Marine Engineering Innovation for Environmental Compliance: An Integrated Environmental Engineering Framework for Indonesian Domestic Vessel Operations

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***Abstract*—** Marine engineering in the contemporary maritime industry is undergoing a fundamental paradigm shift — from a discipline optimized for propulsive performance and fuel economy toward one in which environmental engineering is integral to every shipboard system domain. Indonesian domestic vessel operations face acute pressure from IMO 2050 net-zero targets, MARPOL enforcement tightening, and EEXI/CII compliance requirements, yet systematic assessment of the sector's environmental engineering readiness remains absent from the literature. This study aims to: (a) assess the environmental engineering compliance profile of Indonesian domestic vessels across all MARPOL-relevant system domains; (b) identify and evaluate the most appropriate environmental engineering innovations for the Indonesian domestic fleet through multi-criteria analysis; and (c) develop a prioritized environmental engineering investment roadmap aligned with IMO GHG strategy timelines. A mixed-methods approach was employed, combining a quantitative Environmental Engineering Audit Protocol (EEAP) applied to 72 Indonesian domestic commercial vessels across 10 engineering compliance domains, with Analytic Hierarchy Process–Technique for Order of Preference by Similarity to Ideal Solution (AHP-TOPSIS) multi-criteria assessment involving 24 domain experts. The audit reveals critical compliance gaps in CII monitoring systems (36% compliance), waste heat recovery installation (10%), and eco-compliant antifouling coatings (35%), alongside high-severity deficits in NOx treatment (42%), sewage treatment (44%), and ballast water management (50%). AHP-TOPSIS ranking identifies waste heat recovery and CII digital monitoring as equal top-priority investments (composite score 0.83), followed by nano-hybrid antifouling (0.79), Annex IV sewage treatment (0.77), SCR/EGR NOx reduction (0.72), and LNG dual-fuel conversion (0.68). The resulting Integrated Environmental Engineering Framework (IEEF) organizes these priorities within a three-horizon implementation roadmap — Horizon 1 (2025–2027) deploying proven compliance technologies, Horizon 2 (2027–2032) advancing NOx reduction and hybrid system integration, and Horizon 3 (2032–2050) transitioning toward hydrogen, ammonia, fuel cell propulsion, and on-board carbon capture — providing a structured engineering trajectory aligned with IMO 2050 net-zero ambition.

Keywords— marine environmental engineering; IEEF; waste heat recovery; Indonesian domestic fleet; MARPOL compliance; AHP-TOPSIS; decarbonization; EEXI; CII; environmental compliance framework

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I. INTRODUCTION

Marine engineering the discipline governing the design, installation, operation, and maintenance of the mechanical, electrical, and systems engineering infrastructure of vessels — stands at the epicenter of the maritime industry's environmental transformation. Where the discipline once optimized primarily for propulsive power, fuel economy, and mechanical reliability, the contemporary marine engineering agenda is fundamentally reshaped by the intersection of international regulatory pressure, climate urgency, and materials technology advancement. The result is a new disciplinary paradigm: environmental engineering as integral to shipboard systems design. Every major system in a vessel's engineered environment — propulsion, power generation, exhaust treatment, thermal management, fluid waste handling, hull surface management, and auxiliary machinery — now carries an environmental compliance dimension that must be engineered alongside its primary operational function. The marine engineer of the 21st century is, inescapably, an environmental engineer.

The research problem that motivates this study is both empirically grounded and practically urgent. Indonesia operates one of the largest domestic merchant fleets in Southeast Asia — spanning domestic tankers, ro-ro passenger ferries, coastal bulk carriers, and coastal

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cargo vessels — yet systematic empirical evidence on the environmental engineering compliance profile of this fleet across all MARPOL-relevant system domains is absent from the published literature. The IMO's revised GHG strategy — targeting net-zero shipping emissions by or around 2050 — combined with the EEXI and CII compliance frameworks that entered force in January 2023, has created a regulatory environment in which engineering non-compliance carries direct financial and operational consequences. Yet without a structured, evidence-based diagnosis of where Indonesian domestic vessels stand across the full spectrum of environmental engineering requirements, policymakers, fleet operators, maritime educators, and financing institutions lack the analytical foundation required to prioritize intervention. This study fills that gap directly.

