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Challenges to Adopting Eco-Friendly Maritime Solutions: Barriers and Perceived Impacts of Green Shipping Among Malaysian Maritime Stakeholders

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ABSTRACT

The transition to lower-emission shipping requires coordinated investment in vessel technology, alternative-fuel supply chains, port infrastructure, workforce capability, and regulatory implementation. This study examines the perceived barriers to green shipping adoption and the anticipated or experienced impacts among Malaysian maritime stakeholders. An exploratory questionnaire-based assessment was interpreted using the Relative Importance Index (RII) alongside a contextual review of maritime decarbonisation literature and policy. Six adoption barriers and six reported impact indicators were compared descriptively. Implementation and maintenance costs were the highest-rated obstacle $(RII = 0.80)$, followed by alternative-fuel and infrastructure availability (0.74), technological readiness (0.68), market cost pressure (0.64), regulatory harmonisation (0.62), and workforce capability (0.62). Among perceived impacts, digital emissions monitoring scored highest (0.78), followed by fuel efficiency and alternative-fuel integration (0.70 each); reported greenhouse-gas reduction (0.60) and operational cost savings (0.54) were comparatively lower. These indices represent respondent perceptions, not verified emissions or financial savings. The findings favour a phased transition strategy combining financing support, safe fuel infrastructure, technical capability-building, performance measurement, and public–private cooperation. Interpretation is exploratory because respondent-level observations, a definitive achieved sample count, and inferential model outputs were not available for independent analysis.

Keywords: green shipping; maritime decarbonisation; alternative marine fuels; Relative Importance Index; port infrastructure

1. Introduction

International shipping is central to trade and supply chains, but it generates greenhouse-gas (GHG) and air-pollutant emissions through fuel production, combustion, and port operations. The Fourth IMO GHG Study estimated that total shipping contributed approximately 2.89% of global anthropogenic GHG emissions in 2018 (International Maritime Organization, 2020). With environmental performance becoming increasingly integral to fleet competitiveness and port development, operators face a transition that requires operational improvements and major capital renewal rather than a single technical intervention (Balcombe et al., 2019; Bouman et al., 2017).

The 2023 IMO GHG Strategy sets an ambition to reach net-zero GHG emissions from international shipping by or around 2050, with indicative 2030 and 2040 checkpoints (International Maritime Organization, 2023). The strategy does not mean that every proposed emissions-pricing mechanism or fuel-intensity instrument is already binding. Effective transition planning therefore requires attention to the distinction between adopted standards, policy ambitions, and measures still under consideration. The international fuel transition additionally requires consistent life-cycle assessment, because fuel production and methane or nitrous-oxide emissions can materially alter the apparent advantage of individual fuel options (International Maritime Organization, 2024; Roux et al., 2024).

For Malaysia, geography, port connectivity, existing maritime services, and aspirations to participate in future low-carbon fuel supply chains create opportunities and investment pressures. The National Energy Transition Roadmap recognises marine transport decarbonisation and possible roles for e-methanol and e-ammonia, while also acknowledging uncertainty about the long-term fuel mix (Ministry of Economy Malaysia, 2023). Sector-wide implementation depends on how private operators weigh up the costs and operational readiness of new technologies. The shipping decarbonisation literature identifies investment, alternative-fuel access, regulatory coordination, and organisational capacity as interconnected barriers (Ghaforian Masodzadeh et al., 2022; Jeong et al., 2022).

This research addresses three objectives: (1) identify the main barriers to green shipping adoption in the Malaysian maritime context; (2) compare their perceived importance using reported RII scores; and (3) examine perceived environmental, technological, and economic impacts to propose priorities for stakeholders. The study contributes an exploratory ordering of perceived constraints and a practical, locally framed synthesis, without presenting perception-based indices as validated emissions reductions or representative national population estimates.

2. Literature Review

2.1 Green shipping and decarbonisation pathways

Green shipping encompasses cleaner fuels, vessel and machinery improvements, shipboard energy management, waste and pollution reduction, and operational changes such as speed optimisation. These interventions differ in capital intensity, maturity, required infrastructure, and achievable life-cycle reductions. Bouman et al. (2017) argued that no single measure is likely to deliver deep sector-wide reductions; combined strategies and supportive policy are necessary. Balcombe et al. (2019) similarly compared fuel, technology, and policy pathways and identified the importance of combining efficiency measures with alternative fuels. Maritime innovation should thus be evaluated as a portfolio rather than an isolated fuel substitution.

