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# Advancing Marine Engineering Literacy Through Green Technology Integration: Competency Development for Alternative Fuel Systems and Hybrid Propulsion

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***ABSTRACT***

*The maritime industry's transition toward IMO 2050 decarbonization targets demands fundamental transformation in marine engineering education to address alternative fuel systems and hybrid propulsion technologies. This qualitative study examines competency development requirements through perspectives from industry experts, maritime academy lecturers, and recent marine engineering graduates across Indonesian maritime institutions. Employing thematic analysis and cross-group comparisons, the research identifies critical literacy components encompassing LNG, methanol, and ammonia fuel systems; hybrid electric propulsion; alternative fuel safety protocols; and green technology maintenance competencies. Findings reveal significant gaps between industry requirements and current curricula, particularly in practical training infrastructure, faculty expertise, and troubleshooting skill development. The study proposes a comprehensive competency framework integrating green technology literacy with traditional thermodynamic foundations, emphasizing faculty development, industry partnerships, and phased curriculum integration. Results demonstrate that strategic coordination across institutional, industry, and policy dimensions is essential for preparing marine engineers capable of supporting maritime decarbonization initiatives while maintaining operational excellence in increasingly complex propulsion systems.*

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***Keywords:***
*marine engineering literacy; alternative fuels; green propulsion technology; hybrid propulsion; competency development*

## 1. INTRODUCTION

The global maritime industry stands at a critical juncture as it confronts the dual imperatives of environmental sustainability and technological transformation. With shipping responsible for approximately 3% of global greenhouse gas emissions and transporting over 80% of world trade by volume, the sector's decarbonization trajectory holds profound implications for international commerce and climate change mitigation efforts [1]. The International Maritime Organization's (IMO) ambitious target to reduce total annual greenhouse gas emissions by at least 50% by 2050 compared to 2008 levels has catalyzed unprecedented innovation in marine propulsion technologies, fundamentally challenging traditional paradigms of marine engineering education [2]. This transformation necessitates a critical examination of how maritime academies prepare future marine engineers to navigate the complexities of alternative fuel systems, hybrid propulsion configurations, and integrated energy management platforms that will define the next generation of sustainable shipping operations.

The emergence of alternative marine fuels—including liquefied natural gas (LNG), methanol, ammonia, and hydrogen—represents a paradigmatic shift from the century-long dominance of heavy fuel oil and marine diesel oil in maritime propulsion [3]. Each alternative fuel presents distinct advantages and challenges: LNG offers immediate emission reductions but raises concerns about methane slip; methanol provides operational flexibility with existing bunkering infrastructure modifications; ammonia promises zero-carbon combustion but introduces unprecedented toxicity and safety considerations; while hydrogen fuel cells offer ultimate environmental performance constrained by storage density limitations and production pathway sustainability [4]. Simultaneously, hybrid propulsion systems integrating conventional engines with electric motors, battery storage, and renewable energy harvesting technologies are revolutionizing vessel efficiency and operational profiles, particularly in coastal and short-sea shipping segments. This multiplicity of technological pathways creates profound complexity for marine engineering education, which traditionally focused on mastery of diesel engine thermodynamics, steam turbine operations, and auxiliary machinery systems within relatively stable technological frameworks [5].

However, current marine engineering curricula in many maritime academies, particularly within developing maritime nations, remain predominantly oriented toward conventional propulsion technologies, with limited integration of alternative fuel systems and hybrid configurations. This educational paradigm misalignment creates a critical competency gap as the industry rapidly adopts green propulsion technologies to comply with increasingly stringent environmental regulations and meet corporate sustainability commitments. The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) framework, while comprehensive for traditional marine engineering competencies, has only begun incorporating specific requirements for alternative fuel operations, leaving significant latitude for individual maritime academies to determine the depth and breadth of green technology integration [6]. This regulatory flexibility, while enabling institutional innovation, simultaneously risks perpetuating educational disparities that could disadvantage graduates from institutions slower to adapt their curricula and training infrastructure.

