Digital transitions of critical energy infrastructure in maritime ports: a scoping review

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Review

Digital Transitions of Critical Energy Infrastructure in Maritime Ports: A Scoping Review

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Abstract

This scoping review investigates the digital transition of critical energy infrastructure (CEI) in maritime ports, which are increasingly vital as energy hubs amid global decarbonisation efforts. Recognising the growing role of ports in integrating offshore renewables, hydrogen, and LNG systems, the study examines how digital technologies (such as automation, IoT, and AI) support the resilience, efficiency, and sustainability of port-based CEI. A multi-faceted search strategy was implemented to identify relevant academic and grey literature. The search was performed between January 2025 and 30 April 2025. The strategy focused on databases such as Scopus. Due to limitations encountered in retrieving sufficient, directly relevant academic papers from databases alone, the search strategy was systematically expanded to include grey literature such as reports, policy documents, and technical papers from authoritative industry, governmental, and international organisations. Employing Arksey and O'Malley's framework and PRISMA-ScR (scoping review) guidelines, the review synthesises insights from 62 academic and grey literature sources to address five core research questions relating to the current state, challenges, importance, and future directions of digital CEI in ports. Literature distribution of articles varies across continents, with Europe contributing the highest number of publications (53%), Asia (24%) and North America (11%), while Africa and Oceania account for only 3% of the publications. Findings reveal significant regional disparities in digital maturity, fragmented governance structures, and underutilisation of digital systems. While smart port technologies offer operational gains and support predictive maintenance, their effectiveness is constrained by siloed strategies, resistance to collaboration, and skill gaps. The study highlights a need for holistic digital transformation frameworks, cross-border cooperation, and tailored approaches to address these challenges. The review provides a foundation for future empirical work and policy development aimed at securing and optimising maritime port energy infrastructure in line with global sustainability targets.

Keywords: critical energy infrastructure (CEI); digital transition; maritime ports

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1. Introduction

Maritime ports have long served as pivotal nodes in global trade and energy distribution networks, functioning as gateways between production zones and consumption regions. They enable the flow of goods, fossil fuels, liquefied natural gas (LNG), and renewable energy inputs across international waters [1]. Their strategic locations and multimodal connectivity render them indispensable to national economies, as seen in ports such as Southampton in the United Kingdom and Mombasa in Kenya [2,3]. Ports not only support trade but also underpin sectors such as logistics, warehousing, and transportation. In recent years, the role of ports has evolved beyond their traditional function as cargo handling points to encompass digital integration with land and maritime systems through advanced communication technologies [4]. However, this increased significance also heightens their vulnerability to environmental, technological, or geopolitical disruptions, thereby necessitating robust infrastructure and adaptive governance [5,6].

One of the most critical components of port infrastructure is energy infrastructure, comprising assets such as LNG terminals, offshore platforms, pipelines, and power transmission systems [5]. These installations are central to both national and global energy resilience. As part of the efforts to meet global decarbonization efforts, ports are increasingly integrating their critical energy infrastructure (CEI) with renewable systems, including offshore wind, hydrogen fuel networks, and solar installations [6,7]. The dual imperative of sustaining economic growth and addressing climate imperatives has transformed ports into strategic energy hubs. Yet, these systems operate in complex, exposed environments and are subject to cyber threats, regulatory fragmentation, and environmental risks [5,8].

The evolution of digital transitions within port infrastructure has generally progressed through three distinct phases: digital documentation (paperless systems), operational automation, and the emergence of "smart ports." [9]. Initially, digitalisation focused on transitioning from manual processes to electronic records. However, challenges such as fragmented data and poor system integration limited its impact [10]. Despite these advancements, significant disparities in adoption remain, with many ports yet to fully leverage digital capabilities for managing CEI [6,11]. Numerous challenges hinder the widespread and effective digital transition of CEI. Among the most prominent is the lack of an integrated digital strategy across port ecosystems. Many digital initiatives remain terminal-specific, reinforcing silos and reducing overall system coherence [9,12]. Furthermore, concerns over decision-making centralisation and inter-port competition limit collaborative innovation. The variation in digital maturity levels across stakeholders, particularly between developed and developing regions, further complicates implementation. Moreover, the absence of unified, cross-border regulations complicates efforts to secure shared infrastructure [6].

1.1. Research Gap

While prior studies have examined the operational and environmental aspects of port digitalisation [13–16], relatively little attention has been given to the intersection of CEI and digital transition. In particular, there is no aggregated knowledge connecting the digital transition directly to energy infrastructure, hence the need for this scoping review. The lack of regionally contextualised analysis is especially concerning. For instance, while 72% of European ports report implementing digital strategies, African ports lag behind with an average digital maturity of just 3.0 out of 5 [7]. This disparity underscores the urgency for a comprehensive scoping review that not only maps the current state of digital CEI but also examines variations in adoption, system integration, and governance across different global regions.

1.2. Purpose of the Study

These research deficiencies show the need for a comprehensive review of the digital transition within port-based CEI [17,18]. This will assist port authorities, policymakers, and infrastructure planners in understanding the real-world challenges associated with the digital transition of CEI in maritime ports, which is vital to global trade and sustainable development. Ports now face mounting pressures from climate policies, technological disruption, and geopolitical tensions. As digital systems become increasingly essential for resilience, efficiency, and sustainability, understanding their application in CEI is vital. The purpose of this study is, therefore, to synthesise existing knowledge by conducting a structured scoping review that captures not only academic discourse but also grey literature and policy documents. In doing so, the review will offer evidence-based insights for infrastructure planners, port authorities, and policymakers, helping them make informed decisions about technology adoption, investment prioritisation, and strategic coordination within the port ecosystem.

1.3. Research Questions

To achieve this purpose, the study addresses the following research questions:

RQ1. What is the current understanding surrounding critical energy infrastructure in maritime ports?
RQ2. What is the current state of digital transition in critical energy infrastructure in maritime ports?
RQ3. Why is digital transition important for energy infrastructure resilience in port environments?
RQ4. What are the current challenges associated with the digital transition of CEI in maritime ports?
RQ5. What are the emerging research gaps and future directions for the digital resilience of port-based CEI?

The paper proceeds as follows: Section 2 reviews existing literature on maritime ports, digital transition, and critical energy infrastructure (CEI). Section 3 outlines the research methodology, detailing the scoping review process, inclusion criteria, and data synthesis approach. Section 4 presents findings structured around five research questions, discussing the current understanding, digital state, importance, challenges, and future directions for CEI in ports. Section 5 discusses key insights, and summarises the practical and policy implications, emphasising coordinated governance, investment in smart technologies, and stakeholder engagement. Section 6 concludes with a synthesis of the review's contributions and calls for integrative strategies to guide secure and sustainable digital transitions in port energy infrastructure. It also highlights the limitations of the research.

2. Related Literature

2.1. Maritime Ports

Maritime ports constitute critical nodes in global energy logistics, enabling the transport, storage, and distribution of fossil fuels, liquefied natural gas (LNG), and renewable energy resources [5]. Ports are equipped with specialised infrastructure, such as LNG terminals and oil refineries, which facilitate the efficient movement of energy to domestic and international markets [8]. Their role has expanded with the integration of offshore renewable energy systems, including wind farms and energy islands, which further strengthen their strategic position in energy supply chains [6]. Given this significance, the reliability of maritime ports is central to maintaining global energy stability. Operational disruptions, whether environmental, technical, or geopolitical, can interrupt energy flows, underscoring the need for resilient port infrastructure [6].