The novelty of this study lies in three connected contributions. First, this is the first study to apply a systematic Environmental Engineering Audit Protocol (EEAP) to a representative sample of Indonesian domestic commercial vessels across all 10 MARPOL-relevant engineering domains simultaneously — moving beyond single-system assessments to provide a comprehensive, cross-system compliance profile. Second, it employs AHP-TOPSIS multi-criteria methodology with 24 domain experts — drawn from shipping companies, maritime engineering academia, and government technical offices — to generate vessel-type-specific technology priority rankings that are both analytically rigorous and operationally grounded. Third, it synthesizes audit findings and technology rankings into the Integrated Environmental Engineering Framework (IEEF) — a three-horizon structured investment roadmap that is the first of its kind for the Indonesian domestic maritime sector and provides a direct practical policy instrument for fleet decarbonization planning.

The IMO's revised GHG strategy has established the definitive regulatory architecture for marine engineering's environmental agenda. Research examining EEXI implementation confirms that compliance requires engineering interventions spanning propulsion system modification, waste heat recovery installation, hull hydrodynamic optimization, and auxiliary load reduction — establishing that EEXI compliance is fundamentally a marine engineering challenge with environmental engineering content [1]. System dynamics modelling of maritime GHG emission measures demonstrates that achieving IMO 2050 targets requires the coordinated deployment of multiple technology pathways simultaneously — confirming that no single innovation is sufficient and that an integrated environmental engineering portfolio approach is required [2].

The environmental engineering challenges within marine engineering span all six MARPOL annexes. Annex I requires oil-water separation and oily bilge water treatment; Annex II demands noxious liquid substance containment; Annex IV mandates sewage treatment in environmentally sensitive waters; Annex VI governs SOx and NOx emissions, requiring fuel sulfur compliance or scrubber installation and selective catalytic reduction or exhaust gas recirculation for NOx control [24]. Research developing sewage treatment models using environmentally friendly technology for commercial ships in Indonesian waters demonstrates that sewage management aboard commercial vessels requires genuine engineering design — not merely regulatory documentation — responsive to the physical, chemical, and biological treatment requirements of shipboard wastewater [3].

Waste heat recovery (WHR) systems represent one of the most productive marine engineering innovations for simultaneously addressing thermal efficiency and environmental performance. Research optimizing WHR for marine engines through a Bayesian optimizer demonstrates that the thermal energy in engine exhaust gas and jacket cooling water — representing 50–60% of total fuel energy input — can be recovered to reduce auxiliary boiler fuel consumption, generate shaft power, or produce electricity, with optimization-guided design achieving fuel savings of 8–15% depending on engine type and operating profile [4]. Research on hybrid propulsion energy management confirms that WHR integration within a broader hybrid energy architecture delivers additional efficiency gains through intelligent heat-power co-dispatch [5].

The fuel cell and hydrogen propulsion dimension represents the most technically ambitious frontier of marine environmental engineering. Research on solid oxide fuel cell–gas turbine integrated systems for marine vessels using ammonia and hydrogen demonstrates that near-zero emission propulsion is technically achievable, with SOFC-GT systems achieving electrical efficiencies of 55–65% compared to 40–45% for conventional diesel engines [6]. Research on fuel cell metal hydride thermal management on the first Italian hydrogen propulsion ship demonstrates the engineering challenges of bringing hydrogen fuel cell propulsion to operational reality [7]. Research on ammonia-fuelled propulsion system design and optimization demonstrates the specific challenges of the most promising zero-carbon marine fuel, where ammonia's combustion characteristics, toxicity management, and NOx generation potential demand innovative engine design and exhaust treatment integration [8].

On-board carbon capture (OBC) represents an emerging marine engineering innovation that addresses the challenge of GHG reduction for vessels burning carbon-containing fuels — capturing CO_2 from engine exhaust before atmospheric release. Research on navigating within the safe operating space with on-board carbon capture demonstrates both the technical feasibility of retrofitting carbon capture equipment to existing vessels and the engineering integration challenges that must be resolved for commercial viability [9]. Research on lifecycle assessment of methanol as a marine fuel confirms that the environmental engineering agenda extends beyond exhaust treatment to encompass full lifecycle environmental impact — where fuel production, supply chain, and end-of-life burdens must be considered alongside operational emission performance [10]. The quantitative sustainability assessment of electrofuels for maritime transport confirms that genuine environmental engineering for maritime decarbonization requires lifecycle thinking across the entire energy chain [11].

