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THE IMPACT AND CHALLENGES OF DIGITALISING CRITICAL ENERGY INFRASTRUCTURE IN MARITIME PORTS: A QUALITATIVE STUDY

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Abstract

This research examines the digitalisation of critical energy infrastructure (CEI) in maritime ports, with the aim of assessing its impact and identifying associated challenges. A sequential qualitative research design was adopted, comprising literature review, semi-structured interviews with ten professionals, and a focus group involving six participants from the United Kingdom, Nigeria, Kenya, and Sri Lanka. Thematic analysis was applied to derive key insights. The findings indicate that digitalisation of CEI enhances environmental sustainability, operational efficiency, and workplace productivity. Key benefits include reduced emissions, improved energy management, predictive maintenance, enhanced information sharing, and reduced waste of perishable goods. However, significant challenges persist, including skills shortages, resistance to change, ageing infrastructure, unreliable power supply, limited internet connectivity, and financial constraints. The research provides empirical evidence on the impact and challenges of CEI digitalisation, addressing a gap in existing literature. It offers practical insights for policymakers and industry stakeholders seeking to advance sustainable and efficient energy systems within maritime ports.

Keywords: Critical Energy Infrastructure (CEI); maritime ports; digitalisation; qualititative study; infrastructure.

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1. Introduction

Maritime ports are integral for global trade and promote sectors such as logistics, warehousing, transportation and supply chain; with more than four-fifths of global trade volume carried out by sea [1–3]. They are central hubs in the transport chain as they connect the maritime and land-based transport systems [4]. Maritime ports play a central role in energy logistics and are evolving into complex energy hubs integrating fossil fuels, liquefied natural gas (LNG), and renewables [3]. The energy demand for maritime shipping and ports is on the rise, leading to higher energy costs, increased greenhouse gas (GHG) emissions, and other harmful pollutants [1]. Due to the various functions of maritime ports, they are confronted with challenges such as environmental, energy efficiency enhancement, renewable energy integration, regulatory and legislative policies, power and grid stability, Infrastructure complexity, and increased energy demand [1]. In this study, CEI is therefore redefined in a more context-specific and operational sense. CEI refers to the critical energy systems and assets that directly support the functioning of maritime ports, including on-site power generation and supply systems, fuel storage and distribution infrastructure, shore-side electricity systems, and energy management systems. These systems are essential for enabling port operations such as cargo handling,

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vessel servicing, storage, and logistics coordination, and their disruption would significantly affect port efficiency, safety, and service continuity.

The role of maritime ports in tackling climate change has received significant attention prompting different mitigation solutions [1]; because they are critical enablers for decreasing emissions and pollution, as they connect multiple transport systems [4]. In recent times, maritime ports have been undergoing digitalisation in their critical energy infrastructure (CEI) to improve operational efficiency and energy management, and reduce environmental impact [3, 5]. Digitalisation of CEI in maritime ports is crucial amid the global effort towards decarbonization [3]. The strategic roles ports play in global trade and energy logistics make them increasingly dependent on digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), and automation, enhancing operational efficiency in ports [2, 3].

According to [3], the digital transition of CEI in maritime ports presents both opportunities and challenges. While technological advancements improve operational efficiency, optimise energy management, and facilitate sustainable practices, reliance on digital technologies is fraught with several challenges. Despite the significance of digitalisation of CEI in maritime ports, there is a paucity of empirical studies exploring this area, particularly regarding its impact on the challenges it faces. Previous studies, such as [6], explored this concept, but their study focuses on digital readiness for the smart port, while [7] focuses on shipping digital transformation. However, none of these studies focuses on CEI in maritime ports to identify the challenges and impact of digitalising them. Studies such as [8], explored digital infrastructure and the efficiency of container ports; again, the focus of their study is not CEI in ports. Only [3] explore CEI in maritime ports; however, their work is based on a scoping review and lacks context and primary data. To address this gap, this study explores the digitalisation of CEI in maritime ports to identify the associated challenges and the impact of digitalising these CEI, using primary data from the UK, Kenya, Nigeria and Sri Lanka. The research objectives are: (1) to assess the impact of the digitalisation of CEI in maritime ports; (2) to identify the challenges associated with the digitalisation of CEI in maritime ports.

2. Literature review

2.1. Critical energy infrastructure

Critical energy infrastructure (CEI) is an important installation at maritime ports. These installations play significant roles to both national and global energy exchange and data transmission. Despite these notable improvements at maritime ports, the systems there operate in a complex, exposed environment and are susceptible to numerous challenges, including cyber threats, sabotage, natural disasters, regulatory fragmentation, and environmental risks. For instance, the 2022 Nord Stream pipeline attacks demonstrated the vulnerability of maritime ports' CEI; prompting renewed efforts to protect critical maritime infrastructure [3, 9].