Additionally, the transition towards decarbonised energy systems is reshaping the role of ports. Ports are increasingly accommodating offshore wind energy and hydrogen transport, with responsibilities extending to logistics, maintenance, and energy transmission [19,20]. Some are also incorporating solar and tidal energy systems into their own operations to reduce reliance on conventional energy sources [21]. The expansion of these roles has prompted greater scrutiny of ports' environmental impact and operational safety, particularly concerning surrounding communities [7]. In this context, ports are being repositioned not only as logistical hubs but as active participants in the shift to cleaner, decentralised energy networks [22,23].

2.2. Digital Transition

The digitalisation of port infrastructure is transforming energy operations. Smart port technologies now allow ports to optimise energy consumption, automate logistics, and enhance environmental monitoring. These systems incorporate artificial intelligence, IoT, and real-time data analytics to improve decision-making and operational responsiveness [10]. By dynamically adjusting energy usage based on real-time demand, ports can minimise inefficiencies and better manage their energy footprint [24]. Digital energy management systems (EMS) are central to this transition. These systems regulate energy flow, storage, and distribution across complex port environments, providing both resilience and cost-efficiency [7].

While the integration of digital infrastructure has accelerated, the pace of transformation varies significantly across regions [25]. Although digital systems enhance energy monitoring and control, they also necessitate advanced security protocols and cohesive governance frameworks across jurisdictions [26]. Nonetheless, ports continue to pursue smart systems to support global decarbonisation goals. By combining renewable integration with digital energy optimisation, ports can align their operations with environmental objectives while maintaining competitiveness [7].

2.3. Critical Energy Infrastructure

Critical energy infrastructure (CEI) refers to energy systems whose disruption would severely impact national security, public health, and economic stability [27]. In maritime contexts, this includes LNG /LPG storage, offshore energy platforms, Backup batteries, electric charging stations for cargo handling equipment, electricity cables, and undersea pipelines. These installations are central to global energy exchange and data transmission, particularly as nearly 90% of transcontinental digital traffic relies on submarine cables [28]. As offshore energy generation becomes more prevalent, ports are increasingly connected to energy islands and subsea installations that require secure, high-capacity infrastructure. However, these assets are often exposed to natural hazards, environmental degradation, and limited regulatory protections, especially when located across multiple jurisdictions [6]. The resulting governance complexity presents a persistent challenge for international coordination and risk mitigation.

Furthermore, CEI is vulnerable to both physical damage and digital threats. Infrastructure such as underwater cables and pipelines can be compromised by maritime activities, adverse weather, or sabotage. The operational costs and environmental consequences of these disruptions necessitate advanced surveillance and predictive maintenance technologies [29]. Given the spatial competition between maritime sectors, including energy, trade, and ecosystem conservation, port authorities must develop integrated spatial planning strategies to avoid operational conflicts [30]. In parallel, CEI's energy demands are growing. Port operations, including cold ironing, yard equipment, and container handling, require high levels of energy. Efficient energy management system implementation is therefore essential not only to manage demand but also to integrate intermittent renewable sources such as wind and solar power [13]. The transformation of CEI into digitally enabled, renewable-ready systems is thus fundamental to both maritime energy resilience and broader decarbonisation efforts [22].

3. Materials and Methods

Literature review has been used to develop and establish the state of knowledge in different fields and identify future research direction in various fields such as medical sciences, engineering, maritime sector and construction management [31–33]. According to [33], literature reviews support aggregating information from different publications to make a realistic conceptual contribution and identify new research directions. This study employs a scoping review methodology to systematically map and synthesise the literature on the digital transition of critical energy infrastructure (CEI) within maritime ports. The review follows the methodological framework proposed by Arksey and O'Malley [34]. It adheres to the reporting guidelines outlined in the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) [35]. The process was guided by the five research questions (RQ1–RQ5) detailed in the Introduction and involved systematic stages of identifying relevant studies, study selection, data charting, and synthesis.

Section 3.1 explains the search strategy, which combined academic databases and grey literature to identify relevant studies on digital transitions in maritime CEI. Section 3.2 outlines the inclusion and exclusion criteria used to select 62 key documents. Section 3.3 describes the data extraction process using a structured charting form to capture insights aligned with the research questions. Section 3.4 presents the thematic synthesis approach, using NVivo 14 software to code and categorise data, enabling a narrative analysis of emerging trends, challenges, and knowledge gaps in port-based CEI digitalisation.

3.1. Search Strategy

A multifaceted search strategy was implemented to identify relevant academic and grey literature. The search was performed between January 2025 and 30 April 2025. The strategy focused on databases such as Scopus. Scopus was chosen because it is considered to be one of the largest databases that contains peer-reviewed articles [36].

Using search strings combining keywords related to the core concepts: maritime ports, CEI, and digital transition. Keywords and search terms included variations and combinations of ("maritime port*" OR seaport* OR "port infrastructure") AND ("critical energy infrastructure" OR "energy system*" OR LNG OR pipeline* OR "power grid" OR renewable*) AND ("digital transition*" OR digitali*ation OR "smart port*" OR automation OR cybersecurity OR "digital risk*"). Searches were primarily restricted to English language publications and focused on engineering, computer science, energy, and environmental science, with no year restriction.

The search was conducted on 17 January 2025 and yielded a limited number of directly relevant peer-reviewed articles (18 were initially identified based on keywords). Abstract screening revealed that many primarily addressed broader topics (e.g., greenhouse gases, smart grid, logistics, shipping, general port resilience, biofuels, renewable energy) rather than the specific intersection of CEI and digital transition within ports.

Given the emerging and applied nature of the research topic, and the limitations encountered in retrieving sufficient, directly relevant academic papers from databases alone, the search strategy was systematically expanded to include: Targeted Grey Literature Search: Using the Google search engine with the exact core keywords to identify reports, policy documents, and technical papers from authoritative industry, governmental, and international organisations known to operate in or regulate the maritime and energy sectors. Key sources consulted included publications from the International Maritime Organisation (IMO), national port authorities (e.g., Kenyan Port Authority (KPA), Associated British Ports (ABP)), energy agencies, and significant industry providers such as DNV (Broome, Norway) and Zscaler (San Jose, CA, USA). Snowballing of reference lists of the initially identified relevant academic papers and key grey literature documents was manually scanned to identify further pertinent studies (backwards snowballing). This combined approach was deemed necessary to capture the breadth of knowledge, including practical implementations and policy perspectives often found outside traditional academic journals for this specific, applied topic. Using this approach, 97 related articles were identified, which were further subjected to screening. Figure 1 below is the PRISMA ScR flow chart that explains the identification, screening and final papers selected.