The hull systems dimension — particularly biofouling management — bridges marine and environmental engineering by simultaneously affecting fuel consumption, GHG emissions, and marine ecosystem protection. Research on biofilm impact on ship fuel consumption confirms that hull biofouling generates a 25–40% fuel consumption penalty at the macrofouling stage — an environmental engineering failure with consequences spanning both energy efficiency and aquatic invasive species transport [12]. Chemical and nanotechnology innovations in ballast water management address the parallel challenge of invasive species vector control through engineered treatment systems [13]. The multi-criteria assessment of energy efficiency enhancement systems provides the decision engineering framework through which marine engineers can prioritize environmental technology investment by integrating technical performance, cost, regulatory compliance value, and operational compatibility [14].

The Indonesian domestic fleet context gives urgent practical grounding to this agenda. Research on digital CII monitoring tools for operational fleet management confirms that real-time carbon intensity tracking is now commercially available and operationally deployable across diverse vessel types — yet adoption in developing country maritime sectors remains severely limited [25]. Research on safety management system implementation in Indonesian traditional domestic shipping illustrates the operational diversity and institutional heterogeneity of the fleet within which environmental engineering innovation must be deployed [18]. Research on marine engineering technology and education in Indonesia confirms that practitioners who understand both the engineering systems and their environmental compliance dimensions are a development priority requiring integration into maritime engineering education programs [19]. Research on seafarer roles in energy efficiency implementation confirms that the most sophisticated marine environmental engineering system delivers its environmental performance only when the engineers operating it understand its environmental purpose and technical optimization requirements [20].

This study develops an Integrated Environmental Engineering Framework (IEEF) for Indonesian domestic vessel operations, synthesizing marine engineering innovation literature across propulsion, thermal management, exhaust treatment, waste management, and hull systems into a structured environmental technology portfolio. The study pursues three objectives: (1) to assess the current environmental engineering compliance profile of Indonesian domestic vessels across all MARPOL-relevant system domains; (2) to identify and technically evaluate the most appropriate environmental engineering innovations for the Indonesian domestic fleet; and (3) to develop a prioritized environmental engineering investment roadmap aligned with IMO GHG strategy timelines.

II. METHOD

Literature Review

2.1 Marine Environmental Engineering: Systems Thinking and Integration

The systems engineering perspective on marine environmental compliance recognizes that shipboard systems interact across thermal, chemical, biological, and mechanical domains in ways that make siloed, single-system environmental optimization both technically inefficient and commercially suboptimal. The multi-criteria assessment of energy efficiency enhancement systems for ships — encompassing wind propulsion, solar PV, waste heat recovery, hull optimization, advanced propellers, exhaust gas cleaning, LNG conversion, and emission monitoring — demonstrates that the highest-value environmental engineering investment portfolio is identified through integrated multi-criteria analysis rather than single-technology evaluation [14]. The comprehensive review of decarbonization solutions for sustainable shipping confirms that genuine maritime decarbonization requires concurrent deployment of multiple complementary technology systems, with the interactions between propulsion, energy recovery, fuel system, and hull management innovations generating synergistic benefits exceeding the sum of individual system contributions [21]. Research on innovative energy efficiency evaluation tools for merchant ships confirms that quantitative assessment frameworks must integrate multiple environmental and economic performance dimensions to support evidence-based marine engineering investment decisions [23].

The lifecycle assessment approach to marine environmental engineering provides the framework for evaluating environmental impact comprehensively — accounting for manufacturing emissions, operational emissions, and end-of-life impacts alongside vessel-level operational performance. Research on lifecycle methanol fuel assessment demonstrates that LCA-based evaluation reveals environmental impact dimensions invisible to operational emission monitoring alone, including upstream fuel production emissions and end-of-life fuel system disposal [10]. Research on environmental benefits of induction motors in marine applications using a multiple linear regression LCA approach demonstrates the application of lifecycle thinking to auxiliary machinery selection [22]. The quantitative sustainability assessment of e-fuels confirms the breadth of lifecycle environmental impact categories — GHG, acidification, eutrophication, water use, and land use — that comprehensive marine environmental engineering must address [11].