2.2. Digitalisation of critical energy infrastructure

Osmundsen et al. [10] explained that digitalisation is about leveraging digital technology to alter socio-technical structures. And socio-technical structures refer to the social (human interactions, relationships, norms, etc.) and technical (technology, tasks, routines, etc.) aspects of the structure. For three decades, there has been a growing degree of digitalisation, with previously analogue organisations, including maritime ports, being transformed into efficient and sustainable entities [4]. The central role of ports as transport hubs in the transport system has pushed them to promote sustainability in their operations by reducing emissions and pollution, putting them under pressure to digitise [4]. Kechagias et al. [11] postulates that the operations of maritime ports will be enhanced through the industry's digital transformation. According to [5], the maritime industry is experiencing a significant transformation through digitalisation, enhancing the operational efficiency and competitiveness of ports by streamlining processes, reducing expenses, and optimising service delivery. Digital systems have become increasingly essential for maritime ports' resilience, efficiency, and sustainability. The digital transitions of ports have evolved through three stages: digital documentation (paperless systems), operational automation, and the emergence of smart ports [3, 12]. The digitalisation of maritime ports' infrastructure through the utilisation of smart port technologies incorporating artificial intelligence, IoT, and real-time data analytics to improve decision-making and operational responsiveness; optimising energy consumption, automating logistics, and enhancing environmental monitoring at ports. Thus, digital systems enhance energy monitoring and control, transforming energy operations at maritime ports [3, 5, 13]. The general focus of port digitalisation is to automate routine tasks (such as cargo management, vessel traffic oversight, and logistics processes), administrative and document processing, and port optimisation. It also involves using data analysis and Artificial Intelligence (AI) to forecast and address operational issues at ports. Some of the key features of port digitalisation include predictive maintenance, automated logistics, real-time data tracking, and enhanced safety [2, 14]. The aim of port digitalisation is to enhance operational efficiency, resource allocation, service delivery, competitiveness, and logistics sustainability [12, 15].

As maritime ports transition to low-carbon energy sources in line with global decarbonisation efforts, their role as energy transmission hubs is becoming increasingly significant. This has led to the discourse around the digitalisation of the CEI of ports across the globe, coupled with the operational damage and disruptions, risks and various forms of threats they are exposed to, bringing to the fore the need for port CEI's resilience, efficiency, and sustainability against the interruption of energy flow [3, 9]. Digitalisation of port CEI involves using digital technologies to enable predictive maintenance of port energy infrastructure. Hence, the digitalisation of CEI at ports is integral to maritime success in port operations [3].

It is also important to distinguish between digitalisation and renewable energy adoption, which are conceptually related but distinct processes. Digitalisation refers to the application of digital technologies, such as the Internet of Things (IoT), artificial intelligence (AI), automation, and data analytics, to monitor, control, and optimise energy systems and operational processes within ports [3]. By contrast, renewable energy adoption refers to the transition from fossil-fuel-based energy sources to cleaner alternatives such as solar, wind, and hydrogen [9]. While this transition contributes to sustainability objectives, it does not in itself constitute digitalisation.

3. Materials and methods

This study adopted a sequential qualitative research design to explore the impact of digitalisation of CEI in maritime ports. The first stage of the study was the review of existing literature, followed by semi-structured interviews, and finally, a focus group to validate and refine the themes that emerged from the interview phase. Qualitative research entails conducting research by actively engaging participants, enabling the generation of in-depth insights into a specific topic. This approach enables relevant social actors (including organisations, communities, institutions, and places) to be engaged, which are essential for understanding digital transformation within maritime port infrastructure [16, 17].

The primary data collection methods comprised semi-structured interviews and focus group discussions, due to their effectiveness in eliciting participants' perceptions and values [18]. These methods enabled the study's objectives to be achieved. Although interviews and focus group discussions are well recognised for producing rich qualitative data, they are fraught with challenges, including participants' familiarity with one another and potential moderator bias [19]. The interviews generated the core empirical material and initial themes on the digitalisation of critical energy infrastructure (CEI) in maritime ports. The subsequent focus group was conducted to validate, refine, and contextualise the themes emerging from the interview phase, rather than to generate entirely new or independent findings.

