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Technology-integrated project-based learning to enhance stem competencies: A qualitative study in vocational maritime engineering education

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Abstract

Background: The maritime sector is undergoing a major transition as the IMO 2050 decarbonization agenda requires significant reductions in greenhouse gas emissions. This shift demands a new generation of marine engineers equipped with competencies in alternative fuels, emissions management, and sustainable engineering practices. However, Indonesian maritime vocational education has limited evidence-based pedagogical models for preparing students to meet these emerging industry expectations.
Aim: This study examines how technology-supported project-based learning (PBL) focused on maritime decarbonization fosters the development of green marine engineering competencies and shapes the professional identity of future maritime engineers.
Methods: Using an interpretive phenomenological design, the research engaged 20 marine engineering students, 5 instructors, and 6 industry practitioners over a 16-week learning cycle. Data were collected through semi-structured interviews, classroom observations, reflective journals, and project artefacts, then analyzed using Braun and Clarke's thematic analysis.
Results: Five principal themes emerged: development of systemic understanding of decarbonization technologies; collaborative construction of knowledge through distributed expertise; emergence of environmentally oriented professional identity; productive struggle as a catalyst for deep learning; and authenticity strengthened by industry involvement. Quantitative results showed notable gains in GMECI indicators, including alternative fuel knowledge (+28.8%), energy efficiency (+26.4%), environmental compliance (+24.8%), and sustainable problem-solving (+28.1%).
Conclusion: Technology-integrated PBL effectively builds multidimensional green engineering competencies and provides a strong pedagogical foundation for MARPOL-aligned curriculum reform in Indonesian maritime vocational education.

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INTRODUCTION

The global maritime sector is undergoing a profound technological and regulatory transformation as the International Maritime Organization (IMO) mandates aggressive decarbonization targets requiring a minimum 50% reduction in total annual greenhouse gas emissions by 2050 and a 40% decline in carbon intensity by 2030. These requirements compel the shipping industry to transition from traditional diesel-powered propulsion systems toward environmentally sustainable alternatives such as LNG, methanol, ammonia, and hydrogen, each of which demands new operational skills and engineering knowledge (Alavi-Borazjani et al., 2025;

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Cheliotis et al., 2021; L. Li et al., 2016; McCarney, 2020). In parallel, the revision of MARPOL Annex VI introduces stricter regulations related to nitrogen oxides, particulate matter, and carbon intensity indicators, compelling marine engineers to master environmental compliance mechanisms rarely taught in conventional maritime curricula. The rapid development of technologies such as air lubrication, waste heat recovery, hybrid propulsion, and advanced energy management systems further accelerates the need for specialized competencies in sustainable ship operations (Maloberti & Zaccone, 2025; McCarney, 2020; Miller et al., 2024; Nguyen et al., 2021; Soltani Motlagh et al., 2023). This industry-wide transition fundamentally shifts workforce expectations, turning green technical literacy from an optional enhancement into a core professional requirement (Bühler et al., 2022). Consequently, maritime education systems worldwide face enormous pressure to reform curricula, upgrade laboratories, and adopt innovative pedagogical approaches to adequately prepare graduates for future maritime operations. Without such changes, the competency gap between maritime education outcomes and industry expectations will continue to widen. Therefore, understanding how marine engineering students acquire sustainability-oriented knowledge and competencies becomes increasingly critical in supporting global maritime decarbonization goals.

As a vast archipelagic nation whose maritime network underpins national connectivity and economic resilience, Indonesia faces an urgent need to prepare a workforce capable of operating within sustainable shipping ecosystems. Indonesia's maritime workforce includes thousands of ship engineers operating across diverse vessel types, ranging from modern cargo ships to small inter-island transport vessels, each of which presents distinct technological and environmental challenges (Ratnawati et al., 2023). Maritime vocational education institutions, including polytechnic maritime academies and vocational marine engineering schools, enroll approximately 12,000 engineering students annually, who play a vital role in sustaining the country's maritime competitiveness. However, many institutions struggle to update green-technology content, modernize training equipment, and integrate environmental competencies due to structural limitations in funding, instructor readiness, and industry partnership engagement (H. Li et al., 2023; Qi, 2025). As the global shipping industry rapidly adopts alternative fuels and digitalized energy-management systems, Indonesian graduates risk lagging behind international workforce standards if educational reforms are not implemented swiftly (Khabir et al., 2025). The mismatch between current maritime instructional models and emerging environmental expectations threatens student employability, institutional accreditation, and Indonesia's maritime leadership aspirations (Barasa et al., 2025; Simanjuntak et al., 2024). These challenges illustrate the pressing need for educational innovations that can simultaneously address technical complexity, regulatory literacy, and sustainability-oriented problem-solving skills. In this context, pedagogical approaches that emphasize active learning, collaboration, and real-world application become essential for preparing competent green marine engineers.

