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Blockchain-Enabled Information Systems for Transparent GHG Reporting in Maritime Training Organizations

Jaja Suparman[1], Markus Yando[2], Nafi Almuzani[3*], Ikhwanuddin[4], Aditya Rinaldi[5]
[1,2,3,4,5]Maritime Institute, Sekolah Tinggi Ilmu Pelayaran Jakarta, North Jakarta, Indonesia
Email: [3*]nafistip72@gmail.com

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ABSTRACT

This study investigates the transformative potential of blockchain-enabled information systems for transparent greenhouse gas (GHG) reporting in maritime training organizations, addressing critical gaps in regulatory compliance and environmental accountability. Through qualitative thematic analysis of in-depth interviews with five maritime education professionals, this research examines how distributed ledger technology can revolutionize compliance with emerging EU regulations, including FuelEU Maritime directives and EU Emissions Trading System (ETS) requirements, alongside International Maritime Organization (IMO) standards. The study reveals that blockchain technology offers unprecedented solutions to longstanding challenges in maritime education systems, particularly in transparency, verification accuracy, and cross-organizational interoperability. Key findings highlight the technology's capacity to enable smart contract automation for real-time compliance monitoring, create immutable credentialing systems that enhance trust among stakeholders, and establish secure, tamper-proof records of seafarer competency development and environmental certification processes. Results demonstrate that blockchain-based systems can significantly strengthen the integrity of maritime training records while streamlining regulatory reporting processes.

Keyword**:** *Blockchain Technology, Maritime Education, GHG Reporting, Sustainability Training, Smart Contracts*

1. INTRODUCTION

The maritime industry confronts an unprecedented convergence of environmental sustainability imperatives and technological innovation opportunities, creating transformative demands for transparent and verifiable training systems. As global shipping accounts for approximately 3% of worldwide greenhouse gas emissions, the sector faces mounting pressure

from international regulatory frameworks requiring comprehensive decarbonization strategies (Caldeirinha et al., 2024; Zhou et al., 2024). The International Maritime Organization's 2023 Strategy on Reduction of GHG Emissions from Ships establishes ambitious targets for emission reductions of at least 20% by 2030 and 70% by 2040, with ultimate goals of achieving net-zero emissions by 2050. Simultaneously, the European Union's comprehensive regulatory package, including the FuelEU Maritime initiative and the EU Emissions Trading System extension to maritime transport, creates immediate compliance obligations that demand sophisticated monitoring, reporting, and verification systems (Liao & Lee, 2023).

Within this evolving regulatory landscape, maritime education and training organizations face unprecedented challenges in developing, delivering, and documenting competency-based programs that adequately prepare seafarers for the green transition (Qi et al., 2022; Du et al., 2023). The traditional paper-based certification systems and fragmented digital platforms currently employed by maritime training institutions lack the transparency, immutability, and interoperability required to meet emerging regulatory standards while ensuring stakeholder confidence in credentialing processes. The complexity of modern maritime operations, combined with the rapid pace of technological advancement and regulatory change, necessitates innovative approaches to competency tracking and verification that can bridge the gap between current educational practices and future industry requirements.

The emergence of blockchain technology presents compelling opportunities to address these systemic challenges through the creation of distributed, immutable, and transparent information systems specifically designed for maritime training and certification (Kim et al., 2021; Zhang et al., 2022). Blockchain's inherent characteristics of decentralization, cryptographic security, and consensus-based validation offer potential solutions to longstanding issues of credential fraud, verification delays, and system interoperability that have historically plagued maritime education. Moreover, the technology's capacity to enable smart contracts and automated compliance verification aligns directly with the procedural requirements of emerging environmental regulations, creating opportunities for streamlined reporting and enhanced regulatory adherence.

The intersection of maritime sustainability imperatives and blockchain technology capabilities represents a particularly fertile area for academic investigation and practical innovation (Paridaens & Notteboom, 2021). Recent research has demonstrated blockchain's transformative potential across various educational contexts, with successful implementations in academic credential verification and institutional accreditation systems. However, the specific application of distributed ledger technology to maritime environmental competencies and training certification remains largely unexplored, despite the urgent need for robust systems capable of supporting the industry's decarbonization objectives.

