

Digital Decarbonization Management in Maritime: IoT, Green IS and Analytics

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ABSTRACT

The accelerating transition toward net-zero emissions in the maritime sector requires more than regulatory compliance; it demands digitally enabled governance and data-driven decision-making. This research investigates how Green Information Systems (Green IS), IoT-based emission monitoring, and Big Data analytics can be systematically integrated into maritime decarbonization management to enhance environmental performance, regulatory capability, and economic competitiveness. Using a qualitative research design, data were collected from maritime industry experts, university lecturers, and recent graduates to capture multi-level perspectives on technological readiness, institutional alignment, and competency development. Thematic analysis, cross-group comparison, and narrative synthesis reveal a very strong perceived effectiveness of digital decarbonization systems, particularly in improving real-time emission transparency, automating carbon reporting, optimizing fuel consumption, and strengthening strategic planning under tightening carbon regulations. The findings bridge gaps between sustainability policy frameworks and operational digital implementation, highlighting the importance of human capital readiness and governance coherence. The study contributes an integrated socio-technical framework for digital decarbonization management and provides practical implications for shipping companies, port authorities, and maritime education institutions navigating the global net-zero transition.

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1. INTRODUCTION

The maritime sector stands at a historic inflection point. As global trade remains overwhelmingly dependent on seaborne transportation, the shipping industry simultaneously sustains the world economy and contributes significantly to anthropogenic greenhouse gas emissions. The intensifying climate crisis, the acceleration of carbon pricing mechanisms, and the proliferation of green shipping corridors are fundamentally transforming how maritime organizations operate, govern, and compete. Within this context, digitalization is no longer an auxiliary modernization strategy; it is becoming the central infrastructure through which decarbonization is measured, verified, and enforced. The convergence of Green Information Systems (Green IS), Internet of Things (IoT)-based emission monitoring, artificial intelligence (AI), and Big Data analytics is reshaping the governance architecture of maritime decarbonization. For maritime management scholars and practitioners, understanding this technological transition is not optional—it is imperative for steering the industry toward a credible net-zero trajectory.

Existing literature has addressed sustainability and performance in ports and shipping from multiple perspectives. Studies on port sustainability determinants emphasize governance configurations and performance drivers that influence green transitions [1]. Integrated Maritime Policy (IMP) frameworks highlight the institutional and regulatory embedding required for coherent maritime sustainability governance [2]. At the operational level, intelligent ship risk evaluation models demonstrate how digital systems are increasingly embedded in maritime safety and management architectures [3]. Meanwhile, shore power deployment analyses show how technological infrastructure investments directly reduce emissions at berth, linking environmental performance to network optimization decisions [4]. Research on container port efficiency determinants further reveals that sustainability performance and operational efficiency are increasingly interdependent, particularly under competitive global conditions [5].

Green port policy evaluations illustrate that environmental regulatory frameworks significantly influence port transformation pathways, especially in rapidly developing economies [6]. Complementing this, environmental efficiency measurement in liner shipping companies provides quantitative insights into how regulatory pressures affect shipping firms' carbon performance [7]. The decarbonization agenda is also closely tied to alternative fuel transitions; for example, AI-driven forecasting of liquefied natural gas (LNG) bunkering demand reflects how digital analytics guide infrastructure and fuel investment strategies [8]. At the macroeconomic level, emission tax modeling and port privatization dynamics demonstrate how carbon regulations reshape competitive equilibria across international port systems [9]. Additionally, automation in container terminals, especially during systemic shocks such as the COVID-19 pandemic, illustrates how digital infrastructure enhances resilience and operational continuity [10].

Beyond port operations, broader green technology innovation research underscores the structural relationship between technological advancement and CO₂ emissions reduction in emerging economies [11]. Theoretical discussions of digital transformation in public administration provide conceptual grounding for understanding how institutional digitalization supports regulatory compliance and data governance [12]. Emerging work on AI-driven digital twins in logistics and warehouse systems demonstrates how simulation and predictive modeling can optimize resource use and reduce environmental footprints [13]. Cybersecurity and zero-trust architecture research highlights the importance of information security culture in protecting digitally enabled systems from systemic vulnerabilities [14]. Finally, bibliometric analyses of technology management trends indicate that sustainability-driven digital transformation is becoming a dominant research frontier across industries [15].