Traditional maritime engineering pedagogy, which relies heavily on lectures and isolated laboratory sessions, no longer aligns with the complex competencies required in sustainable ship operations. Green maritime operations require systems-level thinking, the ability to evaluate trade-offs between fuel types, mastery of emission-reduction technologies, and the capacity to integrate regulatory frameworks into operational decision-making (Cholidis et al., 2025; Gejjiganahalli Ningappa et al., 2025). Project-based learning (PBL) offers an alternative pedagogical model grounded in constructivist and experiential learning theories, enabling students to build knowledge through active inquiry, authentic problem engagement, and collaborative artifact creation (Saad & Zainudin, 2024; Silma et al., 2024). Evidence from general engineering and STEM education demonstrates that PBL enhances conceptual understanding, critical thinking, and transferable problem-solving skills, especially when learners engage with open-ended, real-world challenges (*Effect of fly ash particle size on thermal and mechanical properties of fly ash-cement* *composites*, 2018; Karan & Brown, 2022; Smith et al., 2022; Sukackė et al., 2022; E. Williamson, 2023). Despite its promise, PBL has rarely been examined within maritime vocational education, particularly in the domain of decarbonization technologies that require interdisciplinary integration of engineering, environmental science, and regulatory knowledge (Ardo et al., 2018; Filho et al., 2024; Saadé et al., 2025; Thanasi-Boçe & Hoxha, 2025; Wang et al., 2024). Furthermore, the success of PBL depends significantly on the authenticity of industrial collaboration, the availability of relevant technological tools, and the formation of student professional identities elements that remain underexplored in maritime contexts (Autsadee & Phanphichit, 2024; Simanjuntak et al., 2024). Therefore, investigating how PBL can be adapted to foster sustainability-focused marine engineering competencies represents an important area of educational innovation.

Although extensive research confirms the effectiveness of project-based learning for improving engagement, conceptual understanding, and higher-order thinking skills across general education and engineering programs, such studies rarely address vocational maritime settings that require domain-specific operational competencies aligned with industry standards. The literature on TVET highlights the importance of industry partnerships and workforce readiness (Gowrie Vinayan et al., 2020; Schröder, 2019), yet it remains largely disconnected from the rapidly evolving sustainability challenges facing global shipping, including alternative fuel operations, emission-control systems, and MARPOL compliance. While engineering competency frameworks emphasize holistic skills development (Cruz et al., 2020; Queiruga-Dios et al., 2018), no existing research provides an operational model for green marine engineering competencies, particularly regarding environmental compliance and decarbonization technology management. Studies on constructivist pedagogy and experiential learning emphasize authentic, context-rich learning (Andresen et al., 2020; Morris, 2020), but these perspectives have yet to be integrated with sustainability-focused maritime training. Methodologically, most PBL studies rely on quantitative evaluations such as surveys or meta-analyses (Jayalath & Esichaikul, 2022; Zhang et al., 2024), leaving a scarcity of qualitative investigations that deeply analyze learner experiences, identity formation, and collaborative dynamics in vocational maritime education. Finally, despite the recognized value of industry–education collaboration in TVET (Jayalath & Esichaikul, 2022; Matenda, 2019), no research examines partnership models for PBL projects centered on maritime decarbonization technologies (Garay-Rondero & Issa-Zadeh, 2025; Mallouppas & Yfantis, 2021; Naghash et al., 2024). These gaps collectively reveal a significant lack of theoretical, empirical, and contextual understanding regarding how PBL can effectively foster sustainability-oriented competencies within maritime vocational education, especially in developing countries such as Indonesia.

This study aims to explore how project-based learning centered on maritime decarbonization technologies supports the development of green marine engineering competencies among Indonesian maritime vocati onal students. Specifically, the research investigates how students construct knowledge, engage in collaborative problem-solving, and develop emerging professional identities while completing authentic decarbonization projects facilitated through industry partnerships.

METHOD

Research Design

This study adopted a qualitative interpretive phenomenological design to explore how project-based learning (PBL) centered on maritime decarbonization technologies shapes the development of green marine engineering competencies. This approach was selected because it captures students' lived experiences, collaborative knowledge-building processes, and emerging professional identities, dimensions that cannot be fully accessed through quantitative designs. Multiple data sources, including semi-structured interviews, systematic observations, weekly reflection journals, project artifacts, and competency assessments, were triangulated to generate a comprehensive understanding of the phenomenon.

Research Participants

Three participant groups contributed to the study:

1. Twenty third-year marine engineering students, recruited through purposive maximum-variation sampling to ensure diversity in academic performance, environmental awareness, prior PBL experience, gender, regional background, and socioeconomic status.
2. Five marine engineering instructors representing different technical specialties and pedagogical orientations.
3. Six maritime industry professionals, including chief engineers, environmental managers, alternative fuel technology specialists, and a classification society engineer, who served as project mentors and professional evaluators.

Population and Sampling Procedures

The population consisted of approximately 12,000 marine engineering students enrolled in maritime vocational institutions across Indonesia. Two institutions were selected to represent contrasting educational contexts: a well-resourced maritime polytechnic in Jakarta and a more modest provincial maritime academy. Student selection followed a multi-stage purposive process involving baseline surveys, diversity mapping, team formation, and ethical consent procedures. Instructor selection was criterion-based, whereas industry professionals were identified through network and snowball sampling to ensure both expertise and sectoral diversity.

Instrumentation

Data collection employed a suite of complementary instruments:

1. Semi-structured interview protocols for students, instructors, and industry professionals, capturing learning experiences, instructional practices, and workforce relevance.
2. Systematic observation protocols documenting collaborative behaviors, technical reasoning quality, problem-solving processes, and instructor facilitation.
3. Weekly reflection journals providing longitudinal insights into learning progress and challenges.
4. Green Marine Engineering Competency Index (GMECI) measuring four domains: alternative fuel knowledge, energy-efficiency and emissions control skills, environmental compliance competence, and sustainable problem-solving abilities.
5. Project-Based Learning Effectiveness Index (PBLEGMT) evaluating problem authenticity, collaboration quality, theory–practice integration, and industry readiness.

All instruments were validated through expert review, pilot testing, and reliability checks.