Indonesia's position as the world's largest archipelagic nation with over 17,000 islands and maritime zones comprising 75% of its total territory underscores the strategic importance of developing robust marine engineering capabilities aligned with global sustainability transitions. The Indonesian maritime sector, encompassing international shipping, domestic inter-island connectivity, fisheries, and offshore energy operations, employs hundreds of thousands of seafarers and constitutes a vital component of national economic development and regional integration within ASEAN maritime cooperation frameworks [7]. Maritime education institutions across Indonesia, including specialized maritime academies operated under the Ministry of Transportation, bear responsibility for preparing marine engineering officers who can effectively operate and maintain increasingly sophisticated propulsion systems while meeting international competency standards. Yet preliminary observations suggest that many Indonesian maritime academies face substantial challenges in updating curricula, acquiring specialized training equipment for alternative fuel systems, and developing faculty expertise in emerging green propulsion technologies, potentially compromising the competitiveness of Indonesian marine engineers in the global maritime labor market [8].

This research addresses the fundamental question: what competencies must contemporary marine engineering education develop to ensure graduates possess adequate literacy in alternative fuel systems and hybrid propulsion technologies? The study specifically examines three interconnected dimensions of this central inquiry. First, it investigates the technical knowledge domains and practical skills that industry stakeholders identify as essential for marine engineers working with green propulsion technologies, encompassing system operation, maintenance protocols, troubleshooting methodologies, and safety management for alternative fuels. Second, the research analyzes current pedagogical approaches and curriculum structures within Indonesian maritime academies, identifying strengths, limitations, and gaps relative to industry requirements and international best practices. Third, the study explores perspectives from recent marine engineering graduates regarding their preparedness for contemporary maritime industry demands and their experiences transitioning from academic training to shipboard operations involving advanced propulsion systems.

The significance of this research extends across multiple dimensions of maritime education development and industry transformation. From a pedagogical perspective, the study contributes to the limited but growing body of scholarship examining how technical maritime education must evolve to address sustainability imperatives, offering empirical evidence regarding stakeholder perceptions and competency requirements that can inform curriculum revision processes. For maritime education institutions, particularly those in developing nations navigating resource constraints while pursuing educational quality enhancement, the research provides actionable insights regarding priority competency domains, potential industry-academia collaboration models, and phased implementation strategies for green technology integration. From an industry workforce development perspective, the findings illuminate current capability gaps and future training needs, supporting more effective human resource planning by shipping companies, classification societies, and maritime administrations as they manage fleet transitions toward sustainable propulsion systems [9].

Methodologically, this research employs a qualitative approach centered on gathering and analyzing perspectives from three distinct stakeholder groups: maritime industry experts with direct experience in alternative fuel vessel operations, maritime academy lecturers responsible for marine engineering curriculum delivery, and recent marine engineering graduates navigating early career experiences. This multi-perspective design enables comprehensive understanding of competency requirements from both supply and demand sides of the maritime labor market, while simultaneously capturing the lived experiences of those most directly affected by potential curriculum changes. Through semi-structured interviews and thematic analysis, the research identifies commonalities and divergences in stakeholder perspectives, enabling development of a competency framework that balances theoretical rigor with practical applicability [10].

The structure of this paper proceeds through systematic examination of methodology, findings, and implications. Following this introduction, the research method section details the qualitative approach, participant selection criteria, data collection instruments, and analytical procedures employed to ensure research rigor and trustworthiness. The results and discussion section presents thematic findings organized around key competency domains, comparing perspectives across stakeholder groups and relating findings to existing literature on maritime education transformation. The conclusion synthesizes primary contributions, discusses limitations, and proposes directions for future research and practical implementation of competency development initiatives.

## 2. RESEARCH METHOD

This research employed a qualitative methodology designed to capture rich, contextual perspectives regarding marine engineering competency requirements for alternative fuel systems and hybrid propulsion technologies. The qualitative approach was selected as most appropriate for exploring complex, multifaceted phenomena where existing theoretical frameworks remain underdeveloped and stakeholder experiences provide essential insights for theory building and practical application [11]. The research design incorporated semi-structured interviews with purposively selected participants representing three distinct stakeholder categories, enabling triangulation of perspectives and comprehensive understanding of competency development challenges and opportunities within Indonesian maritime education contexts.