Studies of corporate green shipping practices show that internal environmental management, customer requirements, and governance arrangements can influence implementation decisions (Chang & Danao, 2017; Lister, 2015). Empirical work has also linked green management approaches with environmental performance and sustainable economic outcomes, although these associations should not be construed as guaranteed returns for every fleet segment (Felício et al., 2021). This distinction is important when operators face diverse vessel ages, route networks, financing constraints, and customer willingness to pay.

2.2 Investment costs and market pressures

The commercial difficulty of maritime decarbonisation includes the acquisition or conversion of vessels, machinery renewal, the cost and availability of lower-emission fuels, safety systems, training, and continuing compliance expenses. Because ship assets are long-lived, uncertain technology trajectories introduce risk of stranded investments and future retrofit requirements. Ghaforian Masodzadeh et al. (2022) identified economic policy and stakeholder coordination as central elements in overcoming decarbonisation barriers, while Jeong et al. (2022) reviewed the policy pressures that influence operators. Financial readiness also depends on financing costs, contract structures, charter-party incentives, and the ability to recover investment through the supply chain.

High initial expenditure does not preclude longer-term advantages. Fuel efficiency, reduced exposure to specific pollutants, improved monitoring, and regulatory preparedness can create value, but prospective benefits depend on actual operating conditions and fuel prices rather than being automatic consequences of a green technology label (Felício et al., 2021; Hasanspahic et al., 2021). This tension between present expenditure and uncertain future returns provides a rationale for measuring barriers and expected benefits separately.

2.3 Alternative fuels and port-side infrastructure

Alternatives such as biofuels, methanol, ammonia, hydrogen, LNG, and battery-electric systems have substantially different volumetric energy densities, propulsion compatibility, production pathways, and safety considerations. A review by Wang et al. (2022) examined low- and zero-carbon power technologies and their practical adoption challenges. Comparative environmental and economic life-cycle analysis likewise demonstrates that the performance of biofuels, electro-fuels, and blue fuels depends on energy sources and value-chain assumptions (Kanchiralla et al., 2024). LNG may improve certain air-quality outcomes but cannot be equated with zero-GHG shipping, particularly where methane slip is material (Balcombe et al., 2019).

Port infrastructure is a complementary, not downstream, requirement. Storage, bunkering equipment, emergency response capacity, trained personnel, and a dependable fuel-production and logistics chain must develop together. UN Trade and Development (2025) noted that the active fleet remains predominantly dependent on conventional fuels while alternative-fuel orders and port investments are changing. The IMO's 2024 life-cycle guidelines provide a well-to-wake accounting framework for CO_2, CH_4, and N_2O emissions, reinforcing the need to judge fuel transitions against more than tank-to-wake exhaust values (International Maritime Organization, 2024).

2.4 Regulation, skills and institutional collaboration

International standards and regional requirements influence investment decisions, but uncertainty about timing, harmonisation, and enforcement can raise compliance risk. A legal and policy review by Dong et al. (2022) highlights the complexity of maritime decarbonisation governance. For emerging maritime economies, close cooperation across shipowners, ports, regulators, fuel suppliers, financial institutions, and maritime education and training providers may help align implementation with technical and safety readiness (Lister, 2015; Ministry of Economy Malaysia, 2023).

A green transition also raises occupational skill requirements. Alternative fuels can introduce toxicity, fire and explosion risks, unfamiliar transfer systems, and additional emergency-response duties. The IMO issued generic interim guidelines for seafarer training on ships using alternative fuels and new technologies in 2025 (International Maritime Organization, 2025). Training capacity should therefore be regarded as part of enabling infrastructure, alongside bunkering facilities and vessel systems. Industry stakeholders need clear competencies for fuel handling, operational risk assessment, emissions monitoring, and maintenance.

