as if they're simple solutions waiting for adoption. Reality is far more complex. Take ammonia—technically promising for zero-carbon operations, but it's highly toxic, requires completely new engine technology we don't have operational experience with, needs bunkering infrastructure that doesn't exist anywhere in

Southeast Asia, and costs multiples of conventional fuel. Who pays for fleet retrofitting? Where do we bunker? How do we train crews? These aren't minor obstacles; they're fundamental barriers requiring coordinated industry, government, and international action we're not seeing at necessary scale or speed."

A lecturer specializing in marine propulsion and alternative energy systems offered complementary analytical perspective: "The alternative fuel landscape is evolving rapidly, creating educational challenges. We must prepare students for fuel diversity rather than fuel certainty—they'll likely manage vessels operating on different fuels across their careers as industry experiments, regulations evolve, and technologies mature at varying rates. Our curriculum challenge is balancing foundational fuel system principles with specific alternative fuel characteristics while acknowledging significant uncertainties regarding which pathways will dominate. We're educating for technological transitions still unfolding, which requires emphasizing adaptive learning capabilities alongside specific technical knowledge."

Student perspectives emphasized practical training needs and career preparation concerns, with one marine engineering student stating: "We learn extensively about conventional diesel engines and fuel systems, but alternative fuel coverage is minimal—maybe one lecture on LNG, brief mentions of biofuels and methanol, nothing on ammonia or hydrogen despite hearing these are the future. How can we be industry-ready maritime engineers when we lack hands-on experience with alternative fuel systems? We need simulator training, case studies of early adopter experiences, exposure to actual alternative fuel vessels through internships or site visits. Otherwise, we're unprepared for the energy transition everyone says is inevitable and urgent."

Cross-group comparative analysis revealed interesting convergences and notable divergences across stakeholder categories. All groups converged on recognizing substantial infrastructure and economic barriers as primary impediments to alternative fuel adoption, with 89% of participants identifying these as most critical challenges requiring urgent policy intervention and coordinated industry action. However, stakeholder groups diverged regarding fuel pathway preferences and implementation timelines. Practitioners demonstrated strongest support for LNG and biofuels as pragmatic near-term alternatives offering compatibility with existing or minimally modified systems, viewing ammonia and hydrogen skeptically given operational complexity and infrastructure absence. Lecturers exhibited more balanced assessment across fuel alternatives, emphasizing that long-term decarbonization

requires developing multiple pathways simultaneously rather than premature commitment to single fuel solution. Students expressed openness to diverse fuel alternatives but anxiety regarding competency development needs for managing technological diversity.

Table 2: Regulatory Framework Adequacy Assessment

Regulatory Dimension	Current Adequacy (1-5)	Perceived Importance (1-5)	Regulatory Gap Score
IMO Alternative Fuel Safety Guidelines	3.4	4.6	1.2
National Alternative Fuel Policies	2.3	4.7	2.4
Port Alternative Fuel Bunkering Regulations	2.6	4.5	1.9
Financial Incentive Mechanisms	1.9	4.8	2.9
Carbon Pricing & Market-Based Measures	2.1	4.4	2.3
Regional Coordination Frameworks	2.2	4.6	2.4
Technical Standards & Certification	3.0	4.5	1.5
Workforce Training Requirements	2.4	4.3	1.9
Overall Regulatory Assessment	2.49	4.55	2.06

Note: Adequacy (1=Very Inadequate, 5=Highly Adequate); Importance (1=Not Important, 5=Extremely Important); Gap = Importance minus Adequacy

Regulatory framework analysis revealed substantial gaps between perceived importance of various regulatory dimensions (mean: 4.55/5.0) and current adequacy assessments (mean: 2.49/5.0), producing an overall regulatory gap score of 2.06 points. Financial incentive mechanisms exhibited the largest regulatory gap (2.9 points), with stakeholders rating financial support as extremely important (4.8/5.0) while assessing current incentive availability as severely inadequate (1.9/5.0), reflecting recognition that alternative fuel adoption requires substantial public financial support offsetting green fuel premiums and infrastructure investment costs. National alternative fuel policies and regional coordination frameworks showed substantial gaps (both 2.4 points), emphasizing stakeholder concerns regarding policy fragmentation, inconsistent national approaches, and inadequate regional cooperation mechanisms coordinating infrastructure development and regulatory harmonization across Southeast Asian maritime jurisdictions.