The research population encompassed maritime stakeholders directly involved with or affected by marine engineering education transformation toward green propulsion technologies. From this broader population, the study employed purposive sampling to select sixty participants distributed across three categories: fifteen maritime industry experts, twenty maritime academy lecturers, and twenty-five recent marine engineering graduates. Industry experts were selected based on direct professional experience with alternative fuel vessel operations, including fleet managers, chief engineers with LNG or hybrid propulsion experience, classification society surveyors specializing in alternative fuel systems, and technical superintendents overseeing green technology implementation. The expert sample deliberately included representatives from international shipping companies operating in Indonesian waters, domestic shipping enterprises, and maritime service providers to capture diverse operational perspectives and varying levels of technological adoption. Maritime academy lecturers were recruited from five Indonesian maritime institutions, including both Merchant Marine Polytechnics under the Ministry of Transportation and maritime universities offering marine engineering programs, ensuring representation of different institutional contexts, geographical locations, and resource availabilities. Selection criteria required lecturers to have at least five years teaching experience in marine engineering subjects and direct involvement in curriculum development activities. Recent marine engineering graduate participants had completed their maritime academy education within the previous three years and possessed minimum six months shipboard experience as engine cadets or junior engineers, providing contemporary perspectives on educational adequacy and industry transition challenges.

The rationale for this sampling approach centered on capturing maximum variation in experiences and perspectives while maintaining focus on individuals with direct knowledge relevant to the research questions. Industry experts provided authoritative insights regarding competency requirements and performance expectations for marine engineers working with green propulsion systems, grounded in operational realities and business imperatives driving technological adoption. Maritime academy lecturers offered perspectives on pedagogical challenges, institutional constraints, curriculum revision processes, and faculty development needs, representing the educational supply side of competency development. Recent graduates contributed valuable assessments of their preparedness, identified gaps between academic training and workplace demands, and reflected on learning experiences while these remained vivid and readily accessible. This three-category design enabled examination of competency development from complementary angles, identifying areas of consensus that might inform priority interventions and areas of divergence requiring further investigation or stakeholder dialogue [12].

The research instrument consisted of semi-structured interview protocols tailored to each stakeholder category while maintaining consistency in core themes and constructs explored across groups. Interview protocols addressed five primary domains constituting the dependent and independent variables of investigation. The first domain examined technical knowledge requirements, exploring what specific content regarding alternative fuel properties, combustion characteristics, storage systems, fuel handling procedures, and hybrid propulsion architectures marine engineers must master. The second domain investigated practical skills and competencies, including system operation procedures, troubleshooting methodologies, maintenance protocols, and emergency response capabilities specific to alternative fuel and hybrid systems. The third domain addressed safety literacy, encompassing risk assessment, hazard identification, personal protective equipment selection, and regulatory compliance requirements for alternative fuel operations. The fourth domain explored pedagogical approaches and learning strategies, examining how theoretical knowledge and practical skills might most effectively be developed through combinations of classroom instruction, simulator training, laboratory exercises, and shipboard practice. The fifth domain investigated institutional and systemic factors affecting competency development, including curriculum governance structures, industry-academia collaboration mechanisms, faculty professional development opportunities, and training equipment investment priorities. Each interview protocol incorporated open-ended primary questions enabling participants to share experiences and perspectives in their own terms, supplemented by probing questions that explored specific indicators and dimensions within each domain as these emerged through the interview conversation [13].