2.5 Research gap and analytical positioning

The international literature offers substantial technical, financial, and policy evidence, but local implementation choices depend on perceived constraints among participating maritime organisations. This study concentrates on those perceptions and provides a structured descriptive comparison. Its RII results reveal relative ordering within the investigated questionnaire domains, while the contextual literature supports interpretation of why different barriers might be salient. The approach is not designed to establish causal relationships, independently verify emissions savings, or infer population-wide attitudes from a small, purposively approached group.

3. Methodology

3.1 Research framework and design

An exploratory descriptive questionnaire design was used as shown in Figure 1, supported by documentary analysis and a decision-oriented research framework. The analytical sequence was to identify challenges in the literature, obtain ratings from Malaysian maritime stakeholders, compare the ratings using the Relative Importance Index (RII), and interpret reported impacts alongside technological and policy evidence. The research framework describes a broader intention to triangulate expert perspectives and examine relationships among variables; however, only the reported aggregate RII outcomes can be evaluated quantitatively here. Consequently, the results are presented as descriptive rather than as verified correlations or regression estimates.

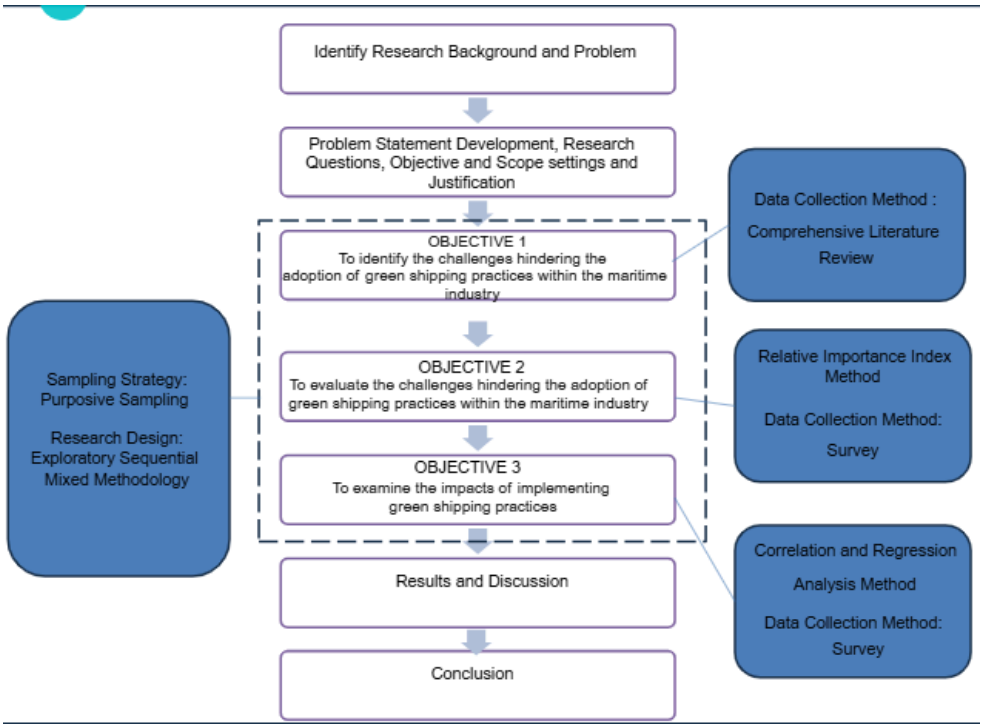


Figure 1. Research framework connecting barrier identification, stakeholder perceptions, RII analysis, and implementation impacts.

3.2 Participants and instrument

Participants were approached through purposive selection from maritime-related backgrounds that included shipping, freight forwarding, port-related activity, and maritime education. The study description refers to approximately 10–15 respondents, but does not provide a definitive achieved number, role-specific counts, or a response rate. Although the intended population included experienced industry professionals, some participants were students or early-career stakeholders. The findings therefore represent the participating group rather than a statistically representative sample of Malaysian shipping companies.

Questionnaire items used a five-point rating scale with higher values representing greater perceived significance. Six adoption barriers were reported: costs; green-fuel and infrastructure availability; technological readiness; market pressure favouring cost efficiency; regulatory enforcement and harmonisation; and skilled workforce availability. The impact questions covered digital emissions monitoring, fuel efficiency, alternative-fuel integration, ship design and retrofits, perceived GHG reduction, and operational cost savings. Detailed questionnaire wording, respondent-level responses, reliability coefficients, and subgroup distributions were not available for independent assessment.