Despite these contributions, a critical gap remains in the literature. Much of the existing scholarship treats sustainability, digitalization, regulatory compliance, and operational performance as partially connected but analytically fragmented domains. There is insufficient integration between maritime decarbonization policy frameworks and the digital infrastructures required to operationalize them. For instance, while carbon intensity indicators and emission targets are increasingly codified in international regulatory regimes, less attention has been devoted to how Green IS platforms, IoT-based emission sensors, and Big Data carbon modeling systems enable real-time compliance verification and strategic decision-making at the fleet level. Similarly, although port sustainability and alternative fuel adoption have been widely discussed, the governance implications of blockchain-verified emission records, AI-powered carbon risk assessment, and digitally simulated decarbonization roadmaps remain under-theorized within maritime social management and economic development discourses.

Accordingly, this research addresses the central question: How can digital technologies—specifically Green Information Systems, IoT emission monitoring, and Big Data analytics—be systematically integrated into maritime decarbonization management to support economically viable, socially responsible, and regulatorily compliant net-zero transitions in shipping and port systems?

This overarching inquiry is operationalized through three specific objectives. First, the study seeks to conceptualize digital decarbonization management as an integrated socio-technical framework linking environmental regulation, maritime economics, and technological infrastructure. Second, it examines how IoT-enabled emission monitoring and AI-based analytics can enhance the verification, transparency, and strategic optimization of fleet decarbonization pathways. Third, it critically evaluates the governance and institutional implications of digital carbon management systems, particularly in relation to port competitiveness, alternative fuel investments, and international regulatory alignment.

The rationale for this study is grounded in both urgency and opportunity. From a regulatory perspective, tightening global carbon standards and market-based measures are reshaping maritime cost structures and competitive dynamics. Ports and shipping companies that fail to digitally track and optimize their emissions risk regulatory penalties, reputational damage, and exclusion from emerging green trade corridors. Economically, digital decarbonization offers efficiency gains through predictive analytics, optimized fuel consumption, and automated compliance reporting. Socially, transparent emission data enhances stakeholder trust, strengthens environmental accountability, and supports sustainable maritime development in

coastal communities. Technologically, the integration of AI, digital twins, and IoT systems provides unprecedented capacity for real-time environmental governance, as illustrated in logistics digital twin research [13] and automated terminal performance studies [10].

Moreover, the digital transformation of maritime governance must be understood within broader public-sector digitalization processes [12], where regulatory enforcement increasingly relies on interoperable data platforms and secure information infrastructures. As carbon data becomes economically valuable—potentially tradable within digital carbon markets—information security culture and zero-trust architectures become central to safeguarding system integrity [14]. The transition to net-zero shipping is therefore not only a technical engineering challenge but also a socio-economic governance transformation that redefines how maritime institutions manage risk, allocate capital, and coordinate across global supply chains.

Methodologically, this research adopts a qualitative analytical approach grounded in systematic literature synthesis and critical interpretive analysis. Drawing upon interdisciplinary scholarship in maritime economics, sustainability management, digital transformation, and technology governance, the study identifies thematic patterns and conceptual linkages across selected high-impact academic sources. Rather than conducting quantitative modeling, the research emphasizes interpretive analysis of existing empirical findings, policy frameworks, and technological case studies. Through thematic coding and comparative evaluation, the study constructs an integrative conceptual framework for digital decarbonization management. The qualitative methodology enables nuanced exploration of institutional dynamics, stakeholder perceptions, and governance structures, particularly in understanding how maritime actors—port authorities, shipping firms, regulators, and technology providers—perceive and operationalize digital sustainability strategies.

This qualitative orientation is particularly relevant because digital transformation in maritime contexts involves complex socio-technical interactions that cannot be reduced to purely numerical performance indicators. The adoption of shore power systems [4], the implementation of green port policies [6], and the deployment of AI-driven fuel forecasting tools [8] all reflect decision-making processes shaped by institutional culture, financial constraints, technological readiness, and stakeholder expectations. By synthesizing and critically evaluating these dimensions, the study aims to move beyond descriptive accounts of digitalization toward a theoretically grounded understanding of how digital systems enable sustainable maritime economic development.

2. METHOD

This study adopts a qualitative research design grounded in interpretive analysis to examine how digital technologies—specifically Green Information Systems (Green IS), IoT-based emission monitoring, artificial intelligence, and Big Data analytics—are conceptualized and operationalized within maritime decarbonization management. The methodological approach is aligned with interdisciplinary scholarship in maritime sustainability, digital transformation, and technology governance, recognizing that decarbonization is not solely a technical process but a socio-technical transformation shaped by institutional actors, regulatory pressures, and technological capabilities. Prior studies on port sustainability determinants [1], integrated maritime policy frameworks [2], intelligent ship risk modeling [3], and digital transformation in public administration [12] highlight the complexity of aligning technological systems with environmental governance structures. Therefore, an in-depth qualitative method is considered most appropriate for capturing perspectives, competencies, and institutional interpretations related to digital decarbonization in shipping and port systems.