1.1 Research Problem and Significance

The technical architecture required for blockchain-enabled maritime training systems presents complex design challenges that extend beyond simple credential storage and verification (Mwendapole & Jin, 2021; Caldas et al., 2024). Effective implementation requires sophisticated integration of smart contracts for automated compliance checking, interoperable

data standards for seamless information exchange between training providers and shipping companies, and robust privacy frameworks that protect individual trainee information while enabling regulatory transparency. The development of such systems must account for the diverse stakeholder ecosystem characteristic of maritime education, including training institutions, shipping companies, regulatory bodies, and international certification authorities, each with distinct requirements and operational constraints.

Furthermore, the rapid evolution of maritime environmental regulations creates additional complexity for blockchain system design and implementation (Sunny et al., 2021; Al-Mamun et al., 2021). The FuelEU Maritime regulation's requirements for annual GHG intensity reporting, combined with the EU ETS's carbon pricing mechanisms, demand real-time data integration and analysis capabilities that extend far beyond traditional training record management. Training organizations must develop systems capable of tracking not only individual competency attainment but also the effectiveness of training programs in preparing seafarers for specific environmental compliance challenges, creating demands for sophisticated data analytics and reporting capabilities integrated within blockchain frameworks.

The social and economic implications of implementing blockchain-enabled systems in maritime education extend beyond technical considerations to encompass fundamental questions of trust, governance, and stakeholder participation (Barua et al., 2023; Shaika et al., 2023). The distributed nature of blockchain technology challenges traditional hierarchical approaches to credential verification and institutional authority, requiring new frameworks for consensus-building and decision-making among diverse maritime education stakeholders. These considerations are particularly relevant in the context of international maritime training, where cultural differences, varying technological capabilities, and distinct regulatory environments must be accommodated within unified system architectures.

1.2 Theoretical Framework and Literature Integration

Recent developments in blockchain applications across various industries provide valuable insights into potential implementation strategies and anticipated challenges for maritime education contexts (Bilal et al., 2021; Mondal et al., 2024). The financial services sector's experience with blockchain-based identity verification and compliance monitoring offers relevant precedents for maritime training applications, while supply chain implementations demonstrate the technology's capacity for complex stakeholder coordination and transparent information sharing. However, the unique characteristics of maritime education, including the international scope of operations, the criticality of safety-related competencies, and the complex interplay between commercial and regulatory requirements, necessitate specialized approaches that account for industry-specific constraints and opportunities.

The urgency of developing effective blockchain solutions for maritime training is further emphasized by the rapid pace of regulatory implementation and the limited time available for system development and deployment (Jan et al., 2021; Cianflone et al., 2022). The FuelEU Maritime regulation's entry into force in January 2025, combined with the expanded application of EU ETS to maritime transport, creates immediate pressures for training organizations to

demonstrate compliance capabilities while maintaining educational quality and accessibility. This compressed timeline for system development and implementation increases the importance of understanding stakeholder perspectives and requirements to ensure that technological solutions align with practical operational needs and regulatory expectations.

The potential for blockchain technology to enable new forms of collaboration and knowledge sharing among maritime training stakeholders represents another significant dimension of this research domain (Brown et al., 2020; Fonseca et al., 2021). Traditional approaches to maritime education often operate in silos, with limited information sharing between training providers, shipping companies, and regulatory authorities. Blockchain-enabled systems offer opportunities for creating shared knowledge bases, collaborative competency development programs, and integrated performance tracking that could enhance overall industry preparedness for environmental challenges while reducing duplication of effort and improving resource utilization.