Data collection proceeded through face-to-face and virtual interviews conducted between March and August 2024, with each interview lasting approximately sixty to ninety minutes. All interviews were conducted in Indonesian or English according to participant preference, audio recorded with informed consent, and subsequently transcribed verbatim for analysis. Field notes captured contextual observations, non-verbal communication, and interviewer reflections that supplemented transcribed content. Prior to data analysis, all transcripts were anonymized to protect participant confidentiality, with individuals assigned coded identifiers indicating their stakeholder category. The data analysis process employed thematic analysis methodology, proceeding through systematic phases of familiarization, initial coding, theme development, theme review, and interpretation. Initial familiarization involved repeated reading of all transcripts to develop comprehensive understanding of the dataset. Open coding then identified meaningful segments of data relevant to the research questions, with codes capturing both semantic content and latent meanings within participant narratives. As coding progressed, related codes were grouped into candidate themes representing patterned meaning across the dataset, with particular attention to how themes manifested within and across stakeholder categories. Theme review involved checking candidate themes against coded data and entire transcripts to ensure themes were coherent, distinctive, and adequately represented in the dataset. Throughout analysis, the research maintained analytical focus on both commonalities indicating consensus perspectives and variations suggesting divergent understandings or priorities among stakeholder groups. This cross-group comparison approach enabled identification of gaps between industry expectations and educational delivery, between lecturer intentions and graduate perceptions, and between different institutional contexts representing varying stages of green technology integration. The analytical process culminated in narrative synthesis that organized findings into a coherent framework explaining current states, challenges, and pathways forward for marine engineering competency development in alternative fuel and hybrid propulsion technologies.

## 3. RESULTS AND DISCUSSION

### 3.1 Results

The qualitative analysis revealed comprehensive insights regarding marine engineering competency requirements for green propulsion technologies, organized into five major thematic domains: technical knowledge integration, practical competency development, safety literacy and risk management, pedagogical innovation requirements, and institutional capacity challenges. Results demonstrated strong consensus across stakeholder groups regarding the urgency of curriculum transformation while simultaneously revealing significant gaps between current educational delivery and industry expectations.

**Table 1: Competency Domain Assessment Across Stakeholder Groups**

| Competency Domain | Industry Experts Priority (%) | Lecturer Readiness (%) | Graduate Preparedness (%) | Gap Analysis |
|---|---|---|---|---|
| **Alternative Fuel Theory** | 95 | 45 | 35 | Critical Gap |
| **Hybrid System Operation** | 90 | 40 | 30 | Critical Gap |
| **Safety Protocols** | 100 | 55 | 50 | Significant Gap |
| **Maintenance Procedures** | 85 | 35 | 25 | Critical Gap |
| **Troubleshooting Skills** | 95 | 30 | 20 | Critical Gap |
| **Environmental Compliance** | 80 | 60 | 55 | Moderate Gap |
| **System Integration Knowledge** | 85 | 25 | 20 | Critical Gap |
| **Traditional Thermodynamics** | 70 | 90 | 85 | Reverse Gap |

*Note: Priority/Readiness/Preparedness scores represent percentage of participants rating domain as "essential" or "highly confident"*

Analysis of technical knowledge requirements revealed that industry experts overwhelmingly emphasized the necessity of comprehensive understanding of alternative fuel properties, handling characteristics, and combustion dynamics. All fifteen industry participants identified LNG systems as immediate priority given current market adoption rates, with methanol systems identified by eleven participants as rapidly emerging alternatives requiring comparable attention. Ammonia propulsion, while acknowledged by thirteen experts as likely future mainstream technology, was generally characterized as requiring monitoring rather than immediate curriculum integration given limited current operational deployment. Hybrid propulsion systems received consistent emphasis from fourteen industry experts, who noted that battery-electric integration, shore power connectivity, and energy management system optimization represented essential competencies even for conventional vessels undergoing efficiency retrofits.

Maritime academy lecturers expressed significant concerns regarding their capacity to deliver adequate instruction in green propulsion technologies. Only nine of twenty lecturer participants reported having direct training or professional experience with alternative fuel systems, while merely six indicated access to dedicated laboratory equipment or simulators for hybrid propulsion training. Eighteen lecturers identified faculty professional development as their highest priority need, with particular emphasis on hands-on exposure to operational systems rather than purely theoretical knowledge transfer. Institutional resource constraints emerged as a persistent theme, with seventeen lecturers describing challenges securing budget allocations for specialized training equipment that senior administrators perceived as serving narrow rather than broad student populations.

Graduate perspectives provided sobering assessments of preparedness gaps. Twenty-three of twenty-five graduate participants reported that their maritime academy education provided minimal or no coverage of alternative fuel systems beyond brief theoretical mentions in environmental compliance courses. When encountering vessels equipped with LNG propulsion or hybrid systems during their cadetships, graduates described relying entirely on shipboard mentoring and manufacturer documentation rather than academic preparation. Fifteen graduates explicitly stated they felt inadequately prepared for contemporary maritime industry technological realities, with several expressing frustration that their education emphasized systems no longer dominant in new vessel construction.