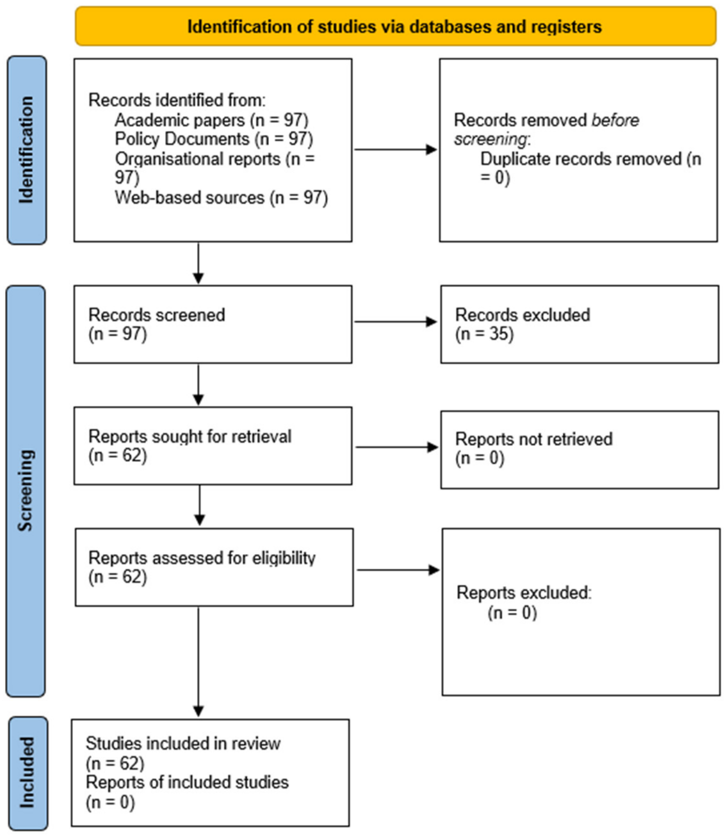

Figure 1. PRISMA-ScR flow chart.

3.2. Study Selection and Eligibility Criteria

Studies identified through the multi-faceted search were screened for eligibility using predefined criteria based on the research questions.

Inclusion criteria:

- Focus on maritime port environments.
- Addresses critical energy infrastructure (including fossil fuels, power, renewables, transmission, storage) within the port context.
- Discusses digital transition, digitalisation technologies, smart port concepts, automation, data integration, or cybersecurity relevant to port CEI.
- Provides insights on the understanding, state, importance, challenges, or future directions of digital CEI in ports (RQ1–RQ5).
- Published in English.
- Includes peer-reviewed articles, conference papers, relevant book chapters, and substantial grey literature (organisational reports, policy documents, technical white papers).

Exclusion criteria:

- Focus solely on general port logistics, shipping operations, or trade without specific linkage to CEI and digital aspects.
- Focus on energy infrastructure outside the maritime port context.

- Focus on port digitalisation without reference to energy systems.

The selection process involved two stages:

The titles and abstracts of all retrieved records were screened for relevance against the inclusion criteria. The project team members retrieved the full texts of potentially relevant documents and assessed them independently for correctness and objectivity. This process included 62 documents (45 academic papers, 3 policy documents, 8 organisational reports, and 6 significant web-based resources deemed credible and relevant) for the data extraction and synthesis review.

Figure 2 shows the distribution of articles across continents, with Europe contributing the highest number of publications (33), followed by Asia (15) and North America (7), while Africa and Oceania account for only 2 publications each. This imbalance highlights regional disparities in the academic exploration of port digitalisation. The dominance of European literature can be attributed to the continent's advanced port infrastructure, strong research funding, and well-established digital governance frameworks that facilitate technological adoption and data availability. In contrast, the limited representation from Africa reflects underlying challenges such as weaker research capacities, lower investment in digital infrastructure, and economic constraints that hinder the deployment of advanced port technologies. These differences underscore how geographical and economic contexts significantly shape the maturity and visibility of digitalisation efforts in maritime ports.

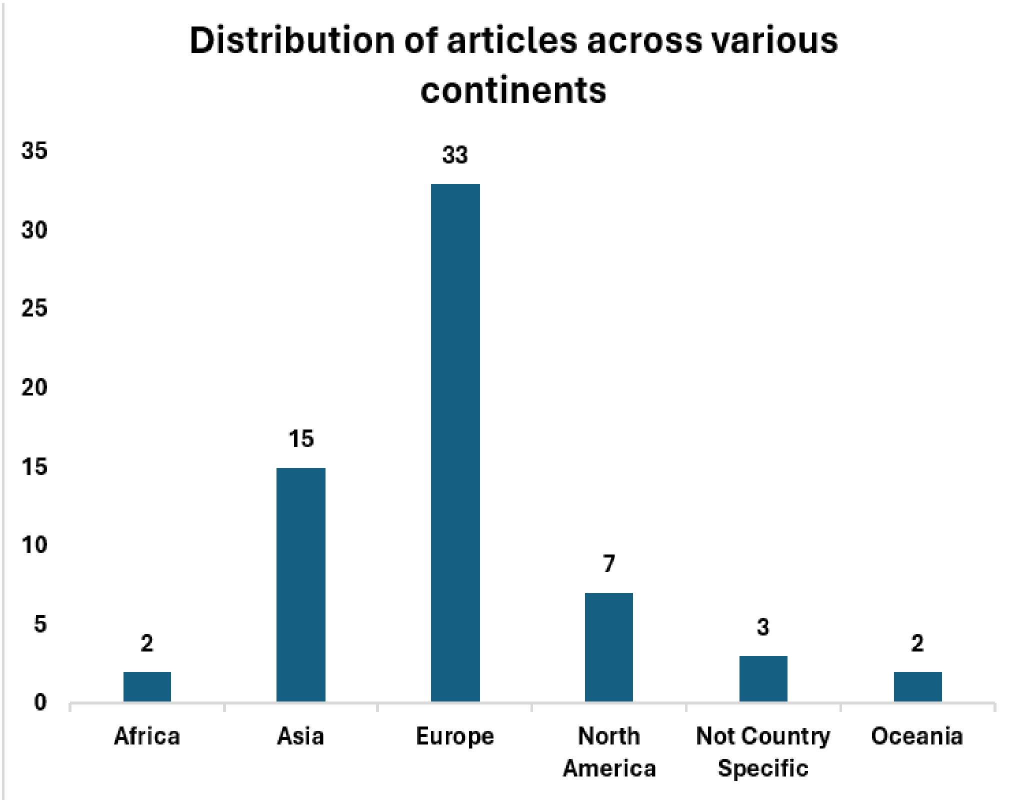

Figure 2. Distribution of publication across the continent.

3.3. Data Extraction and Charting

A standardised data charting form was developed (e.g., in Microsoft Excel) to systematically extract key information relevant to the research questions from each included document. The charting form captured details such as:

- Citation details (Author, Year, Title, Type)
- Geographical context/focus

- Definition/scope of CEI discussed (RQ1)
- Description of digital state/technologies/transition phase (RQ2)
- Stated rationale/importance for resilience (RQ3)
- Identified challenges/barriers/risks (RQ4)
- Mentioned gaps/future directions (RQ5)
- Key findings/conclusions.

3.4. Data Synthesis and Analysis

A narrative synthesis approach was employed, integrating the charted data to map the current knowledge landscape. The synthesis focused on identifying and collating key themes, concepts, challenges, and trends emerging from the literature, structured around the five research questions.

Qualitative thematic analysis was performed on the extracted data. NVivo 14 software was utilised to facilitate the coding process, organising text segments from the included documents according to emergent themes and predefined categories aligned with the research questions (e.g., types of CEI, specific digital technologies, cybersecurity threats, integration challenges, regulatory issues, regional disparities, resilience mechanisms, future research needs). The results were synthesised narratively to provide a comprehensive overview answering each research question, highlighting convergences, divergences, and gaps in the current understanding of digital transitions within port-based CEI, which are presented in the next section.