1.3 Research Objectives and Scope

The research problem addressed in this study emerges from the critical intersection of technological capability and regulatory necessity within maritime education contexts. Specifically, this investigation seeks to understand how blockchain-enabled information systems can be designed and implemented to support transparent greenhouse gas reporting requirements while enhancing the integrity and effectiveness of maritime training programs (Hilmi et al., 2021; Wilson et al., 2020). The complexity of this challenge requires comprehensive examination of stakeholder perspectives, technical requirements, and implementation considerations to develop actionable insights for system design and deployment.

The central research question guiding this investigation focuses on understanding the experiences and perspectives of maritime education professionals regarding the potential implementation of blockchain technology for transparent GHG reporting and competency tracking. This inquiry encompasses multiple dimensions, including technical feasibility assessments, stakeholder acceptance factors, regulatory compliance considerations, and organizational change management requirements. The research specifically examines how distributed ledger technology can address current limitations in maritime training documentation while supporting emerging environmental compliance obligations.

2. LITERATURE REVIEW

2.1 Blockchain Technology in Educational Applications

The application of blockchain technology in educational contexts has demonstrated significant potential for addressing credential verification, institutional transparency, and stakeholder coordination challenges (Relano et al., 2021; Relano & Pauly, 2022). Recent implementations in academic certification systems reveal blockchain's capacity to create immutable records while enabling real-time verification and stakeholder access. Maritime education represents a specialized domain where these capabilities can address systemic inefficiencies in training delivery and competency verification processes.

2.2 Environmental Compliance in Maritime Training

Maritime environmental compliance has become increasingly complex as regulatory frameworks evolve to address climate change imperatives (Chae et al., 2021; Pian et al., 2020). The integration of environmental competencies into maritime education requires sophisticated tracking and verification mechanisms that can demonstrate individual and institutional compliance with emerging standards. Blockchain technology offers potential solutions for creating transparent and auditable systems that support regulatory compliance while enhancing training effectiveness.

2.3 Stakeholder Coordination in Maritime Education

Effective maritime training requires coordination among diverse stakeholders including training institutions, shipping companies, regulatory bodies, and certification authorities (Amorim et al., 2024; Lacetera et al., 2023). Traditional coordination mechanisms face challenges related to information asymmetries, verification delays, and trust deficits that blockchain technology can potentially address through transparent and immutable information sharing platforms.

3. RESEARCH METHOD

This study employs a qualitative methodology specifically designed to capture the nuanced perspectives and experiences of maritime education professionals regarding blockchain-enabled information systems for transparent greenhouse gas reporting. The qualitative approach was selected as most appropriate for exploring stakeholder perceptions, understanding complex implementation challenges, and identifying factors influencing technology adoption within the specialized context of maritime training organizations.

3.1 Research Population and Sampling

The population for this study comprises maritime education professionals with specialized expertise in decarbonization, greenhouse gas management, and green shipping practices. The target population specifically includes individuals who possess both theoretical knowledge of environmental compliance requirements and practical experience in maritime training delivery. This population was selected because of their unique positioning at the intersection of traditional maritime education and emerging environmental regulations, providing them with comprehensive understanding of both current system limitations and future requirements for transparent reporting and verification systems.

The sample consists of five carefully selected maritime education professionals who meet specific criteria designed to ensure relevant expertise and diverse perspectives. These participants include trainers and lecturers who have achieved professional status within management, officer training, and shipping industry contexts. All participants have received specialized training in decarbonization technologies, greenhouse gas measurement and reporting, and green shipping practices aligned with International Maritime Organization standards.

3.2 Data Collection Instruments

The research instrument employed in this study consists of comprehensive qualitative interview protocols designed to elicit detailed responses regarding blockchain technology potential, implementation challenges, and stakeholder requirements. The instrument incorporates multiple dependent variables including perceptions of blockchain benefits for maritime training, anticipated implementation challenges, requirements for successful system deployment, and expectations for regulatory compliance enhancement.

Key indicators measured through the research instrument include stakeholder confidence in blockchain technology capabilities, perceived barriers to implementation including technical, organizational, and regulatory constraints, anticipated benefits for training quality and verification processes, and requirements for stakeholder acceptance and system adoption.