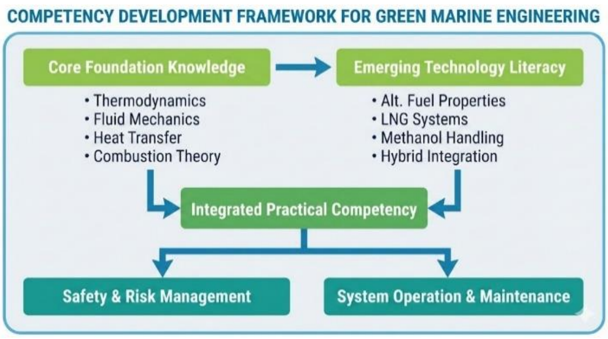


*Figure 1: Competency Development Framework for Green Marine Engineering*

**Table 2: Priority Curriculum Integration Strategies**

| Strategy Component | Implementation Priority | Resource Requirements | Expected Impact | Timeline |
|---|---|---|---|---|
| **LNG Systems Module** | Immediate (Year 1) | Medium-High | High | 1-2 years |
| **Methanol Systems** | Short-term (Year 1-2) | Medium | High | 2-3 years |
| **Hybrid Propulsion Lab** | Short-term (Year 2) | Very High | Very High | 2-4 years |
| **Faculty Development Program** | Immediate (Year 1) | Medium | Critical | Ongoing |
| **Industry Partnerships** | Immediate (Year 1) | Low-Medium | High | Ongoing |
| **Simulator Acquisition** | Medium-term (Year 2-3) | Very High | High | 3-5 years |
| **Curriculum Revision** | Immediate (Year 1) | Low | Critical | 1-2 years |
| **Guest Lecturer Program** | Immediate (Year 1) | Low | Medium-High | Ongoing |

### 3.2 Discussion

The findings illuminate critical disconnects between maritime industry transformation and educational system adaptation, with implications extending across pedagogical, institutional, and policy dimensions. The competency gap revealed through cross-stakeholder comparison directly addresses the central research questions regarding necessary literacy components for green marine engineering, while simultaneously exposing systemic barriers impeding effective competency development within Indonesian maritime education contexts.

The overwhelming industry consensus regarding alternative fuel and hybrid system competency requirements validates concerns expressed in recent maritime education literature about curriculum obsolescence risks in rapidly transforming technical domains [14]. The research findings strongly support arguments by Lloyd's Register Foundation that maritime education institutions face existential challenges adapting to technological discontinuities that render traditional knowledge domains insufficient for contemporary practice [15]. However, this study extends beyond general observations by quantifying specific priority domains and revealing the particular vulnerability of maintenance and troubleshooting competencies, which received highest industry emphasis yet demonstrated lowest lecturer confidence and graduate preparedness. This pattern suggests that conventional maritime education pedagogy—which often emphasizes theoretical principles over practical problem-solving in equipment-specific contexts—may prove particularly inadequate for alternative fuel technologies where operational experience remains limited and troubleshooting protocols continue evolving.

The research findings regarding faculty development needs align with broader technical education scholarship emphasizing that teacher knowledge and confidence constitute primary determinants of curricular innovation success [16]. The disclosed reality that fewer than half of participating lecturers possessed direct alternative fuel system experience illuminates a fundamental capacity constraint that cannot be addressed through curriculum documents or policy directives alone. This finding resonates with concerns raised by the International Association of Maritime Universities regarding the widening gap between maritime industry technological frontier and average faculty expertise, particularly in developing maritime nations where opportunities for lecturer industrial sabbaticals or advanced technical training remain limited [17]. The research contributes original empirical evidence demonstrating that this gap manifests not merely as general concern but as specific impediment to essential curriculum transformation, with lecturers themselves identifying practical exposure to operational systems as their highest priority professional development need.