Semi-structured interviews were conducted with 10 participants, and the focus group discussion involved 6 professionals. Participants for the study were drawn from four countries, including the United Kingdom, Nigeria, Kenya, and Sri Lanka. Participants were not selected on the basis of generating comparative insights from port systems in different countries, neither was it for cross-country validity. Rather, a purposive sampling strategy was utilised to recruit participants with relevant expertise and practical experience in maritime port operations and CEI. This was made possible through the authors' professional connections and also reaching out to experts via LinkedIn. Participants had between three and over twenty-five years of professional experience across fields including maritime engineering, safety management, asset management, transport management, and environmental management, ensuring balanced, informed and contextually grounded contributions.

All participants agreed to participate by signing a consent form describing the purpose of the study. University of Wolverhampton's faculty ethics committee approved the research project before the commencement of the data collection.

Table 1 presents the background information of the interview participants, demonstrating that the interview participants possessed the requisite expertise in both engineering and management functions within maritime ports, enabling them to provide credible insights into CEI digitalisation practices. Interview participants were coded as P001, P002, P003 to P010, with P001 denoting interview participant 1, and P010 denoting interview participant 10.

Table 1. Background information of respondents interviewed

S/N	Participant ID	Position	Specialisation	Years of Experience
1	P001	Maritime and Construction Consultant	Asset Management and Engineering; Risk Reduction and Value Creation	20+
2	P002	Managing Partner	Maritime Transport Management	17
3	P003	Maritime Engineering Department	Marine Engineering	15
4	P004	Naval Architect	Naval Architecture and Maritime Safety	8
5	P005	Naval Architect/Project Engineer	Riser and Hydrodynamic Engineering	4
6	P006	Electrical Engineer	Electrical Systems Design, Maintenance	25
7	P007	Solutions Architect	Software/Product Development	13
8	P008	Administrator	Administration	3
9	P009	Director	Environment	24
10	P010	Chief Safety Officer	Engineering and Safety	20+

Table 2 presents background information on the focus group participants, revealing that they represented various forms of engineering in maritime ports, providing a broad perspective on the technical, operational, and strategic dimensions of CEI digitalisation in maritime ports. The focus groups participants were coded F01, F02, F03 to F06, where F01 represents focus group participant 1, and F06 represents focus group participant 6.

Table 2. Background information of Focus Group Participants

Participant ID	Organisation	Role	Years of Experience
F01	Kenya Port Authority	Electrical Engineer	10
F02	Kenya Port Authority	Marine Engineer	3
F03	Kenya Port Authority	Electrical Engineer	10
F04	Institute of Engineers of Kenya–Coast Branch	Principal Motor Vehicle Inspection	15
F05	Lafarge Bamburi Cement	Environment & Energy Optimisation Manager	20
F06	Kenya Port Authority	Principal Engineer	20

Although the study includes participants from the United Kingdom, Nigeria, Kenya, and Sri Lanka, the focus group participants were drawn exclusively from Kenya. This reflects practical considerations in organising in-person discussions and access to participants with relevant expertise. Accordingly, the focus group was not intended to provide a cross-country comparison or validation across all geographical contexts. Instead, it functioned as a context-specific validation exercise, offering practitioner-based insights to assess the relevance and robustness of the themes identified from the multi-country interview data.

Each interview and focus group discussion lasted between 60 and 70 minutes and was conducted between 26th February 2025 and 2nd July 2025. All interviews were conducted online via Microsoft Teams, while the focus group was conducted in person. Since the interview participants were a homogeneous group, it was possible to reach a saturation point with the ten participants. The saturation point is the point where no new information, insight, or themes emerge from the interview participants [17]. In this study, the saturation point was reached on the 9th and 10th interview. One of the researchers served as the interviewer, while designated moderators facilitated the focus group discussions, with one participant assigned to take notes. Both the interview and focus group discussions were conducted using pre-defined protocols. These protocols were developed from the literature following an initial scoping review [3]. At the conclusion of each focus group, a designated participant presented a summary of the findings for further discussion. Audio recordings of the interviews and focus group discussions were transcribed using Nvivo 15 and stored in a transcribed file. Thematic analysis was then conducted following Braun and Clarke's (2006) six-phase framework [2]. After transcribing the audio recording, labels were allocated to each research questions to enable coding to be constructed for each research question. The descriptive coding, which summarises the primary topic of qualitative data into word or a short phrase at the initial stage of data analysis, was utilised as the coding method. This coding method was utilised to elicit responses that directly addressed the interview questions. The coding process involved searching the transcribed file for relevant responses that addressed the labelled interview questions. A code was formed and linked with an appropriately labelled interview question when relevant material was discovered. Related responses were added to previously established codes, and if a response was unrelated but relevant, then a new code was generated and tied to the research question it addressed. Themes were based on phrases, words or brief statements that indicated a group of connected responses to the study questions from the participants. The initial themes were reviewed and refined through collaborative discussions within the research team, resulting in the final themes which were presented and discussed in subsequent section.

