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Green technology applications in maritime transportation engineering for sustainable operations

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Abstract. This qualitative study investigates stakeholder perspectives on integrating green technologies and sustainability competencies within maritime education frameworks in Indonesia. Through semi-structured interviews with 15 maritime professionals, 10 educators, and 12 recent graduates (N=37), the research examines the alignment between educational preparedness and industry implementation requirements for sustainable maritime operations. Thematic analysis reveals substantial gaps between theoretical knowledge transfer (averaging 8.3/10) and workplace application rates (33-58%), with professionals citing capital constraints, regulatory uncertainties, and technical capacity limitations as primary adoption barriers despite demonstrated green technology benefits. Educators report resource constraints limiting hands-on training capabilities, while graduates identify deficiencies in troubleshooting skills, economic analysis competencies, and stakeholder communication abilities essential for operational contexts. Findings indicate misalignment between curriculum expansion efforts (90% educator support) and immediate industry demand (60% conditional adoption willingness), suggesting potential credential inflation risks. The research contributes empirical evidence linking educational interventions to workforce preparedness outcomes and proposes differentiated implementation pathways addressing scale-dependent barriers in developing maritime economies pursuing sustainability transitions.

1 Introduction

The global maritime industry stands at a critical inflection point between operational tradition and environmental imperatives. Transporting approximately 80% of world merchandise trade while contributing 2-3% of global greenhouse gas emissions, the shipping sector faces unprecedented regulatory pressure to transform operational paradigms toward sustainable practices [1]. The International Maritime Organization's 2018 Initial Strategy mandates a 50% reduction in total annual emissions by 2050 compared to 2008 baselines, compelling maritime stakeholders across educational institutions, regulatory bodies, and commercial operators to fundamentally reconsider how knowledge, skills, and technological capabilities

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are developed, transferred, and implemented [2]. Yet despite expanding availability of green technologies—including liquefied natural gas propulsion systems, hybrid diesel-electric configurations, shore power infrastructure, and renewable energy applications—adoption rates remain substantially below trajectories needed to achieve regulatory targets, revealing complex barriers that extend beyond technological readiness to encompass economic feasibility, workforce preparedness, and institutional capacity [3].

This adoption paradox presents particularly acute challenges for developing maritime economies, where capital constraints, infrastructure limitations, and evolving educational systems intersect with global sustainability mandates. Indonesia, with its extensive archipelagic geography, substantial domestic shipping operations, and expanding maritime education sector, exemplifies these tensions. Maritime education institutions have responded to sustainability imperatives by integrating environmental content into curricula, yet empirical evidence documenting whether these educational interventions effectively translate into workplace competencies capable of driving actual green technology implementation remains limited [4]. While existing literature examines technological performance characteristics, economic feasibility assessments, or curriculum reform initiatives, research integrating stakeholder perspectives across industry professionals, educators, and recent graduates to understand the complex relationships among educational preparedness, implementation capacity, and adoption decision-making remains notably scarce [5].

The research problem addressed in this study centers on understanding how maritime education systems can effectively prepare graduates for sustainability implementation roles while navigating the documented gap between educational outputs and industry absorption capacity. Specifically, this investigation examines three interconnected dimensions: First, how do maritime professionals perceive green technology adoption barriers and enablers within operational contexts characterized by resource constraints and evolving regulatory frameworks? Second, to what extent do maritime education programs effectively develop practical sustainability competencies beyond theoretical knowledge transfer, and what specific gaps constrain graduates' workplace application capabilities? Third, what factors explain the documented divergence between positive stakeholder attitudes toward sustainability and actual implementation behaviors, and how might educational and policy interventions address these barriers? These questions respond to critical knowledge gaps in maritime sustainability literature, which has predominantly focused on developed maritime nations while underrepresenting the experiences, constraints, and adaptation pathways of emerging maritime economies navigating sustainability transitions [6, 7].

Understanding these dynamics holds substantial significance for multiple stakeholder groups. For maritime education institutions, evidence documenting the effectiveness of sustainability curriculum integration informs resource allocation decisions and pedagogical approach refinement, particularly important given limited budgets and competing curriculum priorities. For industry operators, insights into implementation barriers and workforce competency requirements guide adoption strategies and human capital development investments. For policymakers, empirical evidence linking educational preparedness to implementation capacity enables more effective intervention design, ensuring that workforce development initiatives align with actual industry needs rather than creating mismatched credential supply [8]. More broadly, this research addresses fundamental questions about how vocational education systems can effectively support industrial transitions toward sustainability, recognizing that technological availability alone proves insufficient without corresponding workforce capabilities, economic incentives, and institutional support mechanisms.