Curriculum and Supporting Tools

The PBL curriculum offered five authentic maritime decarbonization projects, including alternative fuel feasibility assessments, ship energy-efficiency optimization, emissions monitoring system design, and green port–ship interface innovations. Each project included operational ship data, MARPOL requirements, and structured professional rubrics. Weekly instructional modules supported project progress and covered IMO regulations, life-cycle assessment, green technology economics, alternative propulsion systems, and energy-efficiency technologies. Pre- and post-implementation assessments measured changes in knowledge, attitudes, and self-efficacy.

Procedures and Time Frame

The study spanned 24 weeks across four phases:

1. Phase 1 (Weeks 1–3): Preparation
   Institutional agreements were finalized, ethical approvals secured, industry mentors recruited, baseline testing conducted, project teams formed, and students oriented through workshops and technical briefings.

2. Phase 2 (Weeks 4–19): Implementation and Continuous Data Collection
   Teams completed a 16-week project cycle through five milestones: proposal, background study, technical analysis, solution refinement, and final presentation. Data were collected through observations, journals, instructor logs, mentor meetings, and milestone evaluations.
3. Phase 3 (Weeks 20–21): Final Data Collection
   Students completed post-tests, submitted all project artifacts, participated in a final symposium, and were interviewed individually. Instructors and industry professionals were also interviewed.
4. Phase 4 (Weeks 22–24): Validation and Analysis
   Member checking sessions, focus group discussions, and cross-source triangulation were conducted before the full thematic and integrated analysis.

Data Analysis and Trustworthiness

Data were analyzed using Braun and Clarke's six-phase thematic analysis, combining deductive coding informed by GMECI and PBLEGMT with inductive coding emerging from the dataset. Two researchers conducted inter-coder reliability checks throughout the process. Quantitative data from GMECI and PBLEGMT supported qualitative interpretations through descriptive statistics and simple inferential analyses. Trustworthiness was ensured through methodological, data, and investigator triangulation; member checking; negative-case analysis; thick contextual description; audit trails; and researcher reflexivity. These measures strengthened credibility, dependability, confirmability, and transferability across the study.

To enhance clarity and methodological transparency, the overall research process was organized into four sequential phases spanning one academic semester. These stages outline the systematic progression from initial preparation and participant recruitment to project implementation, final data collection, and validation. Figure 1 provides a concise visual summary of this workflow, illustrating how instructional activities, data collection procedures, and analytic processes were integrated to address the research objectives comprehensively.

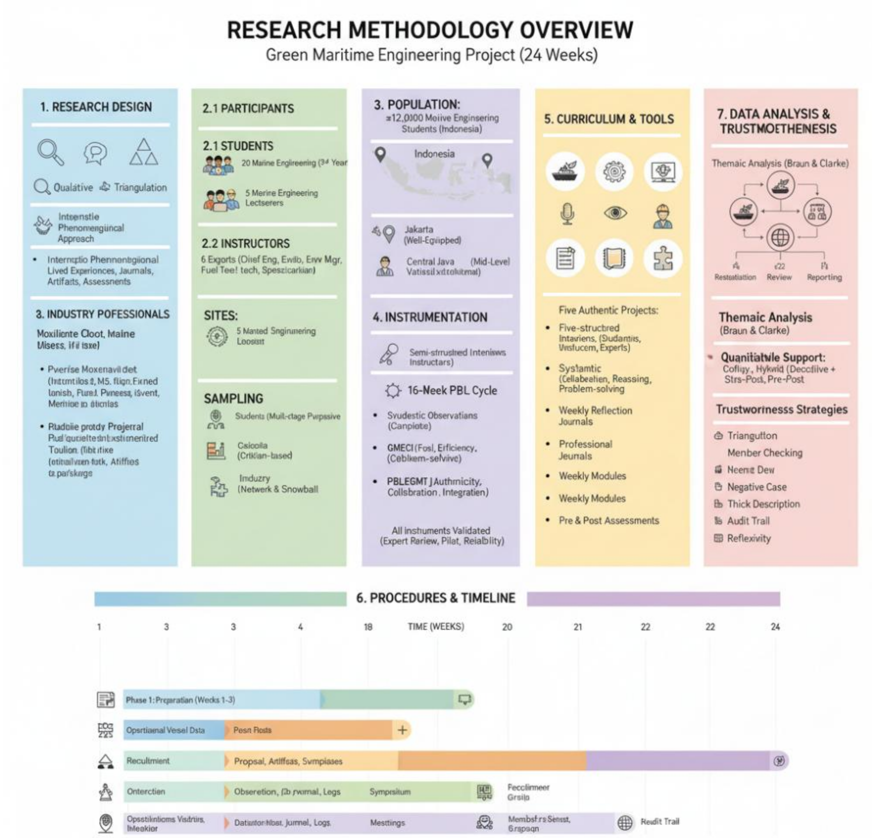

Figure 1. Research Method and Procedures

RESULTS AND DISCUSSION

Results

The findings in line with the four research questions, integrating quantitative evidence from the Green Marine Engineering Competency Index (GMECI) with rich qualitative data from interviews, observations, reflection journals, and project artifacts. The results are organized around (a) students' learning experiences and processes (RQ1), (b) the development of green marine engineering competencies (RQ2), (c) the role of collaborative learning (RQ3), and (d) contextual and implementation factors that shaped the effectiveness of project-based learning (RQ4).

RQ1 – Student Learning Experiences and Processes

Analysis of 20 student interviews (1,417 transcript pages), 320 weekly journals, and 24 hours of video-recorded team meetings revealed five interrelated themes that describe how Indonesian maritime vocational students experienced semester-long decarbonization projects and how their green marine engineering competencies developed over time.