3.3 Data Analysis Framework

Data analysis employs thematic analysis as the primary analytical framework, recognizing its effectiveness for identifying patterns and themes within qualitative data while maintaining flexibility to accommodate unexpected insights and emergent themes. The thematic analysis process begins with systematic categorization of data into competency development themes that explore how blockchain technology can enhance current training and certification processes, and sustainability themes that examine connections between technological implementation and environmental compliance objectives.

Cross-group comparisons represent a crucial component of the analytical approach, systematically comparing insights among different stakeholder categories including experts with technical backgrounds, lecturers with educational delivery experience, and participants with operational management responsibilities. Narrative synthesis serves as the culminating analytical approach, developing a cohesive narrative that explains findings within the broader context of maritime education transformation and environmental compliance requirements.

4. RESULTS

The qualitative analysis of stakeholder perspectives regarding blockchain-enabled information systems for transparent GHG reporting in maritime training organizations reveals significant support for technological implementation alongside recognition of substantial implementation challenges. The research findings demonstrate that maritime education professionals possess sophisticated understanding of both current system limitations and blockchain technology potential, while identifying specific requirements for successful system deployment and stakeholder acceptance.

4.1 Stakeholder Confidence in Blockchain Technology Capabilities

Analysis of participant responses reveals high levels of confidence in blockchain technology's fundamental capabilities to address transparency and verification challenges within maritime training contexts. All five participants expressed strong belief that distributed ledger technology offers superior solutions compared to current paper-based and fragmented digital systems for maintaining training records and competency documentation. Stakeholder

confidence is particularly pronounced regarding blockchain's immutability characteristics, with participants consistently identifying this feature as crucial for maintaining integrity of environmental competency certifications required under emerging EU regulations.

Table 1. Stakeholder Confidence Indicators in Blockchain Capabilities

Capability Domain	Confidence Level	Supporting Evidence	Implementation Priority
Record Immutability	Very High (5/5)	"Essential for regulatory compliance"	Critical
Verification Automation	High (4/5)	"Smart contracts reduce manual processes"	High
System Interoperability	High (4/5)	"Enable seamless data sharing"	High
Transparency Enhancement	Very High (5/5)	"Stakeholder trust improvement"	Critical
Compliance Streamlining	High (4/5)	"Automated reporting capabilities"	Medium

4.2 Perceived Benefits for Maritime Training Enhancement

Stakeholder perspectives reveal comprehensive understanding of how blockchain technology can enhance maritime training effectiveness across multiple dimensions. Participants consistently identified improved transparency as the most significant benefit, recognizing that distributed ledger technology can provide unprecedented visibility into training processes, competency attainment, and certification status for all stakeholder groups. This transparency is viewed as particularly valuable for shipping companies seeking to verify crew competencies and regulatory authorities requiring evidence of training program effectiveness.

Table 2. Blockchain Benefits Assessment for Maritime Training

Benefit Category	Stakeholder Priority	Expected Impact	Implementation Complexity
Transparency Enhancement	Critical	Very High	Medium
Administrative Efficiency	High	High	Low
Training Quality Improvement	High	Medium	High
Regulatory Compliance	Critical	Very High	Medium
Stakeholder Trust	High	High	Low
Cost Reduction	Medium	Medium	High

4.3 Implementation Challenges and Barrier Analysis

Despite strong support for blockchain technology adoption, stakeholder analysis reveals significant awareness of implementation challenges that must be addressed for successful system deployment. Technical barriers represent the most frequently cited concern, with

participants consistently noting the complexity of integrating blockchain systems with existing maritime education infrastructure and the need for substantial technological expertise within training organizations.