Graduate perspectives revealing frustration with educational inadequacy carry profound implications for institutional reputation and competitive positioning within regional maritime labor markets. The finding that graduates felt unprepared for contemporary technological realities despite completing recently revised curricula suggests that superficial curriculum modifications—such as adding brief theoretical coverage of alternative fuels within existing environmental courses—prove insufficient for developing genuine competency. This pattern supports arguments by Ng and colleagues that meaningful technical education transformation requires fundamental pedagogical reconceptualization rather than additive curriculum expansion [18]. The research findings suggest that effective green marine engineering education must move beyond knowledge transmission to emphasize experiential learning, problem-based pedagogies, and authentic assessment aligned with workplace performance requirements. The consistently emphasized inadequacy of troubleshooting and maintenance competencies particularly indicates need for significantly expanded practical training components, potentially through hybrid learning models combining traditional classroom instruction, advanced simulation, and structured industry exposure.

The institutional capacity challenges identified through lecturer interviews—particularly regarding specialized equipment acquisition and budget allocation difficulties—expose structural barriers that individual institutional initiative cannot fully overcome. The research findings support growing recognition within maritime education policy discourse that green technology integration requires coordinated investment exceeding typical institutional resources, potentially necessitating national or regional collaborative infrastructure development [19]. The Indonesian context specifically suggests opportunities for leveraging the concentrated geographical distribution of maritime academies within Java and Sumatra to establish shared specialized training facilities, similar to models implemented in Scandinavian maritime education clusters. However, such collaborative approaches require policy frameworks and funding mechanisms that transcend individual institutional authorities, implying that effective competency development at scale necessitates Ministry of Transportation leadership and potentially legislative support for maritime education modernization initiatives.

The research contributes practical value through its identification of phased implementation priorities balancing impact potential against resource requirements and implementation complexity. The finding that LNG systems, faculty development programs, and industry partnerships represent high-impact interventions achievable with moderate resources suggests actionable pathways forward even for institutions facing significant budget constraints. Conversely, the identification of hybrid propulsion laboratories and advanced simulators as high-impact but very-high-resource interventions clarifies where coordinated investment or shared facility development may prove most strategic. This granular prioritization enables maritime education institutions to develop realistic transformation roadmaps aligned with their specific resource contexts while maintaining focus on competency domains that industry stakeholders identify as most critical.

The study's strengths include its multi-stakeholder design enabling triangulation of perspectives, its focus on Indonesian maritime education contexts that remain understudied in international literature, and its emphasis on practical implementation priorities rather than purely theoretical frameworks. The research achieved data saturation within each stakeholder category, with consistent themes emerging across participants suggesting robust representation of dominant perspectives within each group. The inclusion of recent graduates provided essential "reality checks" on educational effectiveness often absent from research relying solely on institutional or industry viewpoints.

However, several limitations warrant acknowledgment. The study's geographical concentration within Java and Sumatra, while capturing institutions serving majority of Indonesian marine engineering students, may not fully represent challenges facing more remote maritime academies with even more constrained resources. The research's qualitative methodology, while appropriate for exploratory investigation of complex phenomena, limits generalizability and does not enable statistical inference regarding competency development interventions' relative effectiveness. Future research employing quasi-experimental designs comparing alternative pedagogical approaches or tracking graduate performance outcomes across institutions at different stages of curriculum transformation would provide valuable complementary evidence. Additionally, the rapid pace of technological change in alternative marine propulsion suggests need for longitudinal research examining how competency requirements evolve as technologies mature and operational experience accumulates.

## 4. CONCLUSION

This research reveals critical competency development requirements for marine engineering education addressing alternative fuel systems and hybrid propulsion technologies. The study identifies significant gaps between industry expectations and current educational delivery, particularly regarding practical troubleshooting skills, maintenance procedures, and safety protocol mastery for LNG, methanol, and hybrid systems. Faculty development emerges as the most urgent priority, with industry partnerships, phased curriculum integration of alternative fuel systems, and strategic investment in specialized training infrastructure constituting essential transformation components. The findings demonstrate that effective competency development requires coordinated action across institutional, industry, and policy dimensions, moving beyond isolated curriculum revisions toward comprehensive educational system transformation supporting maritime decarbonization imperatives.

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