This study employs a qualitative research design utilizing semi-structured interviews with 37 stakeholders across three groups: maritime professionals with direct operational and decision-making responsibilities (n=15), maritime educators involved in curriculum design and instruction delivery (n=10), and recent graduates currently employed in maritime operations (n=12). This multi-stakeholder approach enables triangulation of perspectives, revealing convergence and divergence across groups regarding sustainability implementation challenges, educational effectiveness, and adoption decision factors. Thematic analysis of interview transcripts identifies recurring patterns, contextual nuances, and explanatory mechanisms linking educational interventions to workplace outcomes and operational adoption behaviors. The Indonesian maritime context—characterized by diverse operator scales, developing infrastructure, expanding educational capacity, and resource constraints typical of emerging economies—provides valuable insights applicable to similar maritime nations navigating comparable sustainability transition challenges. Through systematic examination of stakeholder experiences, perceptions, and reported gaps between educational preparation and operational requirements, this research contributes empirical evidence addressing critical questions about workforce development effectiveness in driving maritime sustainability transitions.

2 Research method

This qualitative investigation employed a purposive sampling strategy to ensure representation across key stakeholder groups possessing relevant knowledge, experience, and perspectives on maritime sustainability education and implementation. The research design recognized that different stakeholders occupy distinct positions within the maritime education-to-implementation continuum, each offering unique insights into how sustainability competencies are developed, transferred, and applied in operational contexts [9]. Maritime professionals (n=15) were selected based on direct involvement in green technology evaluation, adoption decision-making, or operational management, representing organizations ranging from small domestic operators managing 2-5 vessels to regional carriers operating fleets exceeding 20 vessels. This scale diversity proved critical for capturing variation in resource availability, technical capacity, and adoption feasibility across different operator segments. Maritime educators (n=10) were recruited from three Indonesian maritime education institutions—two merchant marine academies and one maritime university—based on their instructional responsibilities in courses addressing marine engineering, environmental management, or sustainability topics, ensuring perspectives from individuals directly engaged in curriculum design and delivery. Recent graduates (n=12) were identified through institutional alumni networks, selecting individuals who graduated between 2021-2023 and currently hold positions in maritime operations, port management, or marine engineering roles where sustainability competencies would be relevant, enabling assessment of educational effectiveness through workplace application experiences.

The research instrument consisted of semi-structured interview protocols tailored to each stakeholder group while maintaining consistency in core thematic areas to enable cross-group comparison [10]. For maritime professionals, the protocol addressed operational experiences with green technologies as independent variables, exploring decision-making processes, perceived implementation barriers, economic considerations, and workforce capability assessments as dependent outcome variables. Specific indicators included capital cost perceptions, payback period expectations, technical integration challenges, regulatory clarity concerns, and workforce competency requirements. For educators, the protocol examined curriculum development processes as independent variables, investigating sustainability content integration approaches, resource availability, pedagogical strategies, and perceived effectiveness as dependent variables, with indicators including contact hours dedicated to sustainability topics, hands-on training equipment access, faculty professional development opportunities, and graduate preparedness assessments. For graduates, the protocol explored educational experiences as independent variables and workplace application patterns as dependent outcomes, with indicators including knowledge transfer effectiveness ratings, competency gap identification, troubleshooting capability assessments, and professional skill requirements. Supporting instruments included demographic questionnaires capturing relevant background characteristics such as organizational size, years of experience, educational qualifications, and current job responsibilities, enabling contextual interpretation of interview responses.

Data collection occurred over a four-month period between August and November 2023, following institutional ethics approval and informed consent procedures. Interviews lasted 45-75 minutes, conducted in Indonesian to ensure participant comfort and depth of expression, with audio recording upon consent. The interview process began with rapport-building through general questions about professional backgrounds before transitioning to specific sustainability topics, allowing participants to contextualize their responses within broader career experiences. Probing questions followed up on initial responses to elicit concrete examples, specific incidents, and detailed explanations rather than abstract generalizations. Interviews continued within each stakeholder group until thematic saturation was achieved—the point at which additional interviews yielded no substantial new themes or insights—ensuring comprehensive coverage of perspectives while maintaining research efficiency. Audio recordings were transcribed verbatim by professional transcription services, then verified for accuracy through researcher review against original recordings. Transcripts were subsequently translated into English by bilingual research assistants with maritime domain knowledge, with translation accuracy verified through back-translation procedures where a second translator converted English versions back to Indonesian, enabling identification and resolution of translation discrepancies.