4. Results and discussions

4.1. Impact and benefits of digitalising CEI in maritime ports

a. Enhanced Information Sharing and Communication

Digitalisation of CEI enhances real-time monitoring, coordination, and control of port energy systems. The integration of sensors, Energy Management Systems (EMS), and digital monitoring tools enables continuous tracking of energy consumption and equipment performance, improving fault detection, reducing downtime, and optimising energy usage across port operations [P006; P010]. According to P006, "energy management system (EMS) also allows us to optimise power usage across different port zones, integrate renewable energy sources where applicable, and ensure efficient load balancing."

Participants explained that digital monitoring systems improve operational coordination by enabling faster access to energy-related information and reducing delays associated with manual reporting processes. Real-time monitoring also supports improved operational decision-making and enhances the reliability of port energy infrastructure.

The use of drones and digital inspection technologies to monitor cranes, bollards, and related infrastructure was also identified as improving maintenance efficiency and oversight of infrastructure [P005]. In addition, vessel dashboards integrating fuel-consumption data with environmental conditions provide operational insights that support energy-efficiency optimisation. As P001 explained, these systems enable operators to evaluate "what speed and current gave optimal usage of the vessel when combined with environmental factors like the wind, and how the vessel used the fuel it got?"

Despite these advances, some ports in developing contexts still rely on manual diesel inventory management and visual observation rather than digital monitoring systems (P002), limiting the efficiency and reliability of CEI operations. Overall, the findings indicate that CEI digitalisation improves operational coordination, energy-system visibility, and infrastructure reliability through real-time monitoring, data integration, and energy optimisation capabilities. These findings align with [1, 3], which emphasise the role of digital technologies in enhancing the management, efficiency, and resilience of ports' critical energy infrastructure.

b. Cost Reduction through Predictive Maintenance

Predictive maintenance is another major benefit. It enables scheduled interventions before equipment reaches a critical failure point, reducing costs and preventing breakdowns (P005). According to P006, "*Our Energy Management System has helped lower energy consumption by about 15%, translating to substantial cost savings on electricity bills. Predictive maintenance tools help us service equipment before failures occur, which has extended asset life and minimized downtime*."

Predictive tools also reduce human error by enabling greater foresight in operations (P007). These practices collectively lower operational costs while enhancing reliability and resilience. The use of the Internet of Things (IoT) and machine learning was identified as a key enabler of predictive maintenance. P005 highlighted this by stating "*you can also predict how long your Equipment is going to last before you start planning to buy a new one. Instead of you trying to do physical observations of* *your ports. You could do a digital representation (digital twin) and a digital simulation of your port activities for you to know what's going to be predictive*."

In addition, P006 agreed, stating that "*Machine learning algorithms analyse equipment data to predict failures before they happen, helping avoid costly outages and enhancing reliability*". This finding agrees with [14], which indicates that machine learning-based predictive maintenance will generate business value in terms of cost reduction, minimal delays and equipment downtime, increased throughput due to fewer unexpected failures, and improved sustainability. This finding also aligns with the report of [3] that one of the significant roles of the digitalisation of ports' CEI is the use of digital technologies for predictive maintenance of port energy infrastructure to enhance energy resilience at maritime ports. Predictive maintenance does not only enhance ports' energy efficiency and resilience, but provides cost-effective energy framework within ports.

c. Flexible Working Options

Another benefit identified is the potential for more flexible working arrangements. Participant (P007) noted that traditional port work often requires long on-site hours, affecting family life and work–life balance. Digitalisation creates opportunities for remote access and more adaptable scheduling, helping retain skilled workers and making port employment more attractive. Although [20] advocates that labour flexibility in container terminal workers leads to a reduction in operating costs and better use of resources in maritime ports, participants highlighted that this is not the reality for engineers and other professionals who deal with CEI in maritime ports, hence the need for digitalisation. This finding aligns with the findings of [1, 3] that the digitalisation of ports' CEI which involves the use of automated systems and processes greatly minimising physical human input and manual labour. This system and its operation allow flexible working options for port workers through the utilisation of digital technologies.

d. Reduction in Waste of Perishable Goods

CEI digitalisation also helps reduce wastage of perishable goods by improving the reliability and monitoring of port energy infrastructure. Participant P004 explained that failures associated with ageing diesel generators have historically disrupted refrigerated storage systems, leading to spoilage of temperature-sensitive cargo and associated environmental and economic losses.