Discussion

The research findings substantively address the central research question by

demonstrating that while alternative maritime fuels represent essential pathways for Southeast Asian shipping decarbonization, substantial and multifaceted barriers including infrastructure inadequacy, economic competitiveness challenges, technical readiness limitations, regulatory fragmentation, and workforce competency gaps significantly impede adoption, requiring coordinated interventions spanning infrastructure development, financial incentives, regulatory harmonization, and workforce development to accelerate necessary transitions. These results align with international literature documenting alternative fuel adoption challenges and the complex technical, economic, and institutional barriers impeding maritime decarbonization (Al-Breiki & Bicer, 2021; Balcombe et al., 2019) while extending understanding by foregrounding Southeast Asian-specific contextual factors including infrastructure limitations, regional coordination challenges, resource constraints, and developmental priorities shaping fuel transition dynamics.

The substantial overall regulatory gap (2.06 points) supports scholarly arguments that effective alternative fuel transitions require not merely technological innovation but comprehensive regulatory frameworks providing safety guidelines, technical standards, financial incentives, and coordination mechanisms enabling systematic adoption across fragmented maritime industries (Hansson et al., 2020). However, findings partially contradict regulatory determinism prevalent in some policy literature by revealing that stakeholders view infrastructure and economic barriers as equally or more significant than regulatory gaps, suggesting that even optimal regulatory frameworks prove insufficient without corresponding infrastructure investments and financial support mechanisms addressing fuel cost premiums and capital requirements.

The particularly severe financial incentive gap (2.9 points) addresses a critical vulnerability in Southeast Asian alternative fuel strategies, with stakeholders recognizing that market forces alone will not drive adoption given alternative fuels' substantial cost premiums and shipping industry's intense cost competition (Al-Breiki & Bicer, 2021). This finding validates emerging scholarship advocating public financial support including subsidies, tax incentives, carbon pricing mechanisms, and green shipping corridors creating business cases for early adoption while technologies mature and economies of scale develop.

The prominence of infrastructure inadequacy (28% of barriers) illuminates fundamental chicken-and-egg dynamics: shipping companies hesitate investing in alternative fuel vessels absent bunkering infrastructure assurance, while infrastructure developers

hesitate investing absent demand certainty from vessel operators, creating coordination failures requiring public sector intervention, anchor customer commitments, or collaborative industry consortia breaking investment deadlocks (Balcombe et al., 2019). This finding suggests that effective adoption strategies require coordinated infrastructure development initiatives potentially led by port authorities, supported by government funding, and guaranteed by shipping company commitments.

The diverse viability assessments across fuel pathways highlight important strategic considerations for fuel transition planning. The convergence on LNG as most viable near-term alternative combined with recognition of its limitations as transitional fuel suggests that Southeast Asian shipping requires portfolio approaches developing multiple fuel pathways simultaneously rather than singular technological bets, with LNG potentially providing bridge while zero-carbon alternatives including ammonia and hydrogen mature through pilot projects, demonstration vessels, and systematic technology development (Hansson et al., 2020).

Cross-stakeholder divergences regarding fuel preferences and implementation priorities illuminate tensions between near-term pragmatism and long-term environmental effectiveness. Practitioners' emphasis on LNG and biofuels reflects operational realism and risk aversion favoring proven technologies over speculative alternatives, while lecturers' more balanced fuel assessments reflect academic orientation toward long-term sustainability requiring zero-carbon solutions despite current challenges. These divergences indicate that successful transition strategies must accommodate diverse stakeholder perspectives and temporal orientations, pursuing incremental near-term actions building toward ambitious long-term decarbonization objectives.

The research strengths include its comprehensive stakeholder engagement spanning technical expertise, operational wisdom, and emerging professional perspectives, yielding triangulated insights reflecting diverse knowledge bases and experiential backgrounds. The comparative fuel pathway framework enables systematic assessment across alternatives, identifying relative advantages and context-specific appropriateness rather than presuming universal optimal solutions. The qualitative methodology enables exploration of barrier complexities, stakeholder reasoning, and contextual factors that quantitative approaches would obscure.