Data analysis employed thematic analysis following established qualitative research protocols, beginning with familiarization through repeated reading of all transcripts to develop comprehensive understanding of dataset contents. Initial coding utilized NVivo 12 qualitative analysis software, with researchers applying descriptive codes identifying specific content elements such as "capital cost barriers," "curriculum resource constraints," or "troubleshooting skill gaps" through systematic line-by-line analysis. These descriptive codes were then grouped into broader analytical themes representing recurring patterns across multiple participants and stakeholder groups, such as "economic adoption barriers," "educational resource limitations," or "competency development gaps." Theme development involved iterative refinement, with researchers reviewing coded segments to ensure thematic coherence while identifying relationships, contradictions, and nuances within and across themes. Cross-group comparison systematically examined theme prevalence, emphasis, and interpretation differences among maritime professionals, educators, and graduates, revealing areas of convergence where stakeholder groups expressed similar perspectives and divergence where interpretations differed substantially. For example, while all groups acknowledged competency gaps, maritime professionals emphasized economic analysis skills, educators highlighted resource constraints limiting hands-on training, and graduates identified troubleshooting capabilities—revealing different perspectives on the same underlying educational effectiveness challenge. Narrative synthesis integrated thematic findings with contextual information from demographic data and field notes, developing coherent explanatory accounts that connected individual quotations and specific examples to broader patterns and theoretical interpretations. Inter-coder reliability was established through independent coding of 20% of transcripts by two researchers, achieving Cohen's kappa coefficient of 0.82, indicating substantial agreement and supporting analytical trustworthiness.

3 Results and discussion

3.1 Results

The qualitative analysis revealed four major thematic domains characterizing stakeholder perspectives on maritime sustainability education and green technology integration: (1) implementation barriers constraining adoption despite positive attitudes, (2) educational effectiveness gaps between knowledge transfer and workplace application, (3) competency development needs extending beyond technical training, and (4) conditional support requiring systemic enabling mechanisms.

3.1.1 Implementation barriers and adoption constraints

Maritime professionals (n=15) universally acknowledged the environmental and operational benefits of green technologies, yet 13 participants (87%) identified capital costs as the primary adoption barrier. Qualitative analysis revealed that these capital concerns extended beyond simple budget limitations to encompass risk perception, access to financing, and temporal misalignment between investment recovery periods and operational planning horizons. A regional shipping company chief financial officer articulated this complexity: "We recognize the 50% emission reduction targets and understand that green technologies will become mandatory. The technical performance data shows clear fuel efficiency improvements. But our challenge is not accepting these realities—it is finding financial pathways that align 7-10 year payback periods with our 5-year investment decision frameworks and 12-15% cost of capital when banks classify these as higher-risk investments requiring additional collateral."

Eight participants (53%) described technical integration challenges that exceeded initial expectations, with implementation timelines extending 20-40% beyond estimates and encountering compatibility issues requiring custom engineering solutions. These experiences revealed capacity gaps extending beyond equipment procurement to encompass system integration expertise, troubleshooting capabilities, and ongoing maintenance knowledge often unavailable locally. Six participants (40%) specifically mentioned regulatory uncertainties creating hesitancy, particularly regarding alternative fuel infrastructure availability, safety protocol variations across port authorities, and emission monitoring compliance pathways.

Despite these documented barriers, nine maritime professionals (60%) expressed conditional willingness to pursue green technology adoption within a 5-year timeframe—a figure indicating moderate receptivity but heavily qualified by external support requirements. Eleven participants (73%) explicitly stated that adoption feasibility depended on government subsidies, concessional financing programs, or risk-sharing mechanisms reducing capital exposure and improving return profiles. This finding revealed a critical attitude-behavior gap: while stakeholders expressed positive dispositions toward sustainability, structural barriers prevented these attitudes from translating into implementation behaviors without systemic interventions addressing documented constraints.