4. Results

4.1. Current Understanding of Critical Energy Infrastructure in Maritime Ports

Critical energy infrastructure in maritime ports consists of offshore installations such as oil and gas platforms, wind farms, and emerging energy islands [6] and plays a vital role in national and global security. Ports house critical installations such as underwater electricity cables and oil pipelines, essential for ensuring stable energy supplies. However, these infrastructures are vulnerable to natural disasters, cyber threats, and sabotage [29]. The 2022 Nord Stream pipeline attacks demonstrated the potential risks associated with undersea energy networks, prompting renewed efforts to enhance the protection of critical maritime infrastructure [6]. Ensuring the security of these infrastructures is paramount, as any disruption could have far-reaching consequences.

Traditionally, ports have relied heavily on fossil fuels to power cranes, yard handling equipment, and vessels. However, advancements in shore-side electricity supply, known as cold ironing, allow ships to connect to renewable energy sources while docking, significantly reducing emissions [37]. Ports are also investing in alternative fuels such as hydrogen and biofuels to support the decarbonisation of maritime transport [38]. Renewable energy communities (RECs) have emerged as a critical framework for ports to engage in energy-sharing models. Under the European Union's Renewable Energy Directive (RED II), ports are encouraged to develop shared renewable energy projects that meet their operational needs and supply surplus energy to surrounding urban areas [39]. This shift positions ports as active contributors to climate neutrality while enhancing their energy security [40]. As a result, ports are adapting to renewable and nuclear energy trends and leading the charge in maritime sector sustainability.

Energy security also depends on the resilience of critical energy infrastructure to physical damage. Underwater power and data cables are particularly susceptible to damage from ship anchors, fishing activities, and adverse weather conditions [41]. Repairing such infrastructures is costly and time-sensitive, as prolonged disruptions can have cascading effects on energy availability, trade, and communication networks [42]. With global energy consumption projected to increase by 50% between 2018 and 2050, the role of maritime ports in meeting rising energy demands is more crucial than ever [41]. Ports are not only responsible for energy distribution but also for ensuring that growing demand is met through sustainable means. The development of integrated energy hubs within ports allows for the efficient transfer of various energy sources, including LNG, hydrogen, and renewables [22].

The demand for sustainable energy solutions in maritime ports has intensified due to the need to reduce carbon emissions and transition to greener alternatives. Ports increasingly integrate renewable energy sources such as solar, wind power and nuclear energy into their operations. Nuclear energy serves as a stable energy source and could be suitable for emerging countries. These measures mitigate environmental impact and enhance energy security by reducing reliance on fossil fuels [7]. Offshore energy production, including wind, wave, tidal, and solar energy, provides sustainable alternatives that contribute to decarbonization efforts [43]. Hydrogen-based energy systems are also being explored as potential solutions for port energy demands, particularly through the transportation of hydrogenated chemical substances for onshore conversion [20].

Maritime ports are crucial energy hubs, connecting offshore renewable energy facilities with continental distribution networks. This strategic positioning allows ports to play a central role in transitioning to sustainable energy. Moreover, advancements in offshore energy production technologies have enhanced the efficiency and viability of integrating renewable sources into port operations [19]. Figure 3 below shows the various critical energy infrastructures in maritime ports.

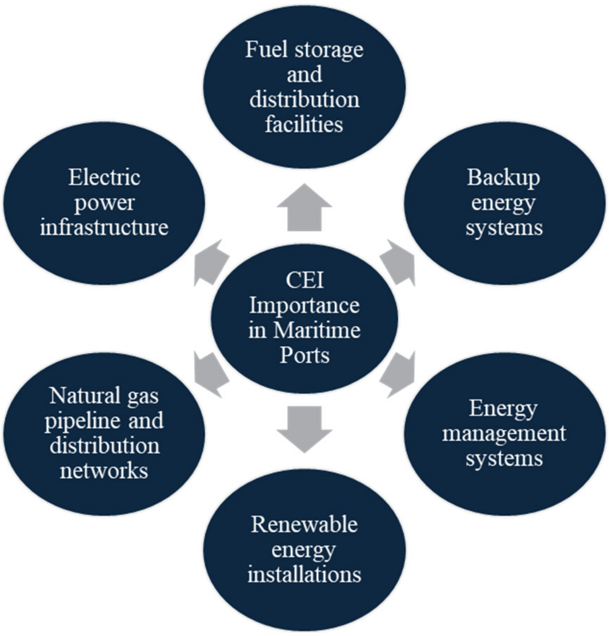

Figure 3. Critical energy infrastructure in maritime ports.

Despite the global push for renewable energy, natural gas remains dominant. Liquefied natural gas (LNG) and pipeline gas are the two primary forms of natural gas utilized in maritime ports. LNG has become the preferred option due to its flexibility in transportation and storage. Natural gas distribution is often constrained by the unequal availability of storage facilities and varying demand across regions, making LNG a more adaptable solution for international energy markets [5].

Maritime ports are major energy consumers, with significant energy demands stemming from crane operations, container handling, yard equipment, and cold ironing, where ships are supplied with shoreside electricity while docked. Implementing advanced energy management systems (EMS) is essential for optimising energy consumption and reducing operational inefficiencies [24]. Such systems regulate energy supply, demand, and storage, ensuring a more sustainable and cost-effective energy framework within ports [24].

Energy efficiency initiatives in ports also contribute to broader decarbonization efforts within the maritime sector. By integrating renewable energy sources, optimizing fuel usage, and improving logistical efficiency, ports can significantly reduce their environmental footprint while maintaining economic competitiveness [44,45]. Unlike land-based infrastructure, repairs to maritime energy systems require specialized equipment and favourable weather conditions, often resulting in extended downtimes and higher costs [46].

Despite their potential, smart ports have yet to fully integrate renewable energy storage solutions into their infrastructure. While offshore wind and solar farms could provide reliable energy, their intermittent nature necessitates advanced storage mechanisms for stability. Although some ports are investing in battery and hydrogen-based storage systems to manage renewable energy where available, more must be carried out.

The growing integration of renewable energy sources and subsea cables within ports has introduced complex spatial and operational challenges. In high-traffic maritime regions, such as the North Sea, Baltic Sea, and South China Sea, ports are increasingly competing for space with offshore energy installations, shipping lanes, and aquaculture farms. The Red Sea, for example, serves as both a critical trade corridor and a key route for undersea data cables connecting Europe and Asia [30]. Expanding offshore wind farms and planned energy islands further complicates spatial management, requiring careful coordination to avoid conflicts between maritime sectors [30].

Governments and port authorities are now implementing spatial planning strategies to balance these competing demands. Policies that designate specific zones for energy infrastructure, shipping, and environmental conservation are essential to ensuring that ports can continue functioning efficiently while accommodating new energy developments [1]. Moreover, technological advancements in automated monitoring and digital mapping tools are helping to optimise port layouts, improving energy efficiency and operational safety zones [6].

4.2. Digital Transition in Critical Energy Infrastructure in Maritime Ports

Digital transformation entails integrating digital technology into every aspect of a business or industry, leading to significant adjustments in how they function and provide value to clients [10]. Furthermore, digital platforms offer the framework to exchange data and are essential to facilitating digital transformation. According to Reis and Melão [47], the process of digital transformation is complex and encompasses several aspects, such as smart cities, sustainability, digital enterprises, business strategies, and human resources.