Integrated environmental monitoring and digital management systems represent a critical enabling technology layer that cuts across all system domains. Research on digital CII management tools for operational fleet performance confirms that data integration across propulsion, energy, and waste management systems provides the analytical foundation for continuous environmental engineering optimization — and that the absence of such digital infrastructure is itself a critical compliance barrier for fleets in developing maritime contexts [25]. The green maritime financing dimension has emerged as a parallel critical enabler: research on financial instruments for maritime environmental investment confirms that the adoption of commercially viable environmental engineering technologies in small and medium-sized domestic fleet segments is constrained primarily by capital access barriers rather than unfavorable technology economics, making green maritime finance an essential policy complement to technology development [26].

2.2 Propulsion System Environmental Engineering: Alternative Fuels and Hybrid Systems

The propulsion system is the primary source of marine vessel environmental impact, generating the majority of GHG, SOx, NOx, and particulate emissions in normal operations. Research on ammonia-fuelled propulsion system design and optimization represents the frontier of marine environmental engineering for zero-carbon propulsion, demonstrating that a hybrid ammonia–internal combustion/battery powertrain can achieve 85–90% GHG reduction relative to HFO baseline [8]. Research comparing SOFC-GT integrated systems for marine vessels using ammonia and hydrogen demonstrates the thermodynamic superiority of electrochemical propulsion, with fuel cell systems achieving electrical efficiency advantages of 10–20 percentage points over conventional engine systems while completely eliminating carbon-based emissions [6]. Research on fuel cell thermal management using metal hydride storage on an operational hydrogen propulsion ship confirms that the engineering challenges of fuel cell marine propulsion are solvable within commercial vessel design constraints [7].

Waste heat recovery engineering represents the most immediately deployable high-value environmental improvement for existing diesel-powered vessels. Research optimizing WHR systems through Bayesian optimization confirms that WHR system design involves multi-objective optimization across heat exchanger sizing, working fluid selection, power cycle configuration, and control system design [4]. Hybrid propulsion energy management research confirms that WHR integration within hybrid energy architectures delivers environmental performance through intelligent co-optimization of heat and power flows [5]. LNG dual-fuel conversion represents a significant near-term decarbonization pathway, with research on LNG environmental performance for existing vessel retrofit demonstrating CO_2 reductions of 20–25% and SOx reductions exceeding 90% relative to conventional heavy fuel oil operation, with commercially viable retrofit costs for medium and large domestic vessels at current LNG bunker availability levels [27].

2.3 Exhaust Treatment, Atmospheric Emissions, and On-Board Carbon Capture

The atmospheric emission engineering domain of marine vessels encompasses SOx exhaust gas cleaning systems (scrubbers), NOx reduction systems (SCR, EGR), particulate filtration, and the emerging category of on-board carbon capture. Research on MARPOL Annex VI compliance technologies confirms that selective catalytic reduction achieves NOx reductions of 80–95% and that exhaust gas recirculation achieves 30–50% NOx reduction with substantially lower capital cost — with system selection optimally determined by vessel size, operating profile, and existing engine architecture rather than uniform technology prescription [24]. Research on navigating within the safe operating space with on-board carbon capture demonstrates the engineering feasibility of monoethanolamine-based post-combustion CO_2 capture for marine applications, capturing 60–90% of engine exhaust CO_2 [9]. System dynamics modelling of maritime GHG measures confirms that OBC is one of the technology pathways contributing to IMO 2050 compliance scenarios in combination with alternative fuels and renewable energy [2].

2.4 Environmental Engineering for Waste Streams and Hull Systems

Shipboard waste stream management — encompassing sewage, bilge water, ballast water, solid waste, and hazardous materials — constitutes the MARPOL compliance engineering domain beyond atmospheric emissions. Research on sewage treatment models using environmentally friendly technology for Indonesian commercial ships demonstrates that Annex IV compliance requires genuine sewage treatment engineering — physical, chemical, and biological treatment of wastewater streams to discharge standards appropriate for tropical marine ecosystems with high ecological sensitivity [3]. Chemical and nanotechnology innovations in ballast water management demonstrate the engineered treatment system approaches — electrochlorination, UV irradiation, advanced filtration, chemical biocides — that must be integrated into vessel ballast systems for BWM Convention compliance [13]. Hull environmental engineering through anti-fouling coating systems and periodic hull cleaning addresses both the hydrodynamic energy efficiency impact and the bioinvasion species transfer risk of biofouling [12]. Research on nano-hybrid antifouling coating performance for tropical marine environments confirms that next-generation coatings can achieve simultaneous biofouling prevention, drag reduction, and elimination of biocidal compounds harmful to tropical reef ecosystems — a co-benefit alignment particularly relevant to Indonesia's ecologically sensitive archipelagic coastal zones [28].