3.3 Relative Importance Index and analytical limits

The RII was defined as $\mathbf{RII} = \frac{\sum W}{A \times N}$, where ΣW is the sum of respondents' ratings for an item or factor, A is the maximum permissible rating (5), and N is the number of valid responses. Under consistent item coding, RII lies between 0 and 1. The index was used to rank reported challenge and impact scores, with tied values sharing equal rank. Values are rounded to two decimal places. Because the individual response records and exact item-level sample sizes were not available, the published indices could not be independently recomputed or accompanied by confidence intervals; differences between close ranks should not be treated as statistically significant.

Although exploratory correlation and regression methods were discussed in the wider research design, no model coefficients, inferential tests, or sufficient observations were reported. No regression results are therefore inferred. Likewise, respondent impressions of emissions or cost effects are not equivalent to measured before-and-after environmental or financial performance. The article separates these evidence levels throughout the results and discussion.

4. Results

4.1 Relative importance of adoption barriers

Table 1 presents the six reported constraints. Implementation and maintenance costs ranked highest $(RII = 0.80)$, followed by fuel supply and infrastructure availability (0.74). Technology readiness (0.68) and market cost pressures (0.64) formed a middle group. Regulatory harmonisation and the availability of skilled personnel both returned 0.62 and were tied. All six scores exceed 0.60, but they describe the relative perceived importance of these barriers rather than the prevalence of actual corporate implementation failures as shown in Figure 2 and 3.

Table 1. Reported Constraints

Rank	Barrier	RII
1	High implementation and maintenance cost	0.80
2	Limited green-fuel supply and infrastructure	0.74
3	Limited technological readiness	0.68
4	Cost-centred market resistance	0.64
5	Regulatory enforcement and harmonisation gaps	0.62
5	Skills and workforce-training gaps	0.62

Note. Rankings follow the reported RII values. The final two barriers share fifth place.

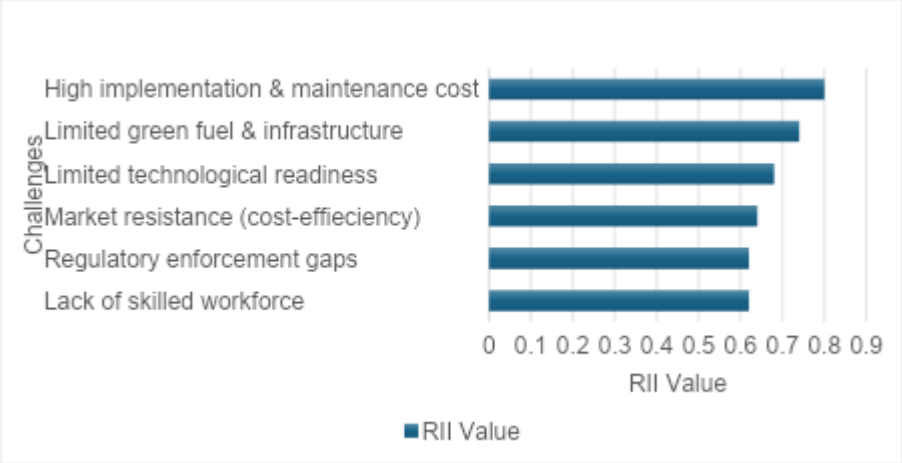


Figure 2. Relative importance of six reported green shipping adoption barriers.