Organisations can improve their competitiveness and response to client demands by incorporating automation into various processes, which will increase the accuracy, speed, and adaptability of operations [48]. Similarly, Behdani [49] highlighted that operations become more intelligent and connected because of utilising digital transformation to improve operational efficiency, security, and sustainability.

The primary goal of digital transformation is to add value to an organisation and this value encompasses various aspects such as increased operational efficiency, enhanced customer experiences, better business models, the creation of innovative goods and services, competitive advantage, beneficial differentiation, enhanced partnerships with stakeholders, and budget savings [50].

4.2.1. Evolution of Digital Transition in Maritime Ports

The digital transformation of seaports has evolved significantly over the years, and it has been shaped by three main generations: paperless procedures, automated procedures, and smart procedures [9]. Each generation is critical in improving port efficiency, reducing manual errors, and enhancing overall operations. This progression (shown in Figure 4) is key in addressing the increasing demands of global trade and supply chain efficiency.

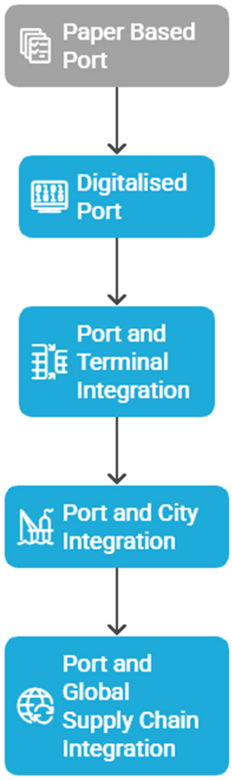

Figure 4. Stages of port connectivity and digitalisation.

First Stage Evolution

The first major transformation in seaports was the move from paper-based processing to paperless procedures. This shift aimed to reduce reliance on physical documents in managing port operations. While ports initially adopted digital systems to streamline administrative processes [51], paperless systems could not fully replace paper-based documents in many areas. Despite advancements, ports today still largely depend on printed documents for handling customs, bills of lading, and other crucial paperwork [9].

Challenges with paperless systems include process errors, inefficiencies, and outdated or incomplete information. Relying on electronic versions of paper documents has not always led to a significant reduction in these errors, mainly because the digitalisation of processes did not address the core issue of real-time data accuracy and cross-departmental coordination [9]. Despite initial digitalisation efforts, paperless systems failed to overcome key operational weaknesses because the success of such systems largely depended on the willingness of diverse port stakeholders to fully adopt digital platforms. In practice, many port activities still depend heavily on physical documents, especially in critical terminal and administrative workflows such as container handoffs to drayage operators. Ports still face challenges like miscommunications and delays resulting from inaccurate documentation or a lack of updated information, hindering overall operational efficiency [9].

Second Stage Evolution

The second generation of digital transformation introduced automated procedures, focusing on integrating terminal equipment and information systems to automate port operations. The goal was to create a seamless connection between the terminals' infrastructure and critical energy systems, improving automation at the terminal level. This automation aimed to increase efficiency and reduce human error by implementing automated cranes, conveyors, and other terminal equipment that could operate independently or in coordination with other systems [9].

A key aspect of this generation was the alignment of information technology (IT) and systems with operational processes. To support automation, new data collection and information allocation processes were established. These changes also led to the introduction of additional checks and control mechanisms to ensure safety, especially in semi-automated processes where human workers were still involved. Even as automation reduced the number of manual labourers, the need for skilled personnel to oversee and manage automated processes remained high, ensuring that operations continued smoothly without risking system failures [52].

Although automation improved equipment-level efficiency, a critical flaw remained in the form of static or delayed information inputs that restricted adaptive decision-making during active operations. The inability to inject real-time data into automated systems constrained responsiveness to unanticipated disruptions, whether caused by equipment failures, weather conditions, or sudden traffic surges. Furthermore, siloed information flows between port actors prevent system-wide situational awareness, severely limiting collaborative problem-solving. These weaknesses exposed a structural gap between technological automation and the complex, fluid dynamics of port ecosystems, underscoring the need for higher-fidelity data integration and real-time operational intelligence [9].

Third Stage Evolution

The third generation of digital transformation represents the shift toward smart procedures, where ports focus on actively measuring, controlling, and assisting port operations using advanced technologies. This generation is characterised by using big data, IoT devices, and machine learning to collect real-time information and make data-driven decisions. The goal is to go beyond automation and begin actively impacting the behaviour and decisions of port actors to optimize overall operations and address key challenges such as environmental sustainability [53].

In this phase, smart ports are not just passive environments but dynamic systems that adapt to changing conditions and actively drive improvements in efficiency and sustainability [9]. This generation reflects the evolution from static automation to dynamic, real-time decision-making, impacting the operational flow, and fostering continuous improvement across the port. A range of enabling technologies has facilitated this progression from paperless procedures to automated and smart seaport systems. These include cloud computing, IoT and cyber–physical systems, mobile computing, business analytics and machine learning [52].

Even as smart port technologies lowered adoption costs and enabled real-time analytics, the full promise of intelligent operations remains compromised by inconsistent participation across the port community. Many actors hesitate to fully align internal business processes with system recommendations, either due to organisational inertia, trust deficits in automated decision support, or concerns over data-sharing transparency. Inadequate integration across heterogeneous data sources further risks generating conflicting or unreliable guidance, eroding confidence in system outputs. Thus, despite advanced technical capabilities, the socio-technical barriers, such as fragmented adoption, trust misalignments, and incomplete data harmonization, remain decisive obstacles to achieving fully optimised port operations [9].

4.3. Importance of Digital Transition of Critical Energy Infrastructure in Maritime Ports

Figure 5 below shows the importance of the digital transition.

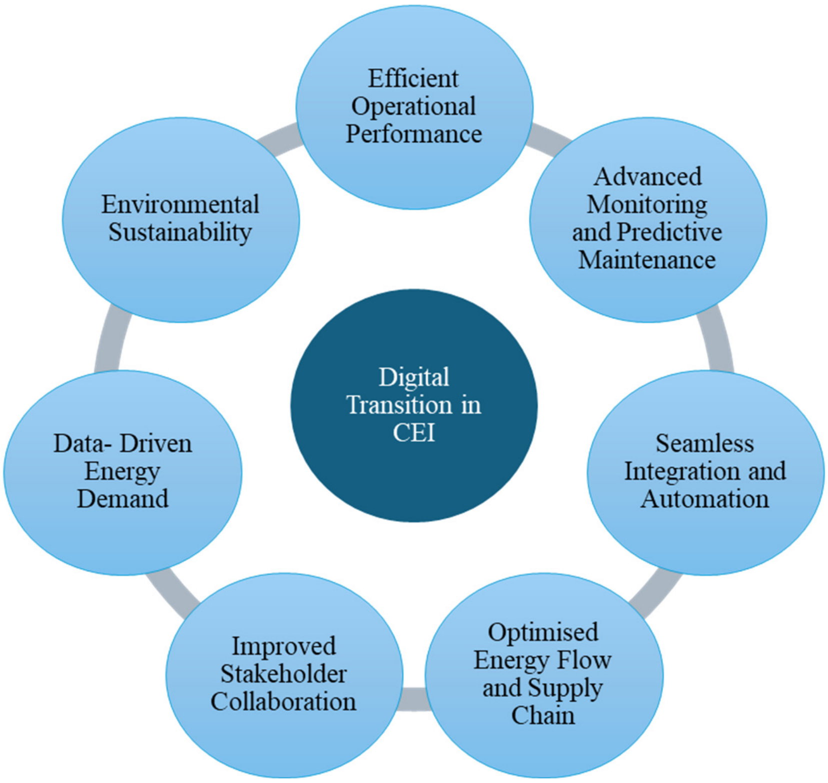

Figure 5. Importance of digital transition in critical energy infrastructure (CEI).