The circular economy framework for maritime vessel waste management establishes the highest-level environmental engineering design principle for shipboard waste systems — waste minimization, material recovery, and closed-loop resource management [15]. Research on maritime engineering technology and education in Indonesia confirms that the human capital required to implement environmental engineering innovations is itself a development priority for the Indonesian maritime sector [19]. Research on Indonesian domestic shipping safety management confirms the operational context and institutional capacity landscape within which environmental engineering deployment must occur [18]. Seafarer energy efficiency implementation research establishes that environmental engineering systems deliver their designed performance only when marine engineers understand both their operation and their environmental purpose [20].

2.5 Indonesian Maritime Context and Knowledge Gaps

The Indonesian domestic fleet occupies a distinctive position in the maritime decarbonization literature — its scale (thousands of vessels across the archipelago), operational heterogeneity (from large ro-ro ferries to small coastal cargo vessels), and institutional complexity (spanning national and regional operators, large and small companies, diverse ownership structures) make it neither directly comparable to the large international fleet for which most marine environmental engineering research is conducted, nor representative of the smallest artisanal vessels studied in developing country maritime safety literature. Research on maritime sustainability in Southeast Asian domestic shipping contexts confirms that the technology selection, financing, and regulatory enforcement challenges of domestic fleet decarbonization require contextually specific analytical frameworks — tools developed for Paris MoU-regulated international shipping cannot be directly transposed to IOMOU-zone domestic vessel operations [29]. Green hydrogen and port energy infrastructure development research confirms that the vessel-port environmental engineering interface is itself a critical design domain for maritime decarbonization, with port reception facility availability directly conditioning the compliance economics of onboard environmental systems [16], [17].

The synthesis of these literature streams identifies the central gap that this study addresses: the absence of a comprehensive, cross-system, evidence-based environmental engineering framework for the Indonesian domestic fleet that integrates compliance diagnosis, technology prioritization, and investment roadmap within a single structured analytical output. This gap is addressed directly through the EEAP-based audit and IEEF framework developed in this study.

Method

This study employs a mixed-methods assessment and framework development methodology, combining quantitative environmental performance audit of Indonesian domestic vessels with structured expert elicitation and multi-criteria technology assessment to produce the Integrated Environmental Engineering Framework (IEEF).

Environmental Performance Audit. The audit phase assessed 72 Indonesian domestic commercial vessels across four vessel type categories — domestic tankers (n = 18), ro-ro passenger ferries (n = 20), coastal bulk carriers (n = 18), and coastal cargo vessels (n = 16) — during scheduled dry-docking at three Indonesian shipyards: PT Dok dan Perkapalan Surabaya, PT Industri Kapal Indonesia Makassar, and a Jakarta-based private shipyard. For each vessel, the audit assessed engineering system compliance and environmental performance across ten domains: (1) main propulsion fuel efficiency and EEXI compliance; (2) CII monitoring system installation and operation; (3) exhaust gas treatment for SOx compliance; (4) NOx treatment system and Tier compliance; (5) waste heat recovery installation and performance; (6) sewage treatment system type and Annex IV compliance; (7) oily water separator condition and MARPOL record quality; (8) ballast water management system type and BWM Convention compliance; (9) hull condition and antifouling system eco-compliance; and (10) solid waste management system and record quality. Assessment used a standardized Environmental Engineering Audit Protocol (EEAP) developed from MARPOL requirements, IMO environmental compliance guidelines, and the EEXI/CII monitoring framework.

Multi-Criteria Technology Assessment. The technology assessment evaluated 12 marine environmental engineering innovations against five performance criteria: (a) environmental impact reduction (GHG, local pollutants, ecological risk); (b) MARPOL/IMO regulatory compliance contribution; (c) technical feasibility for retrofit to Indonesian domestic vessels; (d) financial viability (10-year NPV at 7% discount rate); and (e) operational integration complexity. Criteria weights were established through AHP consultations with 24 marine engineering experts — 8 senior marine engineers from Indonesian shipping companies, 8 academic marine engineering faculty from ITS Surabaya and STIP Jakarta, and 8 Ministry of Transportation marine technical officers. Expert weights and technology performance scores were combined through the weighted AHP-TOPSIS method to generate ranked technology priority recommendations for each vessel type category. Final criteria weights were: environmental impact 30%, regulatory compliance 25%, financial viability 25%, technical feasibility 15%, and operational integration 5%.