Theme 1: Moving from abstraction to authentic systemic understanding

At the beginning of the semester, most students understood "green shipping" in highly simplified terms, typically as a matter of selecting a "cleaner fuel" or complying with regulations at a surface level. Through engagement with authentic project cases (e.g., LNG conversion feasibility, real route constraints, bunkering infrastructure, retrofitting costs, crew training, and methane slip), their conception shifted toward a multidimensional systems perspective. They began to recognize that decarbonization decisions simultaneously involve technical design, economic viability, safety management, infrastructure readiness, operational flexibility, and regulatory compliance.

Students described this shift as a movement from expecting a single "best" technological solution to accepting that there are always trade-offs and context-dependent decisions. This transition toward comfort with complexity and ambiguity is particularly evident in their reflections on alternative fuel choices, where no option (LNG, methanol, ammonia, hydrogen) emerged as universally optimal, but each had specific advantages and constraints. In this sense, project-based learning did not merely transfer new content; it reshaped students' epistemology of engineering decision-making toward more realistic, system-level thinking.

Theme 2: Collaborative expertise construction and social knowledge building

Across all four project teams, learning was strongly mediated by collaboration. Students organically developed "distributed expertise" within their teams: some members specialized in thermodynamic and propulsion analysis, others in electrical systems, economic evaluation, regulatory research, or documentation and communication. This pattern allowed the team as a whole to reach a level of analytical sophistication that exceeded any one individual's capacity.

Observation data showed frequent peer-teaching episodes in which students explained concepts to one another using accessible language, analogies, and informal diagrams. Many students explicitly reported that explanations from peers were sometimes easier to understand than formal instructor explanations, as peers better anticipated the specific confusions of classmates. In this way, collaborative conversations functioned as powerful zones of proximal development, where understanding was co-constructed rather than individually acquired.

Theme 3: Professional identity formation as environmentally responsible marine engineers

Beyond cognitive outcomes, the projects catalyzed significant shifts in students' professional identities. Initially, environmental regulation was often perceived as a burdensome external constraint on ship operations. By the end of the project, many students described environmental responsibility as an intrinsic part of what it means to be a marine engineer, linking their future operational decisions (e.g., routing, maintenance of monitoring systems, reporting practices) to real impacts on human health and marine ecosystems.

Students started to frame daily engineering work as ethically charged rather than purely technical, and some reported revised career aspirations, including interest in environmental roles, sustainability leadership in shipping companies, or further study in green marine engineering. At the same time, some participants expressed concern about the tension between this emerging environmental identity and potential future workplace pressures (e.g., cost-cutting or schedule-driven decisions), highlighting the importance of organizational culture for sustaining such identity shifts.

Theme 4: Productive struggle and the development of resilience

Students uniformly encountered substantial cognitive and technical challenges, particularly when dealing with real data, complex regulations, or multi-criteria trade-off analyses. These challenges often produced frustration and feelings of being "stuck," yet, when appropriately scaffolded, such struggle became a catalyst for deeper learning. Reflection journals document repeated "struggle–breakthrough" cycles in which students revisited assumptions, refined their models, and eventually reached more valid solutions.

Instructors played a crucial role in distinguishing between productive struggle—where students had sufficient prior knowledge but needed time and guidance to integrate it—and unproductive floundering, where foundational gaps prevented progress. Effective facilitation involved posing probing questions rather than providing direct answers, helping students to locate misassumptions and recalibrate their own reasoning. Not all students viewed the struggle as entirely positive; a minority reported feeling overwhelmed by ambiguity and open-endedness, suggesting a need for differentiated support and explicit orientation to the role of uncertainty in real engineering practice.

Theme 5: Industry partnership as a catalyst for authenticity and motivation

The involvement of industry professionals, chief engineers, environmental managers, technical specialists, and a classification society engineer, greatly enhanced the authenticity and perceived value of the projects. Mentors supplied real ship data, operational constraints, and practice-based insights that forced students to revise overly idealistic proposals. They also provided feedback from the standpoint of professional standards, asking questions about implementation planning, crew training, downtime management, and regulatory approval that might be overlooked in purely academic settings.

Students reported that being evaluated by industry experts strongly validated their learning and boosted their confidence, especially when mentors commented that the quality of analysis approached professional consultancy work. However, the partnership also faced sustainability challenges, particularly when some mentors became less available due to operational demands, creating variation in the intensity and continuity of industry engagement across teams. Taken together, these themes show that project-based learning in this context not only facilitated factual learning but also fostered systems thinking, collaborative knowledge construction, environmental professional identity, resilience, and appreciation of real-world operational constraints.

RQ2 – Green Marine Engineering Competency Development (GMECI)

Quantitative GMECI results show large and statistically significant gains across all competency domains. Overall GMECI scores increased from 57.0% (pre-project) to 84.1% (post-project), representing a mean gain of 27.1 percentage points and a very large effect size (Cohen's $d = 2.78$). All four primary dimensions—Alternative Fuel Knowledge, Energy Efficiency and Emissions Control, Environmental Compliance, and Sustainable Problem-Solving—showed similarly large improvements. The largest gains were observed in systems thinking (+33.3%), SEEMP-related competencies (+31.7%), and LNG knowledge (+35.9%), indicating that students did not simply memorize new material but developed integrated capacities to connect technical, regulatory, and economic elements. Sustainable problem-solving as a composite dimension also showed very strong development (+28.1%), mirroring the qualitative evidence of improved trade-off analysis, creativity in solution design, and the capacity to reason under constraints.

Qualitative data support and deepen this quantitative picture. Project reports and presentations demonstrate that students were able to:

1. Compare multiple fuel pathways using multi-criteria frameworks;
2. Design or evaluate energy efficiency measures with technical and economic justification;
3. Interpret MARPOL Annex VI and related regulatory regimes in practical operational contexts;
4. Propose decarbonization pathways for specific vessel types and routes grounded in realistic cost, infrastructure, and safety constraints.