4.3.1. Efficient Operational Performance

The digitalisation of maritime ports is reshaping the operational landscape of energy infrastructure by enhancing performance, monitoring, efficiency, stakeholder communication, energy management, and environmental sustainability. As ports increasingly serve as energy hubs, facilitating storage, distribution, and trade of key energy commodities, leveraging digital technologies has become indispensable for ensuring resilience and competitiveness.

Adopting digital technologies in maritime ports has led to major performance, resilience, and flexibility improvements, enabling ports to adapt to fluctuating energy demands and external disruptions [11]. Since the emergence of containerisation, ports have integrated information systems (IS) and information technology (IT) into their operations, transforming them into strategic enablers of efficiency. The ability to capture, process, and analyse real-time data has strengthened decision-making processes, allowing ports to proactively respond to changing conditions that impact energy infrastructure [9].

4.3.2. Advanced Monitoring and Predictive Maintenance

Digitalisation has revolutionised monitoring and managing subsea and maritime surface energy infrastructure. Traditional surveillance methods struggle to provide comprehensive oversight of underwater pipelines, cables, and offshore platforms, making real-time digital monitoring essential for operational reliability [6]. Big Data analytics and digital twin modelling are increasingly being leveraged to improve monitoring accuracy, predict potential failures, and optimise maintenance schedules. Additionally, redundant systems and real-time tracking technologies [54] ensure continuous operations by mitigating the risks of unexpected breakdowns.

4.3.3. Seamless Integration and Automation

The International Maritime Organisation (IMO) has promoted the automation of ship-to-ship and land-to-ship data exchange, further supporting seamless integration between digital monitoring systems and maritime energy infrastructure [55]. However, despite the increasing generation of large datasets from vessels and port assets, much of this information remains underutilised. Future advancements in data analytics, artificial intelligence, and predictive modelling will enhance efficiency and reliability across critical energy infrastructure.

4.3.4. Optimised Energy Flow and Supply Chain

Integrating digital solutions within ports has streamlined operations, reducing inefficiencies in energy infrastructure management. The increasing digitalisation of global supply chains has compelled ports to evolve into digital nodes, ensuring seamless energy flow and connectivity with logistics networks [56]. Synchronising energy demand and distribution using real-time data enables ports to operate with greater precision, reducing energy waste and enhancing profitability.

Furthermore, the transition toward smart ports has encouraged the adoption of automated control systems, AI-driven decision-making, and IoT-based monitoring. These advancements enhance energy efficiency and ensure ports can dynamically respond to fluctuations in energy consumption, particularly in scenarios involving the handling and storage of liquefied natural gas (LNG), hydrogen, and other critical energy commodities [57].

4.3.5. Improved Stakeholder Collaboration

Digital transformation has improved stakeholder communication across maritime operations, enhancing collaboration between port authorities, energy suppliers, and shipping companies. The ability to exchange and consolidate real-time data has led to more coordinated decision-making, minimising operational delays and disruptions [58].

Digital platforms facilitate instant communication, so vessels and port facilities are evolving into interconnected digital ecosystems. The convergence of AI-powered analytics and cloud-based data-sharing frameworks enables predictive decision-making, allowing stakeholders to anticipate and mitigate potential risks in energy infrastructure operations [22].

4.3.6. Data-Driven Energy Demand

Understanding energy demand patterns within maritime ports is crucial for optimising power distribution and integrating renewable energy sources. Digitalisation has enabled ports to analyse and predict variations in energy consumption, particularly between peak and non-peak operational hours [22].

Energy consumption profiles vary depending on port activities. Some facilities exhibit continuous energy demand, while others experience distinct peaks during industrial operations. By leveraging AI-driven energy management systems, ports can adjust energy distribution, integrate renewable energy storage solutions, and reduce reliance on fossil fuel-based power sources [58].

4.3.7. Environmental Sustainability

The digital transition in maritime energy infrastructure has also introduced a focus on Green IT, aimed at minimising digitalisation's environmental footprint [59]. Sustainable computing practices promote energy-efficient data centres, eco-friendly digital infrastructure, and responsible e-waste disposal strategies.

By integrating Green IT principles, ports can maximise energy efficiency, reduce the use of hazardous materials, and enhance the biodegradability of outdated digital assets. The transition towards smart grids and energy-efficient computing further strengthens the sustainability of critical energy infrastructure, aligning maritime ports with global carbon reduction targets [59]. If one includes underwater infrastructure, these issues become even more prevalent, since, in contrast to the surface, the subsea cannot be effectively monitored from the air or the maritime surface [48].

4.4. Current Challenges Associated with Digital Transition in Critical Energy Infrastructure

4.4.1. Lack of Digital Integration Across All Critical Infrastructures

The ability to cross-fertilise data across all critical infrastructures is becoming a key competitive advantage in maritime ports. Ports that effectively harness data integration enhance operational efficiency, optimize resource allocation, and improve client retention. A notable example is the Port of Rotterdam, which has solidified its position as Europe's largest and most technologically advanced port through continuous investments in automation and digitalisation [7]. These advancements have transformed port operations by improving information flow, streamlining processes, and ensuring optimal resource utilisation [7]. Ignoring such digital integration risks operational inefficiencies and loss of competitiveness in data-driven port environments.

4.4.2. Under-Utilisation of Digital Technologies

While smart port initiatives have primarily focused on adopting and integrating IT and information systems (IT/IS), the full potential of these technologies remains underutilised. A growing demand exists for models that can better exploit real-time data sources to enhance decision-making and operational efficiency. Current research primarily examines specific port areas, particularly container terminals, without addressing the broader interconnectivity between port operations [9]. To achieve a seamless digital transition, future efforts should develop integrative approaches that enhance coordination across various port activities and stakeholders operating under diverse conditions [9]. Figure 6 below summarises the challenges associated with the digital transition in critical energy infrastructure.

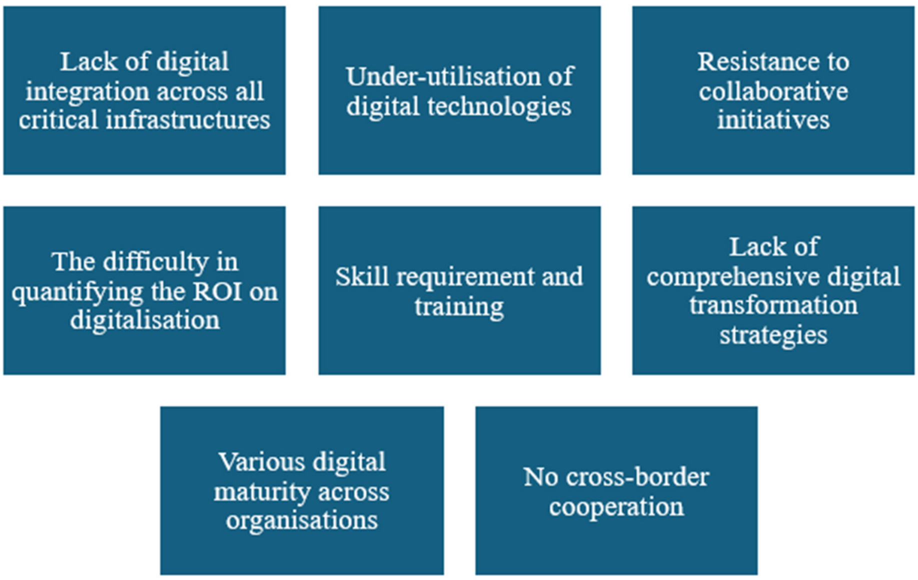

Figure 6. Current challenges associated with the digital transition in critical energy infrastructure.