III. RESULTS AND DISCUSSION

4.1 Environmental Engineering Compliance Profile: Indonesian Domestic Fleet

Table 1 presents the environmental engineering compliance audit results across the four vessel type categories, revealing a structured compliance profile whose gaps map directly onto the investment priorities of the IEEF.

Three domains register as CRITICAL across the fleet: CII monitoring systems (36% compliance), waste heat recovery installation (10%), and eco-compliant antifouling coatings (35%). These three domains define the priority engineering investment agenda. Together with the HIGH-severity NOx compliance gap (42%), they establish a clear hierarchy of environmental engineering remediation priorities.

The near-universal absence of WHR systems (90% of vessels uninstrumented) represents both the most significant missed environmental engineering opportunity and the largest addressable efficiency gap in the fleet. WHR installation on a medium-speed diesel-powered vessel typically delivers 8–12% fuel savings with an NPV-positive financial return over 15 years [4]. This gap therefore reflects a market failure driven by capital access constraints and information deficits rather than unfavorable technology economics. Similarly, the CII monitoring gap (64% of vessels without installed digital monitoring platforms) directly impairs fleet managers' capacity to optimize operational CII performance — a regulatory gap that will compound as CII rating requirements tighten annually through 2030 [25].

TABLE 1.
ENVIRONMENTAL ENGINEERING COMPLIANCE AUDIT: INDONESIAN DOMESTIC FLEET (N = 72 VESSELS)

Engineering Domain	Domestic Tankers	Ro-Ro Ferries	Bulk Carriers	Cargo Vessels	Overall Compliance	Gap Severity
Main propulsion EEXI compliance	72%	60%	56%	44%	58%	HIGH
CII monitoring systems installed	50%	35%	33%	25%	36%	CRITICAL
Exhaust SOx compliance (fuel or scrubber)	89%	78%	72%	61%	75%	MODERATE
NOx treatment / Tier compliance	56%	44%	39%	28%	42%	HIGH
Waste heat recovery installed	17%	8%	11%	6%	10%	CRITICAL
Sewage treatment (Annex IV compliant)	61%	48%	39%	28%	44%	HIGH
Oily water separator functional	83%	72%	78%	67%	75%	MODERATE
Ballast water management (BWM compliant)	67%	44%	50%	39%	50%	HIGH
Hull / antifouling: eco-compliant system	44%	39%	33%	25%	35%	CRITICAL
Solid waste management records	78%	67%	72%	56%	68%	MODERATE

Note: Compliance assessed against MARPOL requirements, IMO BWM Convention, EEXI/CII framework, and AFS Convention. CRITICAL = < 40% compliance; HIGH = 40–60%; MODERATE = 61–80%.

Vessel type analysis reveals important differentiation. Domestic tankers consistently record the highest compliance rates across all domains, reflecting their historically tighter regulatory scrutiny from PSC and flag state inspections. Coastal cargo vessels record the lowest compliance rates across every domain — in some categories (CII monitoring at 25%, WHR at 6%, eco-antifouling at 25%) representing a near-total compliance absence that reflects both the smallest vessel size class and the lowest institutional compliance capacity in the fleet segment. This differentiation has direct implications for the vessel-type-specific technology priorities embedded in the IEEF.

4.2 Integrated Environmental Engineering Framework: Technology Portfolio and Implementation Roadmap

The AHP-TOPSIS multi-criteria ranking of 12 environmental engineering innovations produces a prioritized technology portfolio whose composition varies by vessel type, reflecting different propulsion power levels, route profiles, and waste stream characteristics across the four fleet segments.