Digital monitoring systems, predictive maintenance, and improved energy-management capabilities help reduce these disruptions by supporting more reliable power supply and faster fault detection within port energy systems. According to P004, "there will be less loss due to digitalisation." Perishable goods distribution is often affected by cargo delays, storage failures, food-quality degradation, and waste generation [11]. The findings suggest that digitally enabled energy monitoring and infrastructure management can help minimise these risks by improving the continuity and reliability of refrigeration and storage operations within ports.

Although there is limited literature directly linking CEI digitalisation to reductions in perishable-goods waste, studies such as [3] indicate that digitalisation enhances energy-system resilience, operational continuity, and infrastructure protection, thereby reducing disruptions that could negatively affect time-sensitive cargo handling and storage.

The focus group discussions largely validated the themes emerging from the interview phase, particularly regarding the operational and environmental benefits of CEI digitalisation. Focus group participants [F01, F04, F06] confirmed that real-time monitoring systems, predictive maintenance, and energy-management technologies contribute significantly to improving energy efficiency, reducing downtime, and enhancing operational reliability within ports. Participants [F03, F02] further emphasised that digital monitoring capabilities are increasingly necessary to maintain stable port operations, especially in contexts where infrastructure failures and power interruptions remain common challenges.

The focus group also refined the interview findings by providing more operational detail on the implementation of digital energy systems in port environments. For example, participants highlighted the practical importance of integrating digital monitoring systems with existing infrastructure to improve equipment reliability and energy continuity. These discussions reinforced the interpretation that the principal contribution of CEI digitalisation lies in operational optimisation and infrastructure resilience rather than solely in broader port automation.

Across the four country contexts, the findings suggest that the most significant contribution of CEI digitalisation lies not simply in broader port automation but in improving the resilience, monitoring, optimisation, and operational continuity of port energy systems. While some benefits overlap with general port digitalisation, the findings demonstrate that CEI-specific digitalisation is characterised by a focus on energy management systems, predictive maintenance of energy infrastructure, real-time monitoring of energy flows, and operational reliability in critical port infrastructure. Participants across all contexts identified operational efficiency and improved coordination as key outcomes; however, participants from developing-country settings placed greater emphasis on infrastructure reliability and energy continuity due to more frequent disruptions in electricity supply and digital connectivity. This suggests that the priorities and perceived benefits of CEI digitalisation are shaped significantly by underlying infrastructural conditions.

Table 3 summarises the impact and benefit of digitalised CEI in the maritime port. These have been grouped into three main categories: operational efficiency, workplace productivity, and environmental sustainability.

Table 3. Impact and Benefit of CEI digitalisation in maritime port

Category	Items
Operational Efficiency	Cost Reduction through Predictive Maintenance; Reduction in Waste of Perishable Goods
Workplace Productivity	Flexible Working Options; Enhanced Information Sharing
Environmental Sustainability	Environmental Benefits

4.2. Challenges faced in Implementing Digitalised CEI in Maritime Port

a. National Grid Failures

Participants in developing countries identified unreliable energy supply as a major barrier to digitalised CEI implementation. According to P002, "*the national grid in Nigeria has collapsed more than ten times in 2025, making the national grid unreliable*".

P004 agreed, stating that interruptions in power supply stall port operations, such as when lifting equipment becomes inoperative, leading to congestion, delays, and significant financial losses. Failures of both the national grid and ageing diesel generators create backlogs in container handling, contributing to the long turnaround times often criticised by shipping companies. Some independent service providers supply their own energy and rely on lithium batteries before diesel generators activate (P002). National grid failure will further hinder ships from shutting down their engines while berthed because of unreliable electricity resulting from the failure of the national grid [21]. This finding indicates that some ports in developing countries are challenged with electricity supply which affects the digitalisation of ports' CEI, as ports are major energy consumers. Although there is a scarcity of studies that identified lack of efficient power supply as a challenge to the digitalisation of ports' CEI. [3] stressed that advancements in shore-side electricity supply (known as cold ironing) allow ships to connect to renewable energy sources while docking, significantly reducing emissions. However, without efficient electricity supply, this may not be realisable. This challenge is significant since port infrastructure need to use electricity to function to maximise digital technologies especially in developing countries.

b. Resistance to Change

Resistance among stakeholders and staff also constrains digitalisation. Maritime unions, for example, actively oppose changes, citing concerns about cybersecurity risks and job security. According to P002, "*We are also scared of cyber security as a challenge; the authorities do not want to go fully digital because of cyber security*".

Some employees delay adoption "*due to fear of job displacement or lack of confidence in using digital tools*" (P006), while "*people with years of experience find it hard to change*" (P005).