4.4.3. Resistance to Collaborative Initiatives

Digital transformation has created both opportunities and challenges for port competitiveness. While adopting digital technologies can enhance a port's global standing, it also intensifies competition at the local level. Ports that hesitate to engage in digital transformation risk falling behind technologically advanced counterparts. However, regional rivalries and resistance to collaborative digital initiatives can hinder the development of globally competitive strategies [12]. The increased reliance on digital systems has strengthened the influence of central entities such as port authorities. While centralised control is essential for managing information exchange and optimising port-wide operations, it also raises concerns regarding autonomy. Various stakeholders may resist digitalisation initiatives that appear to centralise decision-making power at the expense of individual actors' interests [12].

4.4.4. The Difficulty in Quantifying the ROI on Digitalisation

The complexity and network effects of smart port initiatives make quantifying their financial benefits difficult. Less powerful stakeholders require support from port authorities or government bodies to integrate their operations effectively into digital frameworks. Additionally, critical evaluations of IT/IS investments are needed to determine the return on investment (ROI) and ensure digital strategies provide measurable benefits [12].

4.4.5. Skill Requirement and Training

The growing reliance on digital technologies in ports demands specialized IT/IS, data analytics, and software engineering expertise. While consultants and IT firms can offer such expertise, a sustainable digital transformation strategy requires a workforce with deep knowledge of port operations and digital technologies [1]. Addressing this gap necessitates collaboration between universities and industry to develop targeted training programs. The maritime transport sector faces an increasing shortage of qualified personnel as emerging technologies require new skill sets [9]. Additionally, employee resistance to change and lack of motivation further complicate digital adoption, emphasising the need for continuous training and change management strategies [12,60,61].

4.4.6. Lack of Comprehensive Digital Transformation Strategies

Despite rapid digital advancements in maritime operations, many stakeholders struggle with developing a comprehensive strategy for digital transformation. A systematic approach is required to ensure smart, innovative port solutions are accepted within the port community. Continuous engagement with stakeholders throughout all project phases is crucial to fostering support and overcoming resistance to digital initiatives [12].

4.4.7. Various Digital Maturity Across Organisations

Variations in digital maturity across organisations create challenges in integrating new technologies. Less digitally advanced entities focus narrowly on individual technologies rather than adopting a holistic transformation strategy. Successful ports, such as Rotterdam, have demonstrated that digitalisation requires technological adoption, a clear vision, and strong stakeholder collaboration. Cultural resistance and a lack of organisational integration remain significant barriers, as many maritime enterprises struggle to align digital strategies across diverse operational environments [12,61,62].

4.4.8. No Cross-Border Cooperation

Maritime infrastructure, including shipping lanes, data networks, and energy transmission lines, often spans multiple jurisdictions, requiring cross-border cooperation for adequate protection and management. The security of these infrastructures depends heavily on diplomatic relations between states, as collaborative frameworks are essential for safeguarding shared assets. However, the maritime environment presents challenges that may render terrestrial-based security strategies ineffective [9]. While cybersecurity remains a common concern across land and sea, specialised measures tailored to maritime conditions are necessary to ensure infrastructure resilience [6].

4.5. Emerging Gaps and Future Directions for the Digital Resilience of Port-Based CEI

4.5.1. Current Research Gaps in Maritime Port Digitalisation

The digitalisation of critical energy infrastructure in maritime ports presents transformative opportunities and pressing challenges as revealed in the recent World Energy Outlook report by the International Energy Agency 2024 [63]. The review reveals significant gaps in the current body of knowledge, particularly regarding the vulnerabilities accompanying rapid digital transition. Most studies tend to focus on the benefits of digitalisation, such as improved operational efficiency and energy optimisation, while insufficient attention has been paid to emerging risks such as cyber threats, infrastructure fragility, and fragmented regulatory oversight [6,11]. This narrow focus underrepresents the complexity of digital integration in critical port systems and underscores the urgent need for more robust and context-specific risk assessments that extend beyond generic or theoretical models.

4.5.2. Limitations in Technology Adoption and Organisational Readiness

Additionally, while digital technologies such as AI, IoT, and automation have been widely adopted to enhance port energy systems [64], their underutilisation remains a challenge. Current smart port initiatives have not yet achieved full integration across all infrastructure components [9]. Moreover, the lack of a unified digital transformation strategy and the disparity in digital maturity levels across organisations further compound this issue [12]. These limitations are further exacerbated by practical barriers, including stakeholder resistance, inadequate training, and ambiguity surrounding return on investment [60–62]. A more holistic approach to digital transformation is required, one that addresses not only technical interoperability but also the social and institutional constraints that shape technology adoption and impact.

4.5.3. Geopolitical and Jurisdictional Complexities in Maritime Digital Governance

Another critical area for future exploration is the geopolitical dimension of digital transition in maritime energy infrastructure. The governance of subsea cables, offshore platforms, and data networks often spans multiple jurisdictions, complicating efforts to establish secure and coordinated responses to infrastructure threats. As highlighted by [6], existing terrestrial-based cybersecurity frameworks are insufficient for addressing the unique vulnerabilities of maritime energy infrastructure. There is a clear need for maritime-specific governance strategies that can manage these cyber–physical risks more effectively. Cross-border policy alignment and international regulatory cooperation should become a core focus of future research and governance efforts.

4.5.4. Inclusive Technological Development

Future studies should investigate the application of advanced technologies such as digital twins, AI-driven predictive analytics, and real-time risk mitigation tools to enhance resilience within maritime energy systems. Also, this work must include empirical validation of proposed risk management models to ensure their real-world applicability. Additionally, the technological advancement of ports in the Global South deserves focused attention. Case studies reflecting these regional disparities can contribute to more inclusive and equitable development strategies. Interdisciplinary approaches that combine technical innovation with institutional reform, stakeholder engagement, and capacity building will be essential. Ultimately, strengthening international collaboration will be key to achieving a secure, sustainable, and resilient digital transition in maritime port energy infrastructure.

5. Discussion

This review has revealed critical insights into the digital transition of critical energy infrastructure (CEI) in maritime ports, demonstrating both progress and persistent limitations. While digital technologies such as automation, IoT, and digital twin modelling have enhanced operational monitoring, energy flow, and maintenance optimisation [10,24], their implementation remains fragmented and largely confined to technologically advanced ports [9,12]. This finding reinforces Heilig et al.'s [9] observation of siloed digital strategies, where initiatives lack interoperability and fail to extend across the wider port ecosystem.