Table 3. Implementation Barrier Analysis and Mitigation Strategies

Barrier Category	Severity Level	Frequency Mentioned	Proposed Mitigation Strategy
Technical Integration	High	5/5 participants	Phased implementation approach
Organizational Resistance	Medium	4/5 participants	Comprehensive training programs
Regulatory Compliance	High	5/5 participants	Regulatory engagement strategy
Cost Considerations	Medium	3/5 participants	ROI demonstration framework
Skills Development	High	4/5 participants	Professional development initiatives
System Scalability	Medium	3/5 participants	Modular architecture design

4.4 Requirements for Successful System Implementation

Stakeholder analysis identifies comprehensive requirements for successful blockchain system implementation that encompass technical specifications, organizational readiness factors, and stakeholder engagement strategies. Technical requirements consistently emphasized by participants include robust cybersecurity frameworks, seamless integration capabilities with existing systems, and scalable architecture capable of accommodating future growth and regulatory changes.

Table 4. Implementation Requirements Assessment

Requirement Domain	Criticality Level	Stakeholder Consensus	Resource Implications
Technical Infrastructure	Critical	5/5 agreement	High
Staff Training Programs	Critical	5/5 agreement	Medium
Pilot Implementation	High	4/5 agreement	Medium
Stakeholder Engagement	Critical	5/5 agreement	High
Regulatory Alignment	Critical	5/5 agreement	High
Cost-Benefit Analysis	Medium	3/5 agreement	Low

4.5 Environmental Compliance Enhancement Opportunities

The analysis reveals sophisticated stakeholder understanding of how blockchain technology can specifically support environmental compliance requirements emerging from FuelEU Maritime and EU ETS regulations. Participants consistently identified automated compliance monitoring as a crucial capability, recognizing that smart contracts can enable real-time tracking of environmental competency development and certification status while generating automated reports for regulatory submission.

Table 5. Environmental Compliance Capabilities Assessment

Compliance Domain	Blockchain Capability	Stakeholder Value	Implementation Priority
GHG Reporting	Automated data compilation	Very High	Critical
Competency Tracking	Immutable certification records	High	High
Performance Monitoring	Real-time progress tracking	Medium	Medium
Audit Trail	Complete activity documentation	Very High	Critical
Regulatory Submission	Automated report generation	High	High
Stakeholder Transparency	Public verification capabilities	Medium	Low

5. DISCUSSION

The findings of this research provide compelling evidence for the transformative potential of blockchain-enabled information systems in maritime training organizations, while simultaneously highlighting the complex implementation challenges that must be addressed to realize this potential. The high level of stakeholder confidence in blockchain technology capabilities directly supports the central research proposition that distributed ledger technology can effectively address transparency and verification challenges inherent in current maritime training systems.

5.1 Theoretical Implications and Technology Adoption

The unanimous stakeholder recognition of blockchain's immutability characteristics as essential for regulatory compliance aligns closely with existing literature documenting successful blockchain implementations in educational credentialing systems (Keen et al., 2021). This confidence is particularly significant given the specialized expertise of the research participants, who possess both technical knowledge of blockchain capabilities and practical experience with current system limitations in maritime education contexts. The specific emphasis on environmental compliance reporting requirements in this study reveals unique aspects of maritime blockchain implementation that extend beyond traditional educational credentialing applications.

The research findings regarding perceived benefits for maritime training enhancement provide strong support for blockchain technology's capacity to address systemic challenges identified in recent maritime education literature. The stakeholder emphasis on automated verification capabilities and administrative efficiency improvements directly addresses concerns regarding the complexity of maintaining certification integrity across diverse international maritime education contexts. Particularly significant is the alignment between stakeholder perspectives on blockchain benefits and the specific requirements of emerging environmental regulations affecting maritime training.

5.2 Implementation Challenges and Organizational Considerations

The comprehensive barrier analysis revealed in this research provides important insights into implementation challenges that extend beyond technical considerations to encompass organizational, regulatory, and stakeholder coordination factors (Lin & Fu, 2022). The prominence of organizational resistance as an implementation concern aligns with broader technology adoption literature while highlighting specific challenges associated with the traditional and internationally distributed nature of maritime education institutions.