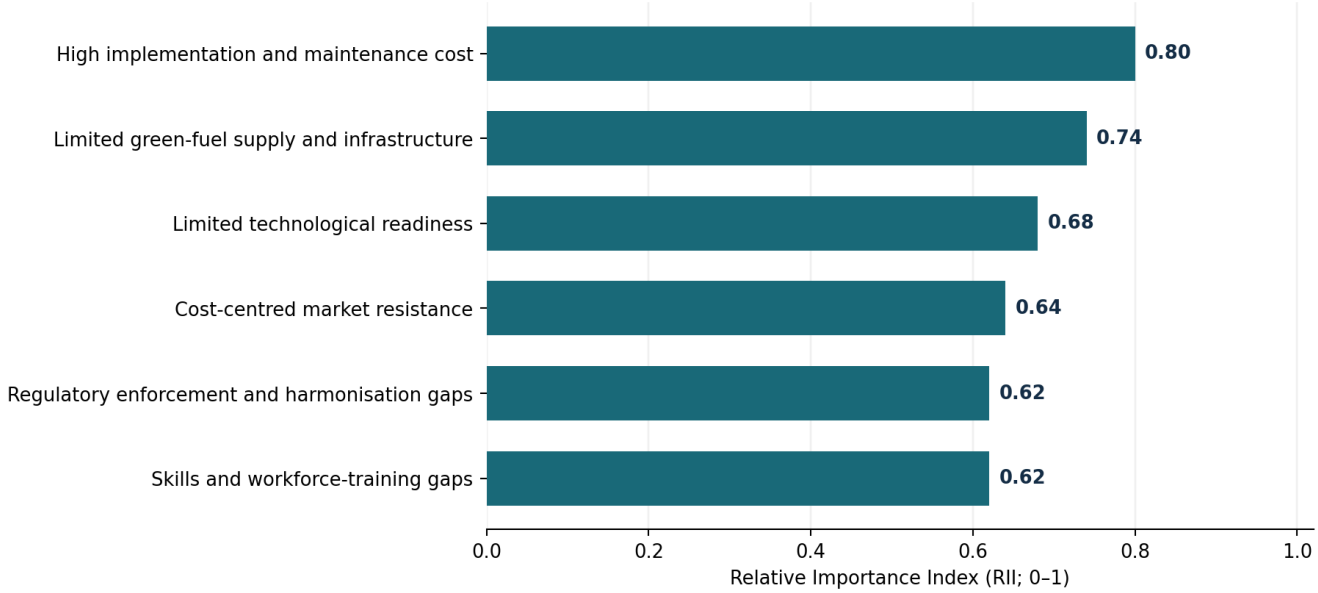


Figure 3. Ranked green shipping adoption barriers with labelled Relative Importance Index values.

The first two barriers have a coherent commercial interpretation: investment can be unattractive when alternative fuel supply, safe bunkering options, and supporting port capabilities are uncertain. Nevertheless, a difference of 0.06 between the first two RII values is a descriptive difference in perceptions, not evidence that financing interventions would produce a numerically larger emissions reduction than infrastructure interventions.

4.2 Perceived impacts of implementation

Reported implementation impacts were not uniform. Digital technologies for emissions monitoring received the highest impact RII (0.78). Fuel-efficiency improvements and alternative-fuel integration each scored 0.70, followed by ship design and retrofit innovation (0.62). Perceived GHG-emissions reduction was scored 0.60, and operational cost savings 0.54 as shown inFigure 4. These measures cannot be interpreted as observed percentages of efficiency improvement or emissions abatement; they are normalised perception scores.