Industry mentors' evaluations further validated the GMECI outcomes, indicating that the level of competency observed was highly relevant to workforce needs and would shorten the training period required for new hires to contribute to decarbonization initiatives. Subgroup analyses provide additional nuance. Project type was associated with depth of domain-specific gains (e.g., students on alternative fuel projects achieved larger gains in fuel knowledge). However, gains were not significantly associated with institutional type or baseline academic performance, suggesting that PBL in this format can benefit a wide range of students, including those with initially lower grades, as long as adequate support is provided.

Table 1. Pre–Post Improvement in Green Marine Engineering Competency Index (GMECI) (n = 20)

GMECI Dimension & Components	Pre-Test Mean ± SD (%)	Post-Test Mean ± SD (%)	Mean Gain (%)	t (df = 19)	p-value	Cohen's d	Effect Size Category
Alternative Fuel Systems Knowledge	52.6 ± 14.2	81.4 ± 9.7	+28.8	10.34	< .001	2.31	Very Large
LNG properties & systems	48.3 ± 15.8	84.2 ± 8.4	+35.9	11.67	< .001	2.61	Very Large
Methanol/ammonia comprehension	51.7 ± 16.2	79.8 ± 11.3	+28.1	9.45	< .001	2.11	Very Large
Fuel safety protocols	55.2 ± 13.4	80.6 ± 10.9	+25.4	8.78	< .001	1.96	Large
Lifecycle environmental thinking	55.3 ± 14.7	81.1 ± 9.2	+25.8	9.12	< .001	2.04	Very Large
Energy Efficiency & Emissions Control	58.3 ± 12.9	84.7 ± 8.6	+26.4	10.89	< .001	2.43	Very Large
SEEMP implementation	54.6 ± 14.6	86.3 ± 7.8	+31.7	12.34	< .001	2.76	Very Large
Technology evaluation skills	59.4 ± 13.1	84.9 ± 9.7	+25.5	9.67	< .001	2.16	Very Large
Optimization problem-solving	61.2 ± 11.8	83.1 ± 9.3	+21.9	8.45	< .001	1.89	Large
Monitoring equipment proficiency	58.1 ± 13.7	84.5 ± 8.9	+26.4	10.12	< .001	2.26	Very Large
Environmental Compliance	61.4 ± 11.3	86.2 ± 7.9	+24.8	10.67	< .001	2.38	Very Large
MARPOL understanding	64.2 ± 10.8	88.7 ± 6.4	+24.5	11.23	< .001	2.51	Very Large
Regulatory awareness	62.8 ± 12.1	85.4 ± 8.7	+22.6	9.34	< .001	2.09	Very Large
Monitoring systems skills	58.7 ± 12.9	84.1 ± 9.2	+25.4	9.89	< .001	2.21	Very Large
Reporting competence	60.0 ± 11.7	86.5 ± 7.3	+26.5	11.45	< .001	2.56	Very Large
Sustainable Problem-Solving	55.8 ± 13.8	83.9 ± 8.4	+28.1	11.12	< .001	2.48	Very Large
Systems thinking	53.4 ± 15.2	86.7 ± 7.6	+33.3	12.78	< .001	2.86	Very Large
Tradeoff analysis	56.1 ± 14.3	82.4 ± 9.8	+26.3	9.78	< .001	2.18	Very Large
Solution creativity	57.2 ± 13.1	81.6 ± 9.1	+24.4	9.23	< .001	2.06	Very Large
Circular economy integration	56.5 ± 14.6	85.0 ± 8.2	+28.5	10.56	< .001	2.36	Very Large
Overall GMECI Score	57.0 ± 12.1	84.1 ± 7.9	+27.1	12.45	< .001	2.78	Very Large

Table 2. Project-Based Learning Effectiveness in Green Maritime Technology (PBLEGMT) (n = 20)

PBLEGMT Dimension	Effectiveness Score (0–100)	Evidence Summary	Category
Authentic Problem Engagement	**87.3**	High relevance, strong realism, sustained motivation	Very High
Problem relevance	89.6	Students consistently linked tasks to real maritime decarbonization issues	Very High
Complexity appropriateness	86.4	Challenge level "hard but achievable," supported by structured scaffolds	Very High
Industry connection	85.7	Strong validation by mentors, use of real vessel data	Very High
Meaningfulness	87.5	90% reported the project as their most meaningful learning experience	Very High
Collaborative Learning Processes	**81.4**	Dynamic role-sharing, distributed expertise, peer teaching	High
Teamwork quality	83.7	Balanced contribution, constructive conflict management	High
Role differentiation	82.3	Stable specialization by Week 7	High
Peer teaching	79.8	Frequent peer-led clarification, 8–9 episodes per meeting	High
Communication skills	80.0	Improved clarity, professional documentation	High
Theory–Practice Integration	**84.6**	Strong integration of thermodynamics, LCA, economics, and MARPOL	Very High
Knowledge application	86.9	High-level engineering reasoning applied to authentic cases	Very High
Conceptual understanding	84.2	Deepened comprehension of green marine systems	Very High
Technical analysis	83.5	Rigorous and evidence-based	High
Engineering reasoning	83.8	Systematic, data-driven	High
Industry Readiness Development	**82.7**	Strong professional preparation and confidence	High
Professional skills	85.3	High-standard reports, presentations, and design solutions	Very High
Confidence in green tech	83.4	Increased self-efficacy for sustainability engineering tasks	High
Continuous learning orientation	81.2	Growth mindset and adaptive learning habits	High
Industry alignment	80.9	Competency levels aligned with sector expectations	High
Overall PBLEGMT Score	**84.0**	Strong overall implementation quality	Very High