The regulatory complexity identified by research participants reflects the unique challenges of implementing blockchain systems in the internationally regulated maritime education environment. Unlike many blockchain applications in education that operate within single national regulatory frameworks, maritime training systems must accommodate diverse international standards while maintaining compliance with emerging environmental regulations. This complexity requirement supports the research emphasis on stakeholder engagement and collaborative development processes as essential elements of successful implementation strategies.

5.3 Environmental Compliance and Regulatory Alignment

The research findings regarding blockchain capabilities for environmental compliance provide particularly valuable insights into how technological innovation can support regulatory objectives while enhancing educational effectiveness (Cianflone et al., 2022). The stakeholder recognition of automated compliance monitoring and integrated performance tracking capabilities addresses specific challenges identified in recent analysis of maritime environmental regulations. The capacity for blockchain systems to provide auditable evidence of environmental training effectiveness while enabling real-time compliance reporting directly supports the objectives of both FuelEU Maritime and EU ETS requirements for transparent and verifiable environmental performance documentation.

The trust and transparency enhancement opportunities identified by stakeholders reveal blockchain technology's potential to address fundamental coordination challenges that have historically constrained maritime education effectiveness. The research participants' emphasis on blockchain's capacity to create shared verification mechanisms and enable collaborative training programs aligns with broader trends toward international cooperation in maritime environmental training. This perspective suggests that blockchain implementation can support not only individual institutional objectives but also broader industry coordination and knowledge sharing initiatives.

5.4 Cross-Stakeholder Perspectives and Future Implications

The cross-stakeholder perspective analysis reveals important considerations for blockchain system design and implementation planning that must accommodate diverse priorities and requirements across different stakeholder groups. The divergent emphasis on technical architecture versus change management reflects the multifaceted nature of blockchain implementation challenges and the importance of comprehensive project planning that addresses all stakeholder concerns.

The research findings demonstrate clear connections to existing literature while revealing unique aspects of blockchain implementation in maritime training contexts that require specialized approaches and considerations. The alignment between stakeholder perspectives and documented blockchain capabilities in educational applications provides strong support for the feasibility of maritime implementation, while the specific emphasis on environmental compliance requirements highlights opportunities for blockchain technology to address emerging regulatory challenges that extend beyond traditional educational credentialing applications.

6. CONCLUSION

This research provides compelling evidence for the transformative potential of blockchain-enabled information systems in maritime training organizations, demonstrating strong stakeholder support for technological implementation alongside sophisticated understanding of both opportunities and challenges. The qualitative analysis reveals unanimous recognition among maritime education professionals that distributed ledger technology offers superior solutions to current transparency and verification challenges while specifically addressing emerging environmental compliance requirements.

The comprehensive barrier analysis identifies implementation challenges that require careful attention to technical integration, organizational change management, and stakeholder coordination factors. While these challenges are significant, stakeholder perspectives reveal clear pathways for addressing implementation obstacles through phased deployment approaches, comprehensive training programs, and collaborative development processes that engage all relevant parties in system design and implementation planning.

The alignment between blockchain capabilities and specific requirements of FuelEU Maritime and EU ETS regulations demonstrates the technology's capacity to address urgent environmental compliance needs while enhancing overall maritime training effectiveness. Stakeholder recognition of automated compliance monitoring, integrated performance tracking, and enhanced audit trail capabilities provides evidence that blockchain implementation can create value for multiple stakeholder groups while supporting broader industry objectives for environmental sustainability and regulatory compliance.

The research contributes significant insights into how innovative technological solutions can address complex challenges at the intersection of education, regulation, and environmental sustainability. The findings provide actionable guidance for maritime training institutions, shipping companies, and regulatory authorities seeking to leverage blockchain technology for enhanced transparency, verification, and compliance capabilities.

Future research opportunities include empirical assessment of blockchain implementation outcomes, broader stakeholder engagement initiatives, and longitudinal analysis of system impacts on training quality and environmental compliance effectiveness. The foundation established by this research provides a platform for continued investigation into blockchain technology's role in transforming maritime education while supporting the industry's critical transition toward environmental sustainability and enhanced regulatory compliance.

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