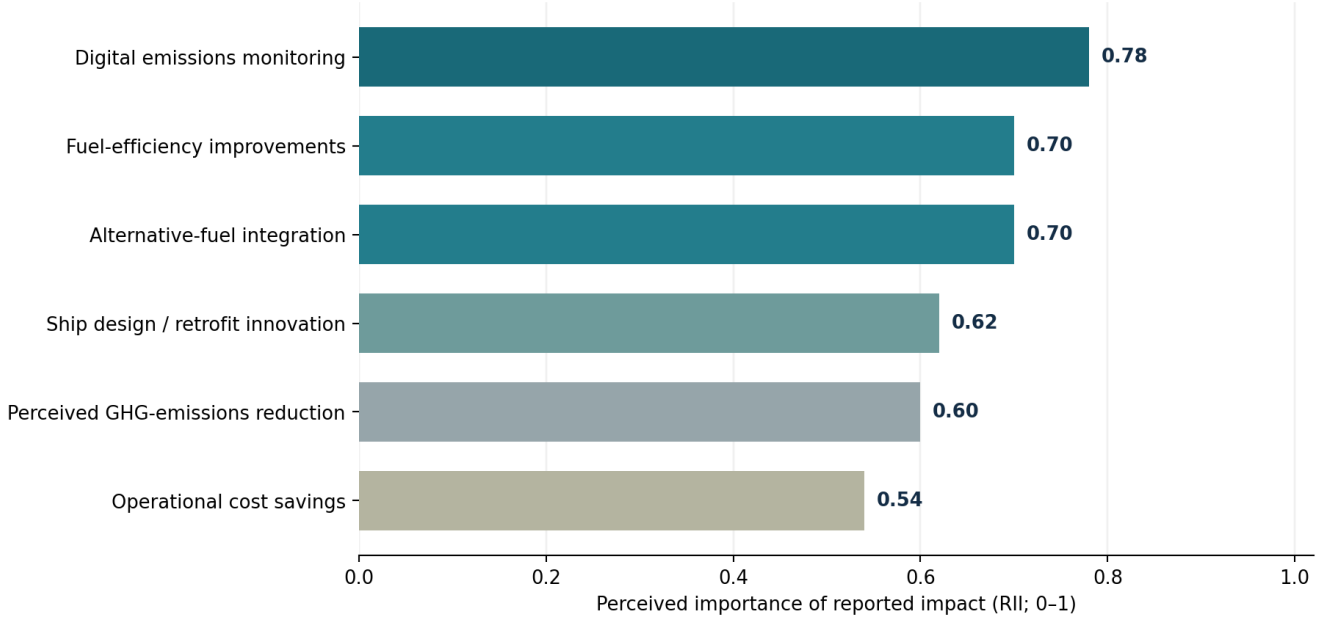


Figure 4. Relative Importance Index values for perceived impacts of green shipping adoption.

The contrast between digital monitoring (0.78) and cost savings (0.54) is analytically useful. Digital monitoring can be adopted or recognised without immediately demonstrating a strong financial return, whereas net cost changes depend on vessel utilisation, fuel prices, maintenance, capital costs, incentives, and contract

terms. No quantified competitiveness index was reported, so the competitiveness discussion is treated qualitatively rather than assigned a derived numerical score.

4.3 Integrated barriers and implementation response

A multi-barrier transition is suggested by the distribution of scores. High capital costs intersect with infrastructure constraints, technology maturity, organisational capability, and the policy environment. The challenge framework in Figure 5 identifies these domains, while Figure 6 translates them into an ordered planning logic. The sequence is intended to guide evaluation and coordination, not to assert a tested causal pathway.

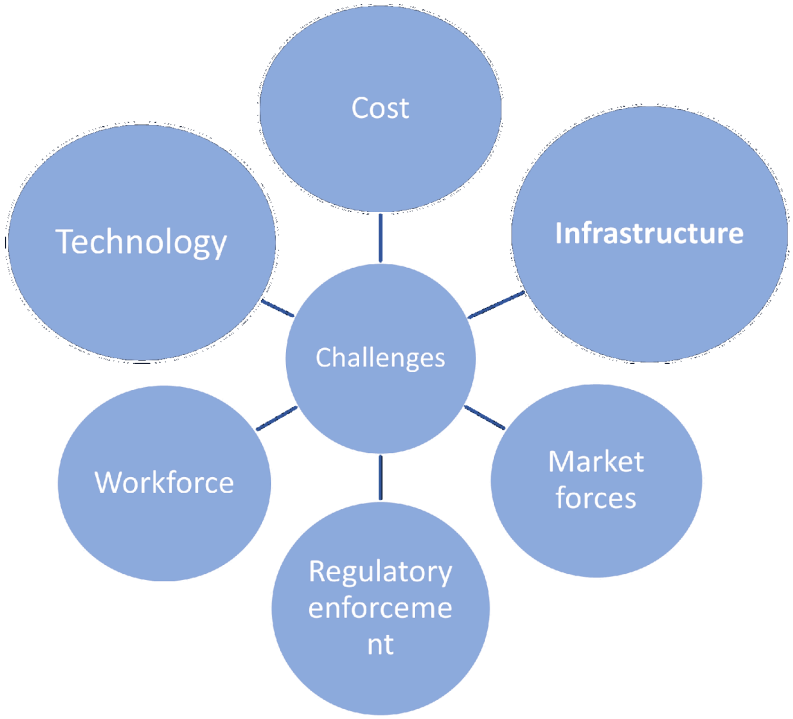


Figure 5. Interrelated challenge domains: cost, infrastructure, technology, market forces, enforcement, and workforce.