This entrenched resistance slows implementation and limits the effectiveness of transformation strategies. Participants also highlighted that perceptions and attitudes towards digitalisation create additional barriers. Some employees resist learning new systems because they perceive them as unnecessary or overly complex (P003).

As P001 explained, "*with any project involving digitalisation there is a certain number of people who will immediately go, I don't understand it*." and P006 added that the demand to learn unfamiliar technologies and software can feel overwhelming, especially for those accustomed to manual work in the port. This finding aligns with [3], who agrees that resistance to change can hinder the digital transformation of ports.

This finding aligns with the report by [3] that some ports are resistant to the digital transformation of CEI at ports, stressing that several stakeholders may resist digitalisation initiatives that appear to centralise decision-making power at the expense of individual actors' interests. In agreement with this study's finding, [3] highlights that the resistance to the digitalisation of ports' CEI also come from port employees who are integral part of ports' operations, complicate the digitalisation of ports' CEI.

c. Skills Shortages

A lack of skilled personnel was repeatedly emphasised. Participants explained that some employees are not recruited on merit, leading to deficits in technical competence and capacity [P002; P003]. Brain drain exacerbates this shortage, as skilled professionals leave for better opportunities abroad (P001). Participants emphasised that employees face significant challenges in adapting to digitalised CEI systems, largely due to limited technical knowledge.

One participant [P003] noted that "*until a problem is encountered, you don't really know how to deal with new emerging issues, unlike the diesel generators that employees literally know all the issues because they've worked with it over time*."

Another [P005] stressed that older technicians often lack the foundational understanding needed to use new systems, making it necessary to "*start upskilling employees, especially old technicians that have been in the system for years*". Training existing staff to maintain and operate advanced systems requires significant time and resources, further delaying effective digital adoption [P006]. Recent research has focused on the analysis of future skills and the associated training needs in the maritime profession [22]. This finding indicates despite the significance of ports' CEI digitalisation, the lack of skills to operate the digital technologies involved could be a significant challenge.

The finding of the study aligns with the findings of [3] that skills requirement and training due to the demands for specialised IT/IS, data analytics, and software engineering skills as a result of the growing reliance of ports on digital technologies. The participants of this study expressed that skills shortage in digital technologies for CEI exist and there is a need to upskill port staff to acquire the needed skills for digital systems for operating port CEI.

d. Ageing and Unequal Infrastructure

The ageing state of port infrastructure is seen as a long-standing challenge. Participants argued that, without modernisation, ports cannot accommodate larger vessels or streamline cargo handling (P002). Digital transformation is viewed as a potential solution [15], but only if accompanied by physical upgrades.

"*Integrating new digital technologies with existing legacy infrastructure, which often requires customized solutions and interface development*" (P006; P010), adds further complexity.

Infrastructure inequalities across regions also create uneven adoption of digital technologies; for example, "*the new Lekki port in Nigeria are more digitally advanced compared to older ports such as Port Harcourt*" (P002).

The finding indicates that operating the existing ageing infrastructure can hamper the digitalisation of ports' CEI, especially in developing countries where some of their ports operate with ageing and sometimes, obsolete port infrastructure. Although there is a scarcity of studies on the challenge of ageing and unequal infrastructure across the same region, this could be linked to a lack of comprehensive digital transformation strategies among some ports. According to [3], several port stakeholders struggle with developing a comprehensive strategy for digital transformation, and this could include the inability to replace ageing port infrastructure that are not compatible with digital technologies. From the responses of the participants, it is most likely that this challenge is more pronounced in developing countries' ports.

e. Connectivity

Limited internet connectivity hampers digital operations, with frequent reports of servers and broadband systems being unavailable. At times, "*the customer shares their own internet hotspot to complete transactions*" in developing countries (P002). Despite recent technological advancements using 5G networks to communicate seamlessly [23], many ports in developing countries still struggle to meet this fundamental requirement for digitalising CEI. This finding indicates that internet connectivity is still a major constraint in developing countries which can affect the digitalisation of ports' CEI in this region. Connectivity is significant because the digitalisation of CEI require digital technologies such as 5G technology and Internet of Things (IoT) [1]. Although this challenge was not among those listed by [3], this study indicates that it a challenge that confronts some developing countries and can hinder digital transitions of maritime ports' CEI in this region.

f. Cost Constraints

High upfront costs, budgetary constraints, and procurement delays also restrict investment in advanced systems such as drones (P005).

According to P006, "*procurement delays can also slow down the rollout of automation systems*".