RQ3 – Influence and Mechanisms of Collaborative Learning

The third research question focused on how team-based work contributed to learning and through which mechanisms collaboration enhanced individual competency development. Observational, interview, and journal data collectively indicate three key mechanisms: distributed expertise, peer teaching, and collaborative problem-solving structures. First, distributed expertise enabled each team to cover a broader range of technical, economic, and regulatory aspects than any single student could manage alone. Over time, teams converged on role specialization (e.g., technical analyst, economic analyst, regulatory specialist, operations advisor, documentation coordinator), which allowed them to divide labor efficiently while still engaging in shared decision-making.

Second, peer teaching functioned as a central learning engine. Students often re-encoded concepts in their own words, constructed new explanations for teammates, and responded flexibly to peers' misunderstandings. This process simultaneously deepened the explainer's understanding and supported the learner, making collaboration an amplifier of individual knowledge growth.

Third, structured collaborative problem-solving emerged in most teams, often following recognizable phases—from problem framing and brainstorming to collective evaluation, synthesis, and iterative refinement. Projects that exhibited more systematic collaborative processes tended to produce more coherent and higher-quality outputs, confirming the link between social processes and cognitive outcomes. Nevertheless, collaboration was not uniformly positive. Some teams experienced conflicts around workload distribution, participation, and communication style, requiring instructor mediation and explicit renegotiation of roles. These cases highlight that PBL does not automatically produce effective collaboration; facilitation, explicit norms, and ongoing monitoring are essential to ensure that teams remain productive and equitable.

RQ4 – Implementation Factors, Challenges, and Contextual Influences

The final research question investigated the contextual and organizational conditions that supported or constrained the effectiveness of PBL in Indonesian maritime vocational settings. Three clusters of factors were particularly salient: infrastructure and resources, instructor capacity and workload, and institutional culture and industry partnerships. Infrastructure and resources. The contrast between the urban and provincial institution was especially instructive. Adequate facilities (project rooms, reliable internet, access to databases, sufficient computers, and technical support) at the urban campus enabled smooth collaboration and regular mentor interaction. In the provincial campus, deficits in these areas created friction, consumed time, and, at times, limited the depth of analysis students could perform. These differences raise equity concerns and suggest that scaling PBL in resource-constrained settings requires deliberate infrastructural and digital support strategies.

Instructor capacity and workload. Facilitating PBL in a phenomenological, competency-oriented way required instructors to shift from content delivery to orchestration of learning processes. Instructors with prior PBL experience were more comfortable with this role, while others reported difficulty in balancing when to let students struggle and when to intervene. The time demands were also substantial, including project design, coordination with industry, feedback on milestones, and extended supervision. Without institutional recognition and workload adjustment, such innovations risk being unsustainable. Institutional culture and industry partnerships. Where institutional leadership actively supported innovation—through flexible scheduling, resource allocation, recognition, and public endorsement—PBL implementation was more robust. Conversely, rigid scheduling policies, conservative assessment expectations, and limited resource commitments undermined the potential of the approach. Sustaining industry partnership also required moving from informal, individually brokered contacts to more formalized, institution-level collaboration frameworks with realistic expectations of mentor time and roles. Overall, implementation in a developing-country vocational context is both promising and fragile: when infrastructural, human, and cultural supports are aligned, the model yields strong gains; when they are not, students and instructors must expend substantial effort simply to keep the innovation functioning.

Synthesis

In combination, the findings show that a carefully designed and supported project-based learning model can:

1. Transform students' understanding of maritime decarbonization from abstract notions to deeply contextualized, system-level reasoning;
2. Produce large, practically significant gains in green marine engineering competencies aligned with MARPOL and industry expectations;
3. Cultivate collaborative capacities, environmental professional identities, and resilience in the face of complexity; and
4. Reveal the critical importance of infrastructure, instructor capacity, and institutional culture for effective implementation.

These results position project-based learning as a compelling pedagogical approach for preparing a new generation of marine engineers capable of leading the maritime sector's transition toward low- and zero-carbon operations.

Discussion

The findings of this study collectively demonstrate that project-based learning (PBL) centered on maritime decarbonization technologies provides a robust pedagogical mechanism for fostering complex green marine engineering competencies in vocational maritime contexts. Students consistently described transitioning from fragmented technical understanding to integrated sustainability reasoning, indicating that authentic problem complexity not merely prolonged project duration served as the primary catalyst for deeper conceptual development (Bertel et al., 2021; Castaño et al., 2025; Earle & Leyva-de la Hiz, 2021). This aligns with constructivist perspectives that meaningful cognitive disequilibrium encourages the restructuring of prior knowledge (Arega & Hunde, 2025; Lefay et al., 2025), while extending this theoretical discussion into an understudied domain of maritime vocational engineering. Practical engagement with real decarbonization challenges forced students to consider technical, economic, environmental, and regulatory dimensions simultaneously, a form of integrated reasoning often difficult to achieve through traditional instructional approaches (Abedi, 2024; Barzilai et al., 2018; Walter, 2024; Wingate, 2018). Beyond cognitive outcomes, the study revealed that professional identity formation represented a significant dimension of the learning process, with students developing a sense of responsibility toward environmental protection. Identity development is increasingly recognized as essential for sustainability-related professions, yet this dimension is often underemphasized in vocational education research (Schutte et al., 2025; F. A. Williamson et al., 2023). The discovery that several students reconsidered their career aspirations in favor of environmental engineering demonstrates that transformative learning experiences can influence long-term professional trajectories. This finding holds strategic importance for maritime workforce planning, especially as global industry demand for environmentally competent personnel expands.