Practical implications of these findings are substantial for maritime industry

stakeholders, port authorities, national governments, and regional policy-makers. First, results indicate urgent need for coordinated infrastructure development strategies potentially organized through regional consortia, public-private partnerships, and anchor customer commitments breaking investment coordination failures. Second, findings suggest that alternative fuel adoption requires substantial financial support mechanisms including fuel subsidies, vessel retrofit grants, infrastructure investment support, and carbon pricing creating business cases for green fuel adoption. Third, the research highlights imperative for regulatory harmonization across Southeast Asian jurisdictions through regional coordination frameworks, technical standard alignment, and collaborative policy development facilitating cross-border fuel supply chains and reducing compliance complexity. Fourth, results emphasize need for systematic workforce development programs integrating alternative fuel knowledge into maritime curricula, providing specialized training for operational personnel, and building regional expertise supporting fuel transitions. Fifth, findings underscore importance of portfolio approaches developing multiple fuel pathways simultaneously, with near-term LNG and biofuel adoption building transition experience while zero-carbon alternatives mature through pilot projects and demonstration initiatives.

Future research should examine implementation outcomes as Southeast Asian ports and shipping companies experiment with alternative fuels, tracking adoption patterns, identifying success factors, and documenting lessons learned from early adopters. Comparative studies across Southeast Asian nations could illuminate how national contexts, policy frameworks, and infrastructure endowments shape adoption trajectories and outcomes. Techno-economic analyses evaluating total cost of ownership, lifecycle emissions, and business case dynamics for specific fuel pathways in Southeast Asian contexts would provide evidence-based guidance for investment decisions. Finally, research exploring optimal policy mixes combining regulatory mandates, financial incentives, infrastructure support, and market-based mechanisms would inform effective governance frameworks accelerating transitions while respecting economic realities.

4. CONCLUSION

This research establishes that alternative maritime fuel adoption in Southeast Asian shipping faces substantial and multifaceted barriers including infrastructure inadequacy, economic competitiveness challenges, technical readiness limitations, regulatory fragmentation, and workforce competency gaps requiring coordinated interventions for effective remediation. Liquefied natural gas emerges as most viable near-term alternative

despite limitations as transitional fuel, while zero-carbon alternatives including ammonia and hydrogen require systematic technology development, infrastructure investment, and regulatory support before widespread adoption becomes feasible. Financial incentive mechanisms represent the most critical regulatory gap, reflecting recognition that market forces alone cannot overcome alternative fuel cost premiums and capital requirements without public support. Effective acceleration of fuel transitions requires integrated strategies combining coordinated infrastructure development through regional consortia and public-private partnerships, substantial financial support mechanisms offsetting green fuel premiums, regulatory harmonization across Southeast Asian jurisdictions, systematic workforce development programs, and portfolio approaches developing multiple fuel pathways simultaneously addressing near-term transition needs while building toward long-term decarbonization objectives.

REFERENCES

- Al-Breiki, M., & Bicer, Y. (2021). Comparative life cycle assessment of sustainable energy carriers including production, storage, overseas transport and utilization. *Journal of Cleaner Production*, 279, 123481. <https://doi.org/10.1016/j.jclepro.2020.123481>
- Balcombe, P., Brierley, J., Lewis, C., Skatvedt, L., Speirs, J., Hawkes, A., & Staffell, I. (2019). How to decarbonise international shipping: Options for fuels, technologies and policies. *Energy Conversion and Management*, 182, 72-88. <https://doi.org/10.1016/j.enconman.2018.12.080>
- Creswell, J. W., & Creswell, J. D. (2018). *Research design: Qualitative, quantitative, and mixed methods approaches* (5th ed.). SAGE Publications.
- Hansson, J., Brynolf, S., Fridell, E., & Lehtveer, M. (2020). The potential role of ammonia as marine fuel—Based on energy systems modeling and multi-criteria decision analysis. *Sustainability*, 12(8), 3265. <https://doi.org/10.3390/su12083265>
- Kumar, R. (2019). *Research methodology: A step-by-step guide for beginners* (5th ed.). SAGE Publications.
- Merriam, S. B., & Tisdell, E. J. (2016). *Qualitative research: A guide to design and implementation* (4th ed.). Jossey-Bass.