Inconsistent government budget cycles result in underfunding and abandoned projects, further stalling progress towards digitalisation, especially in developing countries like Nigeria and Sri Lanka (P004; P010). Regulatory bodies and organisations need to review budget frameworks for the rapid implementation of digitalised systems across ports, and possibly the cost-sharing formula (if any) between industry partners, as well as the sharing of responsibilities with allies [9].

This finding is quite significant because digital transition of CEI would require financial investment that is scarcely reported in existing studies on digital transition of ports, particularly that of port CEI. Although studies like [1–3] mentioned the cost-effectiveness in operation of adopting digitalisation in ports' CEI, the financial implication of such effort is scarcely explored. Meanwhile, this challenge was among those highlighted by [3] as, challenges associated with the digitalisation of ports' CEI.

Table 4 below summarises the primary challenges faced in implementing digitalised CEI in maritime ports. These challenges are grouped into three overarching categories - human capacity, technological infrastructure, and financial, with each representing distinct constraints within organisational or national contexts.

Table 4. Challenges faced in implementing digitalised CEI in maritime port

Category	Items
Human Capacity Barriers	Skills Shortages and Limited Technical Understanding; Staff or Stakeholder Resistance to Digital Transformation
Technological Infrastructure Barriers	Ageing Infrastructure; Limited Internet Connectivity; National Grid Failures
Financial Barriers	Cost Constraints

The focus group findings also confirmed several challenges identified during the interview phase, particularly those relating to ageing infrastructure, unreliable electricity supply, limited technical expertise, and resistance to digital transformation. Focus group participants [F01, F06, F04] stressed that the effectiveness of CEI digitalisation is highly dependent on the availability of stable electricity infrastructure and adequately trained personnel.

In addition, the focus group refined the interview findings by emphasising that integrating digital systems into older port infrastructure often requires significant adaptation and customised implementation strategies. Participants also highlighted that infrastructure inequalities between newer and older ports contribute to uneven progress in digitalisation across port systems. These insights provided additional operational context, strengthening the interpretation of the interview findings and enhancing the credibility of the identified themes.

A key analytical insight emerging from the findings is that the barriers to CEI digitalisation are not experienced uniformly across contexts. While concerns regarding resistance to change, skills shortages, and integration complexity were common across all countries, participants from developing-country contexts consistently highlighted structural constraints such as unstable electricity supply, ageing infrastructure, unreliable internet connectivity, and inconsistent funding frameworks as more immediate barriers to implementation. In contrast, participants operating within more technologically mature environments focused more on optimisation, cybersecurity, and integration challenges within already digitalising systems. These findings suggest that the implementation of CEI digitalisation is strongly conditioned by national infrastructural capacity and institutional readiness, indicating that digital-transition strategies for ports cannot be treated as universally transferable across contexts.

5. Conclusions

This study has examined the digitalisation of CEI in maritime ports, focusing on both its impacts and the challenges of implementation. Drawing on primary data from the United Kingdom, Nigeria, Kenya, and Sri Lanka, along with supporting literature, the findings provide a structured understanding of how digital transformation is reshaping energy systems in port environments while also exposing persistent structural and operational constraints.

The findings demonstrate that the digitalisation of CEI delivers substantial benefits across environmental sustainability, operational efficiency, and workplace productivity. Environmentally, digital systems help reduce emissions by improving energy efficiency, optimising vessel operations, and integrating cleaner energy sources. These improvements support broader global decarbonisation efforts and align with international frameworks such as the Paris Agreement and IMO 2020. Operationally, enhanced information sharing and real-time data integration improve coordination across port activities, reducing delays and enabling concurrent operations. Technologies such as energy management systems, IoT, and machine learning further strengthen system reliability through predictive maintenance, resulting in reduced downtime, extended asset life, and measurable cost savings. In addition, digitalisation introduces more flexible working arrangements and improves the handling of perishable goods by ensuring a more reliable energy supply, thereby reducing waste and associated economic losses.

Despite these benefits, the study identifies significant barriers that constrain the effective implementation of digitalised CEI. Human capacity challenges emerge as a critical concern, particularly resistance to change, skills shortages, and limited technical understanding among personnel. These factors not only slow the adoption of digital systems but also affect their long-term sustainability. The findings highlight that entrenched work practices, combined with fears about job security and cybersecurity, contribute to stakeholders' reluctance to fully embrace digital transformation. Technological infrastructure limitations further complicate implementation efforts. Ageing infrastructure, difficulties in integrating new systems with legacy assets, and disparities in digital readiness across ports create uneven progress. In developing-country contexts, unreliable national grid systems and limited internet connectivity significantly undermine the functionality of digital solutions, reinforcing dependence on less efficient and more polluting alternatives, such as diesel generators. These infrastructural deficiencies directly impact port performance, contributing to delays, increased operational costs, and reduced competitiveness. Financial constraints also play a decisive role in limiting digitalisation efforts. High capital investment requirements, procurement delays, and inconsistent funding frameworks restrict the deployment of advanced technologies and slow the pace of transformation. This is particularly evident in developing economies, where budgetary limitations and policy inconsistencies hinder sustained progress.