The integrated quantitative results reinforce these qualitative insights, showing substantial competency gains across all GMECI domains, with the overall effect size categorized as very large. Literature suggests that PBL is particularly effective for complex, interdisciplinary learning objectives (Warr & West, 2020; Xu et al., 2022), yet little evidence has previously been produced for maritime engineering in developing countries. The strong correlation between PBLEGMT scores and GMECI gains further indicates that high-quality PBL implementation marked by meaningful problem engagement and industry involvement supports competency development. Industry professionals' validation of students' analytical performance provides additional external confirmation that the competencies developed align with actual workforce demands (Hamed et al., 2018; Hidayat-Ur-Rehman, 2024). Collaborative learning mechanisms observed in this study also offer valuable contributions to vocational education theory. Distributed expertise emerged organically as students confronted multidimensional problems, illustrating that complex tasks naturally encourage collaborative specialization (Y. Li & Wang, 2025). This contrasts with prescriptive cooperative learning models that artificially assign roles, supporting arguments that authentic complexity fosters more functional collaboration. Peer-teaching episodes, which played a central role in knowledge consolidation, also align with existing evidence that explaining concepts enhances the accuracy and depth of the explainer's understanding. However, variation in team performance supports earlier findings that collaboration is not universally effective and requires structured support to prevent inequitable participation.

Implementation factors highlighted significant systemic influences affecting the effectiveness of sustainability-focused PBL. Infrastructure disparities between institutions shaped students' analytical depth and overall engagement, demonstrating that technology-rich pedagogies depend heavily on consistent access to adequate resources. Instructor facilitation skills also played a crucial role; research consistently shows that effective PBL requires substantial teacher expertise in guiding inquiry, supporting productive struggle, and managing team dynamics. Findings additionally revealed that industry partnerships are beneficial for contextual authenticity, but their effectiveness depends on realistic time commitments, structured engagement, and sustained collaboration mechanisms. This study also directly addresses several gaps in existing literature. Maritime vocational education in developing countries remains substantially understudied, and this research contributes evidence from Indonesia's diverse institutional contexts. By combining qualitative and quantitative approaches, the study responds to methodological gaps in maritime education research, which has been dominated by surface-level quantitative assessments with limited insight into learning processes. Moreover, documenting implementation challenges rather than focusing exclusively on successful outcomes helps counter the technology-optimism bias common in sustainability education literature.

Theoretically, the findings refine understanding across several domains. In PBL theory, the findings clarify that authenticity requires not just realistic scenarios but functional complexity characterized by interrelated variables, uncertainty, and ambiguous solutions. In sustainability education theory, the observed identity shifts support arguments that long-term, authentic engagement is necessary for developing environmental agency beyond factual knowledge. In collaborative learning theory, the emergence of distributed expertise without prescriptive roles offers evidence that vocational contexts can generate collaboration patterns more sophisticated than those found in academic settings. Practically, the study offers implications for maritime education institutions. Effective PBL requires selecting authentic, multidimensional problems grounded in operational data and regulatory frameworks. Institutions must also invest in digital infrastructure, provide sustained professional development for instructors, and formalize industry collaboration with realistic expectations. For students, project management training and structured collaboration support are essential to maximize learning outcomes in long-cycle projects. For policymakers, updating STCW guidelines to explicitly incorporate green technology competencies, prioritizing infrastructure funding, and incentivizing industry education partnerships could strengthen national workforce readiness for maritime decarbonization.

Implication

The findings of this study generate several critical implications for maritime education, instructional practice, and national policy as the sector prepares for an accelerated decarbonization transition. First, the compelling evidence that authentic and complex project-based learning fosters substantial gains in green marine engineering competencies highlights the necessity for maritime institutions to redesign curricula around real-world decarbonization challenges rather than relying on traditional lecture-based delivery. This shift requires embedding operational ship data, MARPOL requirements, and multidimensional decision-making scenarios as core learning components, demonstrating that authenticity and functional complexity—not simulation alone—are essential for developing both technical proficiency and sustainability-oriented professional identity. Second, the unequal infrastructure conditions observed across institutions underscore the urgent need for policy-driven investment in digital tools, laboratory facilities, and ship energy management systems to ensure equitable opportunities for students across urban and provincial contexts, thereby preventing widening competency disparities in the national maritime workforce. Third, because instructor facilitation quality was shown to significantly influence implementation effectiveness, institutions must invest in long-term professional development programs focusing on inquiry facilitation, interdisciplinarity, and project management rather than providing short-term workshops disconnected from classroom realities. Fourth, the study's evidence that industry mentorship strengthens relevance, motivation, and analytical rigor implies that maritime education systems should formalize sustainable collaboration mechanisms—such as structured mentorship schedules, shared data platforms, and integrated assessment roles—to overcome the common fragility of informal partnerships. Fifth, the emergence of distributed expertise and authentic collaborative problem-solving indicates that students require explicit training in teamwork, communication, and reflective practice to benefit fully from long-cycle projects, suggesting that soft-skill development must be treated as an intentional learning outcome rather than a by-product of group work. Finally, the documented alignment between PBL-driven competency development and workforce expectations reinforces the need for regulatory bodies and policymakers to update STCW interpretations, accreditation criteria, and curriculum standards to explicitly incorporate green technology competencies, ensuring that maritime vocational education contributes meaningfully to Indonesia's national decarbonization commitments and the global maritime industry's shift toward sustainable operations.