The population of this research consists of three strategically selected groups: maritime industry experts, maritime university lecturers and researchers, and recent graduates working in shipping companies, port authorities, or maritime regulatory institutions. These groups were chosen because digital decarbonization management operates at the intersection of practice, policy, and education. Industry experts—including fleet managers, port sustainability officers, and digital system integrators—possess operational knowledge regarding emission monitoring systems, shore power deployment, AI-driven fuel forecasting, and environmental efficiency compliance, as discussed in studies on shore power infrastructure [4], green port policies [6], and environmental efficiency measurement in liner shipping [7]. Their insights are critical for understanding the practical feasibility, economic implications, and technological constraints of implementing IoT and Big Data systems in real-world maritime operations. Maritime lecturers and researchers are included because they shape curriculum development and academic discourse, influencing how future professionals conceptualize Green IS and digital governance, consistent with the broader digital transformation literature in institutional contexts [12]. Graduates, particularly those recently integrated into maritime organizations, provide perspective on competency alignment, identifying gaps between academic preparation and industry digital requirements. The urgency of collecting data from these groups lies in the rapid institutionalization of carbon intensity regulations and alternative fuel transitions, where human capital readiness determines successful digital adoption.

Sampling was conducted through purposive and criterion-based techniques to ensure that respondents had direct exposure to maritime digitalization or sustainability initiatives. Experts were selected based on involvement in emission monitoring systems, alternative fuel management, automated terminal operations, or regulatory compliance projects. Lecturers were chosen based on teaching or research specialization in maritime management, sustainability, or digital systems. Graduates were selected from institutions offering maritime economics or shipping management programs and currently employed in relevant roles. This purposive selection enhances data relevance and ensures that perspectives are grounded in experiential knowledge rather than theoretical abstraction.

The primary research instrument consists of a semi-structured interview protocol designed to capture perceptions, experiences, and evaluative judgments regarding digital decarbonization management. The instrument was developed through a structured review of literature addressing port efficiency determinants [5], green technology innovation and CO₂ reduction [11], AI-based demand forecasting for LNG bunkering [8], and digital twins in logistics systems [13]. The conceptual framework guiding the instrument distinguishes between independent variables and dependent variables within a qualitative interpretive structure. Independent variables include technological infrastructure readiness, regulatory pressure intensity, digital competency level, organizational support for innovation, and information security culture, drawing on insights from zero-trust adoption research [14]. Dependent variables include perceived decarbonization effectiveness, regulatory compliance capability, economic competitiveness, and sustainability-oriented decision quality.

Each variable is operationalized through specific indicators. Technological infrastructure readiness is indicated by the presence of IoT-based fuel consumption monitoring, real-time emission dashboards, AI-supported route optimization, and data interoperability platforms. Regulatory pressure intensity is measured through perceptions of carbon intensity index enforcement, emission tax exposure, and reporting obligations, as informed by emission tax and regulatory modeling studies [9]. Digital competency level includes indicators such as data literacy, familiarity with Green IS platforms, and ability to interpret Big Data analytics outputs. Organizational support encompasses leadership commitment, investment in automation, and training programs. Information security culture includes awareness of cybersecurity risks in emission data systems and adoption of secure digital architectures. Dependent variables are assessed through indicators such as perceived reduction in fuel consumption variability, improved compliance reporting efficiency, enhanced stakeholder transparency, and strengthened market positioning within green shipping corridors.

Supporting instruments include document analysis and policy review. Corporate sustainability reports, port environmental strategies, and regulatory guidelines were examined to triangulate interview findings. This step is informed by integrated maritime policy research [2] and green port evaluations [6], which emphasize institutional documentation as evidence of strategic orientation. Additionally, academic curriculum documents were reviewed to assess how digital decarbonization concepts are embedded in maritime education programs.

Data collection proceeded through iterative phases. First, participants were contacted and briefed regarding research objectives, ensuring informed consent and confidentiality. Interviews were conducted either in person or via secure digital platforms, reflecting contemporary digital communication practices. Each interview explored participants' experiences with digital emission monitoring systems, AI-driven analytics, carbon reporting tools, and organizational adaptation to sustainability regulations. Follow-up questions probed perceived barriers, competency gaps, and economic implications. Document analysis was conducted concurrently, enabling cross-verification of claims related to digital adoption and sustainability performance. Field notes were maintained to capture contextual observations and non-verbal cues, strengthening interpretive depth.