The findings further indicate that CEI digitalisation should not be understood merely as an extension of general port digitalisation. Rather, it represents a more specialised form of digital transformation focused on the resilience, optimisation, monitoring, and continuity of critical energy systems that support port operations. The study also demonstrates that the implementation realities of CEI digitalisation differ substantially across national contexts. While developed settings appear more focused on optimisation and systems integration, developing-country contexts continue to face foundational infrastructural barriers, particularly unstable electricity supply, ageing infrastructure, limited connectivity, and constrained financial capacity. These contextual differences highlight the need for differentiated policy and implementation strategies rather than uniform digital-transition approaches across maritime ports.

The study contributes significantly to the existing body of knowledge as it combines interviews and focus group discussions to present empirical evidence of the impact of digitalisation of CEI at maritime ports and the challenges confronting this process. The study's findings have several implications for practice, policymakers, and future research. For practice, there is a need to upskill port workers in the digital technologies utilised in CEI through adequate training and skill acquisition. Policymakers in maritime ports across the globe need to maximise the benefits of CEI digitalisation by formulating and enforcing policies that motivate and drive port authorities to transition their CEI digitally. Meanwhile, strategies should be introduced to overcome some of the challenges to the digitalisation of CEI, such as cost constraints, connectivity issues, and electricity issues. For future research, the study presents challenges of digitalisation of CEI peculiar to developing countries. However, there should be more research that clearly focuses on and differentiates between regions and between countries (developing versus developed) to adequately capture the peculiarities of the digitalisation of CEI in each region and country.

In conclusion, the findings indicate that while the digitalisation of CEI in maritime ports offers clear and measurable advantages, its successful implementation depends on addressing interconnected human, technological, and financial challenges. The study highlights the importance of aligning infrastructure development, workforce capability, and investment strategies to support the effective and sustainable digital transformation of maritime port energy systems. However, the study has limitations due to its qualitative nature and small sample size. Future studies should consider using quantitative and mixed methods designs.

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Appendix A. Study Contribution and Limitation

This study contributes to the existing body of knowledge by providing empirical, context-specific insights into the digitalisation of critical energy infrastructure (CEI) in maritime ports across multiple national settings. Unlike much of the existing literature, which focuses broadly on smart ports, logistics automation, or general port digitalisation, this study specifically examines the digital transformation of port energy systems and infrastructure. The findings demonstrate that CEI digitalisation is analytically distinct from broader port digitalisation, as it primarily concerns energy-system monitoring, operational resilience, predictive maintenance, energy optimisation, and infrastructure continuity in critical port operations.

The study also contributes comparatively by revealing how the implementation and perceived benefits of CEI digitalisation vary across developed and developing-country contexts. While operational optimisation and efficiency gains were observed across all settings, developing-country contexts were characterised by more severe infrastructural barriers, including unreliable electricity supply, ageing infrastructure, limited connectivity, and financial instability. These findings extend existing knowledge by demonstrating that the effectiveness and priorities of CEI digitalisation are shaped significantly by local infrastructural and institutional conditions.

Despite its contributions, this study has several limitations. First, the study adopted a qualitative research design with a relatively small sample size, which limits the statistical generalisability of the findings. The findings should therefore be interpreted as analytically and contextually informative rather than universally representative of all maritime ports. Second, participants were recruited purposively through the authors' professional networks and LinkedIn connections. While this approach enabled access to participants with relevant expertise in maritime-port operations and CEI, it may also have introduced selection bias and limited the diversity of perspectives represented in the study.

Third, although the interview participants were drawn from four countries (the United Kingdom, Nigeria, Kenya, and Sri Lanka), the focus group participants were exclusively from Kenya. Consequently, the focus group primarily provided context-specific validation rather than balanced cross-country verification of the interview findings. The operational realities and infrastructural conditions discussed in the focus group may therefore reflect the Kenyan context more strongly than the other national settings included in the interviews.

In addition, the study did not aim to conduct a formal comparative analysis between countries. As a result, differences in institutional structures, technological maturity, regulatory environments, and infrastructural capacity across the participating countries may not have been fully explored. Future studies could address these limitations by conducting larger comparative studies that use mixed-methods or quantitative approaches across multiple port systems and geographical regions.