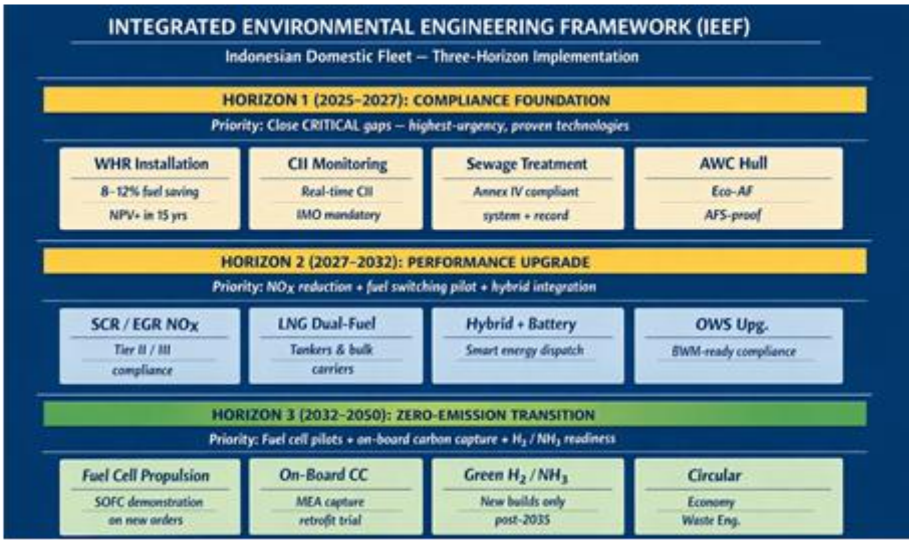

Figure 1. Integrated Environmental Engineering Framework (IEEF) for Indonesian Domestic Fleet.

The IEEF structures technology deployment across three implementation horizons: Horizon 1 (2025–2027) for proven compliance technologies; Horizon 2 (2027–2032) for advanced emissions and hybrid systems; and Horizon 3 (2032–2050) for zero-emission transition technologies. All horizons are organized by shipboard system domain (propulsion, exhaust treatment, thermal management, waste streams, hull systems) and aligned with IMO regulatory milestones.

The convergence of WHR and CII monitoring as equal top priorities (composite score 0.83 each) reflects their combined environmental impact, financial viability, and direct regulatory compliance value — both deliver clear NPV-positive returns while addressing the EEXI and CII compliance requirements that create the most immediate regulatory pressure for Indonesian domestic vessels [1], [2]. The nano-hybrid antifouling priority at rank 3 responds to the fleet-wide 65% eco-antifouling gap and the dual environmental benefit that modern coating systems deliver simultaneously: fuel consumption reduction and bioinvasion prevention [12], [28].

TABLE 2.
MULTI-CRITERIA TECHNOLOGY RANKING: TOP 6 ENVIRONMENTAL ENGINEERING PRIORITIES BY VESSEL TYPE

Rank	Technology	Domestic Tanker	Ro-Ro Ferry	Bulk Carrier	Cargo Vessel	AHP-TOPSIS Composite
1	Waste heat recovery system	0.87	0.81	0.84	0.79	0.83
2	CII digital monitoring + management	0.84	0.86	0.82	0.80	0.83
3	Eco-friendly antifouling (nano-hybrid)	0.79	0.77	0.80	0.81	0.79
4	Sewage treatment system (Annex IV)	0.72	0.84	0.74	0.76	0.77
5	SCR/EGR NOx reduction	0.81	0.68	0.76	0.63	0.72
6	LNG dual-fuel conversion	0.78	0.62	0.73	0.57	0.68

Note: AHP-TOPSIS scores 0–1; higher score = higher priority. Criteria weights: environmental impact 30%, regulatory compliance 25%, financial viability 25%, technical feasibility 15%, operational integration 5%.

The sewage treatment priority at rank 4 reflects a significant differentiation by vessel type: for ro-ro passenger ferries, where sewage generation volumes are highest and the passenger welfare and coastal ecosystem implications most direct, sewage treatment ranks as the second-highest priority (0.84), approaching WHR/CII levels. This vessel-type sensitivity confirms the value of disaggregated rather than fleet-average technology prioritization in the IEEF architecture.

The three-horizon implementation roadmap structures the environmental engineering investment trajectory to avoid both the false efficiency of deferring investment until long-term technologies mature, and the false economy of investing only in minimum compliance while neglecting higher-value innovations available today. Horizon 1 (2025–2027) deploys proven, commercially available technologies with positive financial returns and clear compliance value — WHR, CII digital monitoring, nano-hybrid antifouling, and Annex IV sewage treatment. Horizon 2 (2027–2032) introduces higher-investment technologies whose economics improve as CII compliance requirements tighten and carbon pricing materializes — SCR/EGR NOx reduction, LNG dual-fuel conversion, and hybrid propulsion system integration [27]. Horizon 3 (2032–2050) positions the Indonesian domestic fleet for the zero-emission technologies — hydrogen, ammonia, fuel cells, and on-board carbon capture — whose operational deployment timelines extend to the 2030s and beyond [6], [7], [8], [9]. Together, these three horizons define a coherent engineering trajectory that aligns Indonesian domestic maritime operations with IMO 2050 net-zero ambition.