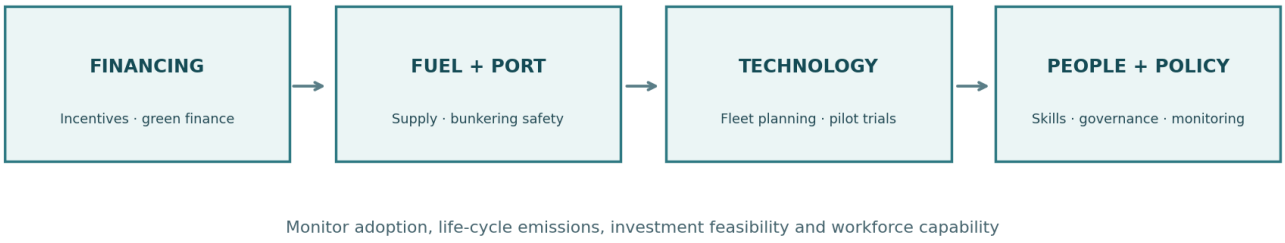


Figure 6. Proposed transition pathway integrating finance, fuel infrastructure, technology, skills, and policy.

5. Discussion

5.1 The financing–infrastructure dependency

Cost and infrastructure were the leading perceptions, consistent with broader reviews showing that investment decisions and physical fuel readiness develop together (Ghaforian Masodzadeh et al., 2022; UN Trade and Development, 2025). Vessel retrofits or fleet renewal may be deferred when bunkering coverage, fuel specifications, and long-term supply prices are uncertain. Conversely, infrastructure investors may be reluctant to commit when shipowner demand is insufficient. Coordinated pilot projects, demand aggregation, port readiness assessments, appropriate financing instruments, and transparent life-cycle accounting could help reduce this interdependence.

In Malaysia, potential development as a green bunkering and maritime services hub should be considered alongside actual fuel supply, vessel demand, land-side permitting, emergency response and occupational preparedness. The National Energy Transition Roadmap provides a strategic context for fuel diversification, but it does not by itself demonstrate the commercial feasibility of a specific ship-fuel or port project (Ministry of Economy Malaysia, 2023). The study therefore supports pre-investment feasibility evaluation rather than an unconditional recommendation for any individual fuel.

5.2 Regulatory clarity and differentiated fuel pathways

Although policy and workforce barriers received lower scores than cost and infrastructure, a lower RII does not make them immaterial. Stable and legible regulation affects fleet investment horizons, access to finance, and long-term emissions commitments. Dong et al. (2022) describe the importance of harmonised legal and policy frameworks, while the 2023 IMO GHG Strategy provides the international ambition against which future measures are being developed (International Maritime Organization, 2023). Industry planning should distinguish currently applicable requirements from future proposals and should monitor revisions to international rules.

Alternative fuels must be evaluated against life-cycle GHG intensity, land-side production emissions, onboard engine performance, training and safety requirements, and asset-specific commercial feasibility. Kanchiralla et al. (2024) demonstrate how life-cycle cost and climate outcomes differ across fuel pathways, while Roux et al. (2024) identify substantial inconsistencies and transparency gaps in published fuel life-cycle assessments. These results caution against assuming that LNG, hydrogen, ammonia, or biofuels deliver uniform reductions independent of production method and equipment type.

5.3 Digital measurement, human capability and real performance

The relatively strong perceived benefit of emissions monitoring supports investment in measurement capability, but improved data visibility is not synonymous with lower measured emissions. Shipboard sensors, fuel reporting, voyage optimisation, energy-management systems, and appropriately governed digital infrastructure can enable more reliable baselines and decision-making. Any actual emissions benefit should be quantified using documented fuel consumption and consistent well-to-wake factors, with clear system boundaries and uncertainty reporting (International Maritime Organization, 2024; Hasanspahic et al., 2021).