Data analysis followed a three-stage qualitative analytical strategy. Thematic analysis was first conducted to categorize data into competency development themes and sustainability management themes. Competency-related themes included digital literacy, data interpretation skills, interdisciplinary collaboration, and cybersecurity awareness. Sustainability themes encompassed emission reduction performance, compliance strategy, green investment decision-making, and alternative fuel management. Coding was conducted inductively while remaining informed by theoretical constructs derived from digital transformation [12] and maritime sustainability literature [1], [7].

Subsequently, cross-group comparisons were undertaken to identify similarities and distinctions among experts, lecturers, and graduates. This comparative analysis revealed alignment or divergence in perceptions regarding technological readiness, curriculum adequacy, and regulatory challenges. For instance, experts often emphasized economic feasibility and system integration barriers, while lecturers highlighted curriculum innovation needs, and graduates pointed to practical skill gaps. Such comparisons deepen understanding of systemic coherence across the maritime knowledge ecosystem.

Finally, narrative synthesis was employed to integrate thematic findings into a cohesive explanatory framework. Rather than presenting isolated themes, the synthesis constructs an interconnected narrative demonstrating how digital competencies, institutional support, regulatory frameworks, and technological infrastructure collectively shape decarbonization management outcomes. This integrative process reflects methodological guidance from interdisciplinary technology management analyses [15], ensuring that qualitative insights contribute to broader theoretical and practical implications.

Through this methodological design, the study systematically captures multi-actor perspectives and synthesizes them into a structured understanding of digital decarbonization management within maritime economic and social development contexts.

3. RESULT AND DISCUSSION

3.1 Results

The qualitative findings reveal a strong and consistent perception across experts, lecturers, and graduates that digital decarbonization management—through Green Information Systems (Green IS), IoT-based emission monitoring, and Big Data analytics—significantly enhances operational efficiency, regulatory compliance capability, and sustainability performance in maritime organizations. The thematic analysis categorized responses into five principal indicator domains: technological infrastructure readiness, regulatory compliance capability, digital competency development, organizational and governance support, and sustainability performance impact. Each indicator was evaluated using a qualitative scoring conversion derived from participant consensus (1 = very low to 5 = very high). The aggregated results demonstrate an overall weighted mean score of 4.41, categorized as “very good,” indicating high perceived effectiveness and efficiency of digital decarbonization management practices.

Table 1. Integrated Indicator Assessment of Digital Decarbonization Management

Indicator Domain	Key Indicators	Mean Score (1–5)	Interpretation	Analytical Implication
Technological Infrastructure Readiness	IoT fuel monitoring, real-time dashboards, AI analytics, interoperability	4.52	Very Good	Strong digital foundation supports data-driven emission management
Regulatory Compliance Capability	Carbon reporting automation, CII monitoring, emission tax simulation	4.47	Very Good	Digital tools enhance compliance accuracy and timeliness
Digital Competency Development	Data literacy, Green IS understanding, cybersecurity awareness	4.28	Good–Very Good	Skills improving but require continuous curriculum alignment
Organizational & Governance Support	Leadership commitment, green investment, digital strategy integration	4.35	Very Good	Institutional alignment critical for sustainability transformation
Sustainability Performance Impact	Fuel optimization, emission reduction transparency, market competitiveness	4.44	Very Good	Digitalization directly linked to environmental and economic gains
Overall Average	—	4.41	Very Good	Digital decarbonization management perceived highly effective

The distribution of overall performance categories derived from cross-group scoring is illustrated conceptually below:

This pie distribution demonstrates strong consensus toward positive evaluation. Experts particularly emphasized real-time emission dashboards and AI-supported fuel optimization systems as transformative tools in achieving measurable reductions in fuel consumption variability, aligning with environmental efficiency measurement literature in shipping [7]. Lecturers highlighted improvements in curriculum adaptation toward digital sustainability management, although they acknowledged remaining gaps in advanced Big Data modeling skills. Graduates frequently pointed to practical exposure to automated terminal systems and LNG bunkering forecasting technologies as critical to their competency formation, consistent with findings on AI-based demand forecasting [8] and automated container terminal performance [10].

Thematic coding further identified recurring patterns. First, IoT-based monitoring systems significantly improved transparency in carbon reporting, reducing reliance on manual documentation. Second, predictive analytics facilitated proactive decision-making regarding alternative fuel deployment and route optimization. Third, institutional digital transformation strategies enhanced coordination between port authorities and shipping firms, resonating with broader digital governance frameworks [12]. Fourth, cybersecurity culture emerged as a growing concern, particularly in relation to carbon data integrity, echoing concerns in zero-trust architecture research [14].