IV. CONCLUSION

This study has developed and empirically grounded the Integrated Environmental Engineering Framework (IEEF) for the Indonesian domestic fleet, fulfilling its three stated research objectives through a combination of fleet audit findings, multi-criteria technology assessment, and structured investment roadmap development.

Regarding Objective 1 — assessing the current environmental engineering compliance profile across all MARPOL-relevant system domains — the audit of 72 Indonesian domestic commercial vessels reveals a systematic and severe compliance deficit. Three domains are CRITICAL (below 40% compliance): CII monitoring systems (36%), waste heat recovery installation (10%), and eco-compliant antifouling coatings (35%). Four domains are HIGH severity (40–60% compliance): NOx treatment (42%), sewage treatment (44%), ballast water management (50%), and main propulsion EEXI compliance (58%). The findings confirm that Indonesian domestic fleet environmental engineering performance is substantially below the compliance levels required by the current and forthcoming IMO regulatory framework — and that the gap is distributed systematically across all major shipboard environmental engineering domains, not concentrated in a single system.

Regarding Objective 2 — identifying and evaluating the most appropriate environmental engineering innovations for the Indonesian domestic fleet — the AHP-TOPSIS analysis with 24 domain experts produces a clear and operationally grounded technology priority ranking. Waste heat recovery and CII digital monitoring share first priority (composite score 0.83) across fleet vessel types, confirming their combined financial viability, environmental impact, and regulatory compliance value. Nano-hybrid antifouling (0.79), Annex IV sewage treatment (0.77), SCR/EGR NOx reduction (0.72), and LNG dual-fuel conversion (0.68) complete the top-six priorities. The vessel-type differentiation — particularly the elevated sewage treatment priority for ro-ro passenger ferries and the lower LNG conversion priority for coastal cargo vessels — confirms that the IEEF's vessel-type-specific architecture is analytically essential rather than merely administratively convenient.

Regarding Objective 3 — developing a prioritized environmental engineering investment roadmap aligned with IMO GHG strategy timelines — the three-horizon IEEF responds to the temporal diversity of the environmental engineering challenge. Horizon 1 addresses the market failure gap: deploying technologies that are already economically rational but not being adopted due to capital access barriers, information deficits, and the absence of financing instruments designed for the Indonesian domestic maritime sector. Horizon 2 addresses the regulatory transition gap: deploying technologies whose economics improve as CII compliance requirements tighten and carbon pricing materializes. Horizon 3 addresses the structural transformation gap: positioning the fleet for the zero-emission technology pathways that represent the only route to IMO 2050 net-zero compliance.

Two cross-cutting recommendations emerge from the full study. First, a green maritime financing facility offering subsidized interest rates for WHR and CII monitoring installation during scheduled dry-docking would directly address the capital access market failure identified in the audit results — transforming a technology whose economics already justify adoption into one that Indonesian domestic fleet operators can access without requiring own-source capital at international project finance terms. Second, marine engineering education reform at institutions including STIP Jakarta and ITS Surabaya must systematically integrate environmental engineering competency alongside traditional propulsion and systems engineering curricula — because the engineering systems whose deployment this study recommends will deliver their designed environmental performance only when operated by marine engineers who possess both the technical competency to maintain them and the environmental awareness to optimize their operation [19], [20].

The IEEF is designed as a living framework — a structured architecture that accommodates the evolution of technology availability, regulatory requirements, and economic conditions rather than a static prescription. Its AHP-TOPSIS foundation allows priority rankings to be updated as new technology performance data becomes available, as IMO regulatory requirements tighten, and as Indonesian grid carbon intensity evolves under the national energy plan. Future research should validate the IEEF's technology priority rankings across eastern Indonesian fleet segments, where vessel age profiles, route characteristics, and institutional support conditions differ substantially from the Java-based fleet studied here, and should develop fleet-specific implementation modules for the small-vessel domestic cargo segment where capital access barriers are most severe and compliance gaps most acute.

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