Workforce capability merits a coordinated response. Maritime training providers can adapt syllabi for hazardous fuel characteristics, new machinery, maintenance, bunkering coordination, emergency response, and digital measurement competence. The IMO generic interim guidance on alternative-fuel training provides a practical reference while specific requirements continue to develop (International Maritime Organization, 2025). Cooperation among ports, training institutions, ship managers, class societies, and regulators may increase the feasibility of deployment and improve operational readiness.

5.4 Practical transition priorities

An operationally useful response is phased. Initially, operators can establish fleet-level emissions and fuel-cost baselines, assess technical and commercial constraints, and screen eligible technologies against vessel age, duty profile and regulatory exposure. A second phase can identify fuel-infrastructure partners, evaluate bunkering and shipboard hazards, and design financing and contractual arrangements. A third phase can conduct pilot deployment, competency assessment, independent emissions accounting, and periodic review. Throughout implementation, engagement with policy agencies and customers is necessary to avoid infrastructure and vessel investment occurring in isolation (Chang & Danao, 2017; Ghaforian Masodzadeh et al., 2022; Lister, 2015).

The resulting roadmap should include indicators for (i) actual investment and operating costs, (ii) well-to-wake GHG intensity, (iii) energy and fuel efficiency, (iv) port and fuel-supply readiness, (v) workforce training and emergency preparedness, and (vi) operational reliability. These indicators can test whether initially favourable stakeholder perceptions correspond to realised environmental and economic outcomes. This approach is more defensible than treating RII rankings as direct measures of emissions abatement or as proof that a particular intervention will be effective.

5.5 Study limitations and future research

The exploratory results require cautious interpretation. The achieved number of valid respondents was not consistently specified beyond an approximate range, and the participants included heterogeneous maritime roles, including students. The underlying response matrix, questionnaire item text, missing-data treatment, and

participant-level demographic distributions were not reported. Consequently, the RII figures cannot be independently recalculated, confidence intervals cannot be generated, and hypothesis tests or regression associations cannot be assessed. An intention to use mixed methods cannot substitute for accessible interview or focus-group protocols, coded evidence, or reported qualitative findings.

Future work should recruit an explicitly defined population of Malaysian shipping and port organisations, report sampling and response rates, publish anonymised item-level data where ethical and commercially permissible, examine questionnaire reliability, and evaluate alternative weighting or ranking robustness. Longitudinal vessel or fleet studies should then compare actual pre- and post-adoption fuel use, life-cycle GHG emissions, costs and safety outcomes. Multi-stakeholder analysis across shipowners, terminals, fuel suppliers, financiers and training providers could evaluate whether the ranked barriers differ by organisation size, fleet segment, and operational role.

6. Conclusion

Malaysian maritime stakeholders rated implementation and maintenance costs $(RII = 0.80)$ and limited green-fuel infrastructure (0.74) as the most important barriers to green shipping adoption. Technological readiness, market pressures, regulation and workforce capability were also material perceived constraints. Digital emissions monitoring was the highest-rated impact domain (0.78), while perceived GHG reduction (0.60) and cost savings (0.54) were less strongly rated. These values describe stakeholder judgements, not verified changes in emissions or operating costs.

The results favour coordinated action across financing, ports, shipowners, fuel suppliers, regulators, and training providers. Investment decisions should be based on vessel- and route-specific feasibility, safe fuel handling, credible life-cycle emissions measurement and transparent assessment of commercial returns. Strengthening workforce readiness and policy coordination is essential even when these factors receive lower perception scores. A larger, well-documented dataset and direct performance measurements are needed to assess the effectiveness of interventions and the generalisability of the findings.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the author used OpenAI's ChatGPT to assist with manuscript structuring, language refinement, and improving the clarity and readability of the text. All AI-assisted content was critically reviewed, verified, and edited by the author. The author takes full responsibility for the accuracy, integrity, originality, and final content of the published work.

Conflict of Interest

The author declares no financial, professional, or personal conflicts of interest that could have influenced the research, analysis, interpretation, or presentation of the findings.

Author Contributions

Data availability

No public data available

Ethics

The research was conducted in accordance with established principles of academic integrity, accurate reporting, and responsible use of published information.

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