Limitations

Despite generating rich insights into the mechanisms through which project-based learning fosters green marine engineering competencies, this study is subject to several limitations that should be considered when interpreting its findings and generalizing them to broader maritime education contexts. The qualitative interpretive phenomenological approach, while appropriate for capturing lived experiences and developmental processes, relies on relatively small participant groups that inherently limit statistical generalizability, and the absence of a true control group restricts the ability to draw definitive causal inferences beyond the strong convergent patterns observed across data sources. Institutional differences—particularly disparities in digital infrastructure, simulation access, laboratory capacity, and instructor experience—likely influenced the quality and depth of project implementation, suggesting that the outcomes documented here may not be directly replicable in institutions with substantially different resource profiles. Industry mentor involvement, although beneficial, varied in consistency and depth due to professional time constraints, creating heterogeneity in mentorship quality and limiting the ability to attribute outcomes uniformly to industry engagement. Additionally, the study captured competency development over a single 16-week project cycle, which may not fully reflect long-term retention, transferability, or professional application of sustainability competencies in real shipboard environments. Self-reported data from interviews and reflection journals, despite triangulation, remain vulnerable to social desirability bias, particularly because students may perceive environmental responsibility as an institutionally favored stance. Finally, while the GMECI and PBLEGMT instruments demonstrated strong construct validity, their application within a developing-nation maritime context may require further longitudinal calibration to ensure sensitivity across diverse educational cultures, technological infrastructures, and regulatory environments. Collectively, these limitations highlight the need for future research employing mixed-methods longitudinal designs, broader institutional sampling, and deeper integration of shipboard internships to more comprehensively capture the long-term impacts of decarbonization-oriented project-based learning.

Suggestions

Building on the findings and limitations of this study, several recommendations can be proposed to strengthen future research and enhance the implementation of sustainability-oriented project-based learning in maritime vocational education. First, future studies should adopt mixed-methods or longitudinal designs that track competency development, retention, and workplace transferability over multiple semesters or during shipboard internships to more comprehensively evaluate long-term impacts of decarbonization-focused learning experiences. Second, broader institutional sampling across diverse maritime academies—ranging from well-resourced polytechnics to remote provincial schools—is needed to capture contextual variations and refine pedagogical models that remain effective under different infrastructure constraints. Third, stronger and more structured industry–education partnerships should be formalized through long-term agreements, scheduled mentoring frameworks, and shared data repositories to ensure consistent engagement and minimize the variability in mentor contributions observed in this study. Fourth, maritime institutions should invest in sustained professional development for instructors, focusing on facilitation of interdisciplinary inquiry, collaborative learning management, and integration of real operational data into project activities. Fifth, curriculum designers should embed explicit training in project management, teamwork, conflict resolution, and reflective practice to better equip students for long-cycle projects requiring distributed expertise and complex decision-making. Sixth, policymakers and accreditation bodies should consider updating national maritime competency frameworks to explicitly incorporate alternative fuel systems, emissions monitoring, and environmental compliance competencies, thereby aligning educational standards with global decarbonization requirements. Finally, researchers should continue refining and validating instruments such as GMECI and PBLEGMT across culturally and technologically diverse contexts to ensure that future assessments accurately capture the multidimensional competencies required of green marine engineers in the evolving maritime industry landscape.

CONCLUSION

This study provides substantial evidence that project-based learning centered on maritime decarbonization technologies offers a powerful pedagogical framework for cultivating the multidimensional competencies required of future green marine engineers in Indonesia's maritime vocational institutions. By engaging students with authentic, complex, and industry-relevant problems, the learning process facilitated not only significant gains in domain-specific knowledge—such as alternative fuel systems, energy efficiency strategies, emissions monitoring, and environmental compliance—but also fostered higher-order capabilities including systems thinking, trade-off analysis, and sustainable problem-solving, as reflected in robust improvements across all GMECI indicators. The integration of qualitative and quantitative findings reveals that collaborative knowledge construction, distributed expertise, and sustained interaction with professional mentors served as critical mechanisms enabling deep learning and professional identity formation, positioning students to navigate the technological, regulatory, and ethical demands of maritime decarbonization. At the same time, the study highlights important contextual and systemic factors—such as institutional infrastructure, instructor facilitation competency, and variability in industry engagement—that influence the effectiveness and equity of PBL implementation, underscoring the need for coordinated investments in instructional capacity, technology access, and structured partnerships. Collectively, the findings advance theoretical understanding of authentic PBL in vocational settings, address literature gaps in developing-nation maritime education, and provide actionable guidance for curriculum designers, educators, and policymakers seeking to prepare a sustainability-ready maritime workforce capable of contributing meaningfully to national and global decarbonization goals.

AUTHOR CONTRIBUTIONS STATEMENT

This research was collaboratively conducted by two authors. Nafi Almuzani, as the first author, led the overall conceptualization of the study, including the development of the research framework, formulation of the methodological design, and synthesis of the theoretical underpinnings guiding the project-based green technology learning model. He also played a central role in qualitative and quantitative analyses, including coding procedures, thematic consolidation, triangulation across multiple data sources, and integration of findings into a coherent analytic narrative. Tri Kismantoro contributed extensively to field implementation, coordinating institutional engagement across participating maritime academies, supervising data collection activities, and managing the organization of observational records, interview transcripts, and assessment datasets. He also provided critical evaluative insight into the interpretation of results and supported methodological refinement throughout the research process. Both authors jointly drafted, critically reviewed, and revised the manuscript, approved the final version for submission, and assume full responsibility for the integrity, accuracy, and scholarly rigor of the study.

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