The uneven digital maturity between developed and developing regions, exemplified by European ports surpassing 70% adoption rates compared to a 3.0/5 maturity score in African ports [7], has major implications for global energy resilience. As Bueger and Liebetrau [6] argue, ports form part of transnational CEI networks and thus require coordinated security and governance. However, our findings highlight how geopolitical tensions, regulatory fragmentation, and the absence of cross-border protocols continue to impede harmonised digital transition [6,30].

Moreover, while smart port solutions offer substantial benefits in energy optimisation and environmental sustainability [22,56], their full potential is undermined by several entrenched barriers. These include the under-utilisation of real-time data, insufficient workforce capacity, lack of stakeholder alignment, and challenges in demonstrating return on digital investment [12,60]. These constraints mirror those identified by Tijan et al. [12], who contend that digitalisation must be embedded not just in infrastructure, but in institutional mindsets, policy frameworks, and cultural practices. Additionally, the scarcity of skilled personnel and inadequate digital literacy, especially in the Global South, threatens the scalability of even proven technologies [1,9].

In contrast to prior reviews that have explored port logistics or decarbonisation strategies independently [13,14], this study integrates both perspectives by situating digitalisation at the intersection of infrastructure resilience and energy transition. By doing so, it strengthens arguments made by Buonomano et al. [22] and Kumar et al. [20], who advocate for energy-aware digital transformation strategies as essential to maritime sustainability. However, this review reveals that such strategies remain rare in practice, often hampered by short-term operational priorities and unclear regulatory mandates.

The growing geopolitical importance of subsea CEI, particularly in areas like the North Sea and the South China Sea, calls for enhanced international governance mechanisms [6,30]. Yet, as our findings suggest, most national strategies remain terrestrially biased and ill-equipped to address the cyber–physical threats specific to maritime environments. This gap aligns with the concerns raised by Bueger and Liebetrau [6], who warn that ignoring subsea vulnerabilities may result in systemic risk cascades across critical infrastructure sectors.

To move beyond pilot projects and isolated innovations, future efforts must prioritise system-wide digital integration, co-developed with stakeholders across sectors and jurisdictions. A strong case exists for the development of international standards and regional alliances that foster shared risk management, cybersecurity readiness, and capacity building. Furthermore, ports should adopt adaptive digital strategies aligned with climate, security, and trade agendas to remain resilient amid rising complexity.

5.1. Summary of Key Findings

The study reveals that the digital transition of maritime port energy infrastructure brings both opportunities and challenges. While digitalization enhances operational efficiency and sustainability, it also comes with challenges like underutilisation of technologies and lack of digital integration with legacy systems [65].

One of the primary findings is the strategic importance of maritime ports in global energy distribution. Ports play a central role in importing, exporting, and storing energy commodities, including LNG and renewable sources such as offshore wind and hydrogen-based energy [5]. However, the review identifies significant variation in the digital maturity of ports, with many in developing regions lacking cohesive strategies for CEI digitalisation. While European ports report digital strategy adoption rates of over 70%, others remain at an average maturity level of 3.0 out of 5, leading to fragmented infrastructure and limited coordination [7]. This disparity hinders the integration of renewable energy systems and weakens system-wide resilience.

The research also identifies the growing reliance on automation and AI-driven technologies to optimize port operations. Although these tools offer predictive maintenance, real-time monitoring, and improved operational performance [10,24], their implementation is often terminal-specific and lacks scalability. The full potential of digital systems to reduce inefficiencies and support sustainability remains unrealised. While these innovations improve efficiency, they also introduce risks related to system failures, human oversight, and overreliance on digital systems [1]. The study calls for a balanced approach that integrates digital resilience measures alongside technological advancements.

5.2. Implications of Research

The review has important implications for advancing the digital transition of critical energy infrastructure (CEI) in maritime ports. Firstly, the findings highlight that digitalisation cannot be viewed as a purely technical upgrade but must be embedded within broader port governance, regulatory alignment, and energy transition agendas. Ports are evolving into complex energy hubs, and their transformation requires coordinated strategies that link infrastructure, policy, and stakeholder collaboration across jurisdictions [6,12].

Secondly, while tools like AI, IoT, and digital twins are available, their adoption remains fragmented, often limited to isolated terminal operations. This undermines system-wide resilience, predictive maintenance, and energy optimisation potential [10,23]. Addressing this requires not only investment but also improved digital literacy and skills within port ecosystems.

As ports integrate offshore wind, hydrogen, and other renewable sources in the transition to sustainable energy, they must develop robust digital infrastructure that optimises energy management and reduces dependence on fossil fuels. This shift will require substantial investment in smart grid technology and energy storage solutions.

Moreover, the findings emphasise the need for cross-sector collaboration [6]. Ensuring the security of maritime energy infrastructure requires coordinated efforts between governments, private sector stakeholders, and technology providers. Establishing public–private partnerships can help develop innovative solutions that enhance both security and operational efficiency [18].

The study contributes to theoretical advancement by framing digitalisation of critical energy infrastructure (CEI) in maritime ports as a multidimensional process that extends beyond technical adoption to encompass governance, regulatory alignment, and cross-jurisdictional coordination. This broadens existing theoretical perspectives that often focus narrowly on technological capabilities, and instead integrates organisational, policy, and socio-technical dynamics into the digitalisation discourse. Practically, the study highlights specific areas for action, such as the need for holistic governance frameworks, cross-sector partnerships, and workforce capacity building to ensure system-wide resilience and optimise the integration of renewable energy sources.

6. Conclusions

This study investigated the digital transition of critical energy infrastructure (CEI) in maritime ports through a scoping review guided by five research questions. The following conclusions are drawn:

- The study found that (RQ1) maritime ports play a central role in energy logistics and are evolving into complex energy hubs integrating fossil fuels, LNG, and renewables. However, CEI in ports remains highly vulnerable to environmental, cyber, and geopolitical threats due to its physical exposure and jurisdictional complexity.
- Furthermore, the study reveals that (RQ2) the digital transition of CEI is advancing in stages from paperless operations to smart port systems, but remains uneven. Many ports, especially in developing regions, lack cohesive strategies, resulting in fragmented adoption and limited interoperability.
- The investigation revealed that (RQ3) digital technologies enhance CEI resilience through predictive maintenance, energy optimisation, and stakeholder coordination. Yet, their transformative potential is constrained by insufficient integration, underutilised data, and misalignment between stakeholders and governance structures. The study found that (RQ4) the key challenges to digital transition in CEI in maritime include skill shortages, resistance to collaboration, unclear ROI, and wide disparities in digital maturity. These factors weaken systemic resilience and delay the scaling of smart infrastructure across entire port ecosystems.
- The study recommends that (RQ5) future research must address gaps in cross-border governance, cybersecurity protocols, and regional equity. Holistic digital strategies are needed, underpinned by international cooperation, empirical validation, and investment in workforce capacity.

Nevertheless, this review is based on secondary literature and lacks empirical fieldwork. It draws from selected academic and grey sources available in English, which may limit representativeness. Future research should include case studies, comparative regional analyses, and stakeholder interviews to validate these findings and refine digital transition models of CEI in maritime ports for global applications. Empirical investigations could offer deeper insights into real-world applications and the effectiveness of digital resilience strategies. Expanding data sources beyond the current scope and incorporating multiple port contexts will enhance generalisability. Continued effort is required to build cohesive international frameworks that support secure, efficient, and sustainable digital transitions in maritime CEI.

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