Cross-group comparison revealed partial divergence in emphasis rather than contradiction. Industry experts rated technological readiness highest (mean 4.63), while lecturers rated digital competency development slightly lower (mean 4.19), indicating curriculum enhancement needs. Graduates expressed strong confidence in operational systems but moderate concern regarding strategic-level carbon market analytics. These distinctions enrich the interpretive depth of the findings rather than undermining overall consistency.

3.2 Discussion

The results directly address the central research question: how digital technologies can be systematically integrated into maritime decarbonization management to support economically viable and regulatorily compliant net-zero transitions. The high overall effectiveness score supports the proposition that Green IS platforms, IoT emission monitoring, and Big Data analytics collectively form an enabling infrastructure for digital decarbonization governance. These findings reinforce sustainability determinant research in ports [1] and integrated maritime policy frameworks [2], which emphasize governance coherence as essential for effective environmental transformation. However, this study extends those works by explicitly linking governance outcomes to digital technological capability, thereby filling an identified gap between policy aspiration and operational digital implementation.

The strong rating of regulatory compliance capability demonstrates that digital systems substantially reduce compliance uncertainty. This complements emission tax modeling research [9], which highlights economic implications of carbon regulation but does not fully elaborate on technological verification mechanisms. The present findings suggest that digital dashboards, automated reporting tools, and predictive analytics transform compliance from a reactive obligation into a proactive strategic function. This transition shifts maritime sustainability from regulatory burden to competitive advantage.

The importance of technological infrastructure readiness aligns with intelligent ship risk modeling [3] and AI-driven logistics digital twin research [13], confirming that digital integration enhances system resilience and operational optimization. Yet, this study adds a social and managerial dimension by illustrating how human competencies mediate technological effectiveness. While systems are highly rated, digital competency development scored comparatively lower, indicating that technological deployment must be accompanied by educational adaptation. This addresses a limitation in earlier port efficiency research [5], which focused predominantly on structural determinants without fully integrating human capital dimensions.

The study also contributes to green technology innovation discourse [11] by providing micro-level insight into how innovation translates into perceived emission performance improvement within maritime organizations. Unlike macroeconomic analyses, this research captures practitioner and educator perspectives, offering grounded understanding of implementation realities. Furthermore, the cross-group comparison strengthens validity by demonstrating coherence across institutional levels—industry, academia, and emerging professionals—thus enhancing the robustness of findings.

A notable strength of the research lies in its triangulated qualitative methodology. By integrating interviews with document analysis and policy review, the study ensures interpretive reliability and contextual depth. The purposive sampling of multi-actor groups enables comprehensive understanding of systemic alignment in maritime digital transformation. Additionally, the thematic-comparative-narrative analytical sequence ensures that findings are not isolated observations but interlinked explanatory constructs.

Practically, these findings have significant implications. For shipping companies, investing in IoT-based emission monitoring and AI-powered fuel optimization is not merely environmentally responsible but economically strategic. For port authorities, integrating Green IS into sustainability governance enhances transparency and attractiveness to green shipping corridors. For maritime universities, curriculum redesign should prioritize Big Data carbon analytics, cybersecurity awareness, and interdisciplinary digital literacy. Policymakers may utilize these insights to design digital-ready regulatory frameworks that encourage interoperable reporting standards and blockchain-based emission verification.

Despite the positive results, limitations must be acknowledged. The qualitative design emphasizes perception rather than direct quantitative emission measurement, which future research could complement with empirical performance data. Moreover, while the sample captured diverse stakeholder perspectives, broader international comparative studies would enhance generalizability. Future research should explore AI-driven carbon market participation strategies, blockchain-based emission certification, and digital twin simulation of fleet-wide decarbonization scenarios. Longitudinal studies assessing actual emission reduction outcomes over time would further validate the perceived effectiveness identified here.

4. CONCLUSION

This research demonstrates that digital decarbonization management—through the integration of Green Information Systems, IoT-based emission monitoring, and Big Data analytics—constitutes a critical enabler of the maritime sector’s transition toward net-zero operations. The qualitative findings indicate a very strong level of perceived effectiveness across industry experts, lecturers, and graduates, particularly in enhancing regulatory compliance, operational efficiency, and sustainability performance. By linking technological infrastructure readiness with governance alignment and competency development, the study fills a significant gap between maritime sustainability policy aspirations and practical digital implementation. The results confirm that decarbonization is not solely a technical or regulatory challenge, but a socio-technical transformation requiring institutional coordination and human capital adaptation. Ultimately, digital transformation emerges as a strategic foundation for strengthening maritime economic resilience, environmental accountability, and long-term competitive advantage in a carbon-constrained global economy.

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