3.1.2 Educational effectiveness and knowledge-practice gaps

Maritime educators (n=10) reported substantial curriculum expansion efforts undertaken between 2020-2023 in response to sustainability imperatives. Eight institutions (80%) added dedicated sustainability modules ranging from 12-24 contact hours, six institutions (60%) incorporated green technology case studies into existing marine engineering courses, and four institutions (40%) included hands-on laboratory training with renewable energy equipment. These curriculum changes represented significant institutional investments and demonstrated educational sector responsiveness to evolving industry requirements and regulatory frameworks.

However, nine educators (90%) acknowledged significant resource constraints limiting the depth and practical orientation of sustainability instruction. Access to advanced training equipment—particularly hybrid propulsion simulators, LNG fuel handling systems, and shore power infrastructure components—remained limited by budget constraints, with most institutions unable to provide hands-on experience beyond basic solar panel demonstrations and energy management system interfaces. Seven educators (70%) identified faculty capacity limitations, noting that while instructors possessed strong expertise in traditional marine engineering, many were still developing knowledge of emerging green technologies through self-directed learning, professional development programs, and industry collaboration rather than possessing established teaching expertise in these areas.

Graduate perspectives (n=12) revealed critical gaps between educational preparation and workplace application requirements. While graduates rated knowledge transfer effectiveness relatively highly—averaging 8.3 on a 10-point scale across sustainability-related courses—only 33-58% reported applying this knowledge in professional roles within 6-18 months post-graduation. Qualitative analysis identified three specific competency gaps constraining workplace application:

1. Troubleshooting and Diagnostic Skills
   Seven graduates (58%) reported that while they understood green technology operating principles theoretically, they lacked practical skills in diagnosing malfunctions, resolving integration issues, or adapting systems to specific operational contexts. A marine engineer with two years of experience explained: "When hybrid propulsion battery management faults occurred, I could explain how the system should work—the charge-discharge cycles, power distribution logic, efficiency parameters. But I couldn't systematically diagnose what was actually failing. The curriculum taught us ideal operation, not troubleshooting real-world problems under resource constraints."
2. Economic and Financial Analysis Competencies
   Nine graduates (75%) identified gaps in economic feasibility assessment capabilities that proved critical in professional decision-making contexts. While environmental benefits and emission reduction calculations were covered extensively in coursework, payback period analysis, net present value calculations, risk assessment frameworks, and cost-benefit modeling under different operational scenarios received limited attention. A port operations officer noted: "Management expected me to evaluate shore power business cases—analyzing connection fees, utilization scenarios, grid cost variations, and payback timelines. I had learned that shore power reduces emissions by 95% during berthing, but I was unprepared for financial modeling that determines whether we actually invest."
3. Professional and Communication Skills
   Eight graduates (67%) emphasized gaps in stakeholder communication, business case presentation, regulatory navigation, and cross-functional collaboration capabilities extending beyond technical knowledge. A maritime sustainability coordinator explained: "Technical competence is necessary but insufficient. I needed skills in communicating sustainability value propositions to executives focused on quarterly earnings, negotiating with financial institutions unfamiliar with maritime green technologies, and engaging regulatory authorities on compliance pathways—capabilities my technical education barely addressed."

These competency gaps reveal a fundamental educational effectiveness challenge: successful knowledge transfer—evidenced by high test scores and theoretical understanding—does not automatically translate to practical implementation capacity. Graduates possess conceptual knowledge about green technologies but often lack the integrated skill sets required to evaluate, implement, troubleshoot, and advocate for these technologies within organizational and operational constraints.

3.1.3 Competency development needs and pedagogical implications

Cross-group analysis revealed convergence around competency development needs extending beyond current curriculum scope. Maritime professionals identified economic literacy (ability to conduct cost-benefit analyses, understand financial instruments, evaluate investment risks) as critical workforce competencies often underdeveloped in maritime engineering graduates. Educators acknowledged these gaps but cited curriculum structure challenges, noting that integrating interdisciplinary content spanning engineering, economics, environmental science, and professional communication within credit-limited programs requires difficult tradeoffs against traditional maritime competencies still demanded by licensing requirements and industry employers.

Recent graduates consistently emphasized experiential learning deficits—opportunities to work with actual equipment, encounter real-world integration challenges, practice troubleshooting under time pressure, and develop judgment through trial-and-error learning that classroom instruction cannot replicate. Five graduates (42%) suggested mandatory 3-6 month industry internships specifically focused on sustainability implementation projects, rather than general shipboard training, would substantially improve practical preparedness. Four graduates (33%) recommended collaborative industry-academia equipment sharing arrangements, enabling multiple institutions to jointly invest in expensive training infrastructure (hybrid propulsion testbeds, LNG simulation systems) that individual programs cannot afford independently.

3.1.4 Conditional support and systemic enablers

Despite documented barriers and competency gaps, stakeholder attitudes remained generally positive toward maritime sustainability transitions when accompanied by appropriate enabling mechanisms. Maritime professionals' 60% conditional adoption willingness—while lower than educators' 90% curriculum expansion support—represented moderate receptivity rather than fundamental resistance. Qualitative analysis revealed that this apparent divergence stemmed not from attitudinal differences but from stakeholders' distinct positions within implementation pathways: educators face primarily resource and capacity constraints within their institutional control, while maritime professionals confront capital, regulatory, and market uncertainties requiring external interventions.

Eleven maritime professionals (73%) explicitly stated that targeted financial mechanisms—such as interest rate subsidies reducing effective capital costs by 3-4 percentage points, which could bring hybrid propulsion payback periods from 7.2 years to 5.3 years within acceptable investment horizons—would substantially shift adoption feasibility calculations. Eight participants (53%) emphasized regulatory clarity needs, particularly standardized LNG fuel quality specifications, harmonized bunkering safety protocols across port authorities, and clear emission monitoring compliance pathways eliminating regulatory uncertainty risks.

Educators identified three specific enablers that would enhance curriculum effectiveness: industry advisory boards providing direct input on competency priorities and curriculum relevance (desired by 9/10 educators, 90%), faculty professional development programs including industry secondments to build practical expertise in emerging technologies (requested by 8/10 educators, 80%), and collaborative equipment sharing arrangements enabling institutions to pool resources for expensive training infrastructure (supported by 7/10 educators, 70%).

3.2 Discussion

3.2.1 Interpreting the attitude-behavior gap

The documented divergence between stakeholder attitudes and adoption behaviors illuminates fundamental challenges in sustainability transitions that extend beyond technological readiness or environmental awareness. Maritime professionals' positive sustainability attitudes (60% expressing adoption intent) combined with low actual implementation rates reveal that behavioral change requires more than attitude shifts—it demands structural enablers aligning financial incentives, risk profiles, and capacity requirements with organizational capabilities. This finding extends theoretical frameworks emphasizing that pro-environmental attitudes predict behavior only when moderated by perceived behavioral control—the extent to which individuals believe they possess the resources, capabilities, and opportunities needed to perform behaviors. Maritime professionals recognize sustainability imperatives and genuinely support green technology adoption, yet perceive substantial constraints—capital availability, technical expertise, regulatory clarity—limiting their behavioral agency [11].

The educational effectiveness gap—high knowledge transfer scores (8.3/10) yet modest workplace application rates (33-58%)—reveals a parallel dynamic in workforce development. Maritime education successfully transfers conceptual knowledge, evidenced by graduates' ability to explain green technology operating principles, environmental benefits, and regulatory frameworks. However, operational contexts demand competencies beyond conceptual understanding: troubleshooting diagnostic skills, economic feasibility analysis capabilities, stakeholder communication proficiencies, and adaptive problem-solving under resource constraints. These practical competencies develop through experiential learning, trial-and-error practice, and situated application rather than classroom instruction alone—pedagogical approaches constrained by limited equipment access, faculty capacity gaps, and curriculum structure limitations that maritime educators face.

3.2.2 Competency development and pedagogical reform implications

Graduate-identified competency gaps—troubleshooting skills, economic analysis capabilities, professional communication competencies—suggest that effective maritime sustainability education requires integrated curriculum approaches bridging technical, economic, and professional domains rather than discipline-isolated instruction. Current maritime engineering programs emphasize technical understanding: how systems operate, what components comprise green technologies, how emission reductions are achieved. Yet operational implementation demands interdisciplinary integration: technical troubleshooting combined with economic feasibility assessment, environmental benefit quantification alongside stakeholder persuasion, regulatory compliance navigation integrated with organizational change management [12].

This finding aligns with competency-based education frameworks emphasizing outcomes—what graduates can actually do in professional contexts—over inputs measured by contact hours or content coverage. Competency-based approaches prioritize authentic assessment through performance tasks, workplace simulations, and portfolio demonstrations over traditional examinations testing knowledge recall. For maritime sustainability education, this suggests pedagogical reforms including: problem-based learning using real implementation cases requiring students to integrate technical, economic, and professional considerations; industry-based project experiences where students participate in actual feasibility studies, technology evaluations, or implementation planning; and simulation-based training enabling realistic troubleshooting practice without expensive equipment requirements [13].

3.2.3 Systemic barriers and differentiated intervention strategies

The conditional nature of stakeholder support—maritime professionals requiring financial mechanisms, educators needing resource investments, graduates seeking experiential opportunities—indicates that sustainability transitions require coordinated interventions across multiple domains rather than isolated initiatives. Technology-focused approaches assuming that green equipment availability will drive adoption prove insufficient when capital constraints, capacity gaps, and regulatory uncertainties create adoption barriers. Similarly, education-focused approaches assuming that curriculum expansion will produce workforce preparedness prove inadequate when resource limitations prevent hands-on training and industry adoption lags behind educational output, creating potential credential inflation where graduates possess competencies lacking immediate employer demand.

Effective intervention strategies must recognize heterogeneous stakeholder capabilities and constraints. Small maritime operators (2-5 vessels) face capital access limitations suggesting interventions emphasizing incremental efficiency improvements (energy management systems, operational optimization) with 40-50% capital subsidies and simplified application processes. Medium operators (5-20 vessels) may pursue hybrid propulsion or energy-efficient retrofits with concessional financing at 3-4% interest rates and technical assistance programs. Large operators (20+ vessels) can contemplate LNG conversions or shore power compatibility with tax incentives and accelerated depreciation. This differentiated approach recognizes that universal mandates or one-size-fits-all support mechanisms may be ineffective or inequitable when applied across diverse operator scales with substantially different resource profiles and capability constraints.

3.2.4 Study contributions and future research directions

This research contributes empirical evidence documenting the complex relationships among educational interventions, workforce preparedness, and operational implementation in maritime sustainability contexts. By integrating stakeholder perspectives across maritime professionals, educators, and recent graduates, the study reveals how implementation barriers, competency gaps, and systemic constraints interact to shape actual adoption outcomes despite positive stakeholder attitudes and expanding curriculum initiatives. These findings extend maritime sustainability literature by moving beyond technological performance assessments or curriculum descriptions to examine whether educational investments actually translate into workforce capabilities driving operational change.

Future research should pursue several directions building on these findings. Longitudinal studies tracking graduate cohorts over 5-10 years would reveal how workplace competencies evolve with experience and whether identified gaps diminish through on-the-job learning or persist as fundamental educational limitations. Comparative studies across multiple developing maritime economies would test whether documented patterns reflect Indonesian-specific contexts or represent broader challenges facing emerging maritime nations navigating sustainability transitions [14]. Quasi-experimental evaluations of specific pedagogical interventions—problem-based learning modules, industry internship programs, simulation-based training—would provide causal evidence regarding curriculum reform effectiveness rather than relying on correlational stakeholder assessments. Finally, studies examining the industry-education feedback mechanisms and governance structures enabling or constraining curriculum alignment with evolving workforce demands would inform institutional reform efforts seeking to enhance maritime education responsiveness and relevance.

4 Conclusion

This qualitative investigation of 37 stakeholders across maritime professionals, educators, and recent graduates reveals substantial gaps between educational preparation and operational implementation requirements for maritime sustainability transitions. While maritime education institutions have integrated sustainability content into curricula and successfully transfer theoretical knowledge (evidenced by 8.3/10 knowledge ratings), only 33-58% of graduates apply this knowledge in workplace contexts due to competency gaps in troubleshooting skills, economic analysis capabilities, and professional communication competencies extending beyond technical understanding. Maritime professionals express moderate conditional adoption willingness (60%) yet identify capital constraints, technical capacity limitations, and regulatory uncertainties as primary implementation barriers requiring systemic interventions beyond attitudinal change. The documented divergence between educators' curriculum expansion support (90%) and industry adoption readiness suggests potential workforce development misalignment risks requiring stronger industry-education feedback mechanisms and differentiated intervention strategies addressing heterogeneous stakeholder capabilities and constraints in developing maritime economies pursuing sustainability goals.

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