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Review

From Smart Green Ports to Blue Economy: A Review of Sustainable Maritime Infrastructure and Policy

Setyo Budi Kurniawan ¹, Mahasin Maulana Ahmad ², Dwi Sasmita Aji Pambudi ³, Benedicta Dian Alfanda ⁴ and Muhammad Fauzul Imron ^{5,6,7,*}

- ¹ Research Centre for Environmental and Clean Technologies, National Research and Innovation Agency (BRIN), Jakarta Pusat 10340, Indonesia; setyo.budi.kurniawan@brin.go.id
 - ² Study Program of Piping Engineering, Department of Marine Engineering, Politeknik Perkapalan Negeri Surabaya, Jalan Teknik Kimia, Kampus ITS Keputih, Sukolilo, Surabaya 60111, Indonesia; mahasinmaulana@ppns.ac.id
 - ³ Study Program of Marine Electrical Engineering, Department of Marine Electrical Engineering, Politeknik Perkapalan Negeri Surabaya, Jalan Teknik Kimia, Kampus ITS Keputih, Sukolilo, Surabaya 60111, Indonesia; dwi.sasmita@ppns.ac.id
 - ⁴ Study Program of Marine Engineering, Department of Marine Engineering, Politeknik Perkapalan Negeri Surabaya, Jalan Teknik Kimia, Kampus ITS Keputih, Sukolilo, Surabaya 60111, Indonesia; benedictadian@ppns.ac.id
 - ⁵ Study Program of Environmental Engineering, Department of Biology, Faculty of Science and Technology, Universitas Airlangga, Kampus C UNAIR, Jalan Mulyorejo, Surabaya 60115, Indonesia
 - ⁶ Research Group of Sustainable Environmental Technology, Faculty of Science and Technology, Universitas Airlangga, Kampus C UNAIR, Jalan Mulyorejo, Surabaya 60115, Indonesia
 - ⁷ Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, CN 2628 Delft, The Netherlands
- * Correspondence: fauzul.imron@fst.unair.ac.id or m.f.imron@tudelft.nl

Abstract

Ports play a pivotal role in global trade but are also associated with significant environmental and social challenges. Despite growing research on green ports, existing studies remain fragmented, with limited integration between technological, environmental, and governance perspectives within the blue economy framework. This review examines the transition from green port initiatives toward integrated blue-economy-oriented port systems by synthesizing recent advances in sustainable maritime infrastructure, smart port technologies, renewable energy integration, and policy frameworks. The analysis reveals three major findings. First, ports are increasingly evolving into energy-integrated hubs, with leading examples adopting shore power systems, renewable energy microgrids, and hydrogen-based infrastructure, thereby contributing to emissions reductions. Second, digitalization through artificial intelligence, IoT, and data-driven logistics significantly enhances operational efficiency, reduces energy consumption, and improves real-time decision-making. Third, effective governance frameworks that combine regulatory measures and incentive-based instruments are critical to accelerating sustainability transitions while ensuring economic competitiveness. In addition, the review highlights the growing integration of biodiversity conservation, marine pollution mitigation, and community engagement into port management strategies, reflecting a shift toward ecosystem-based approaches. Overall, the findings demonstrate that ports are transitioning from conventional logistics hubs into integrated socio-technical systems that enable low-carbon maritime transport while supporting inclusive and resilient coastal development.



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Keywords: blue economy; green ports; decarbonization; smart ports; sustainable maritime infrastructure

1. Introduction

Ports play a crucial role in global trade and maritime logistics, serving as strategic gateways connecting international shipping networks to regional supply chains and coastal economies [1]. As global maritime trade continues to expand, ports increasingly function not only as transportation hubs but also as complex infrastructures supporting industrial activities, energy distribution, and logistics services [2,3]. However, the growing intensity of port operations has also generated significant environmental and social challenges, including greenhouse gas emissions, marine pollution, ecosystem degradation, and impacts on surrounding coastal communities [4–6]. These pressures have intensified the need for ports to adopt more sustainable operational models that balance economic efficiency with environmental protection and social responsibility.

In response to these challenges, the smart green port concept has emerged as an important framework for improving the environmental performance of port operations [7]. Early green port initiatives primarily focused on regulatory compliance and pollution control, including waste management and emissions-reduction measures [8,9]. Over time, this concept has evolved into a broader sustainability-oriented approach integrating renewable energy systems, digital technologies, circular economy principles, and environmentally responsible logistics management [10]. At the same time, the blue economy framework has gained increasing global attention, emphasizing the sustainable use of ocean resources to support economic development while protecting marine ecosystems [11]. Within this perspective, ports play a strategic role as operational nodes linking maritime transport with ocean-based industries such as fisheries, offshore renewable energy, coastal tourism, and marine biotechnology.

Table 1 presents a critical comparison of existing review studies on smart ports and maritime sustainability, revealing a clear evolution in the literature from narrowly defined, single-dimensional analyses toward increasingly complex and integrative perspectives. Early contributions, such as those focusing on environmental certification frameworks and green port concepts, primarily emphasize environmental performance, pollution control, and benchmarking mechanisms [9]. While these studies provide valuable foundational insights, they often lack integration with broader dimensions, including digital transformation, governance structures, and socio-economic considerations. Subsequent research expands the scope by addressing technical and operational measures for decarbonization, energy efficiency, and green innovation [12]. However, these studies remain largely technology-centric, with limited attention to systemic interactions between policy frameworks, institutional capacity, and stakeholder dynamics.

The more recent literature reflects a shift toward incorporating emerging themes such as energy transition, artificial intelligence, and system-level port evolution [10,11,13]. Despite this progress, these studies still tend to examine individual components, such as digitalization, energy systems, or governance, rather than offering a fully integrated analytical framework. In addition, several studies demonstrate geographical and methodological limitations, including regional focus, reliance on bibliometric approaches, or insufficient empirical validation, which further constrain their generalizability and practical applicability. Notably, only a few contributions explicitly engage with the blue economy paradigm, and even then, the linkage between port development and broader maritime sectors remains underexplored.

Across the reviewed literature, a consistent and critical gap emerges: the absence of a comprehensive, multidimensional framework that integrates technological innovation, governance mechanisms, environmental sustainability, and socio-economic development into a unified transition pathway. This fragmentation limits the ability to fully understand how ports can evolve beyond isolated green or smart initiatives into holistic, sustainable maritime systems. In response, the present study advances the field by synthesizing

these previously disconnected dimensions into an integrated conceptual framework that explicitly connects smart green port development with Blue Economy principles. By doing so, it not only provides a more coherent analytical foundation but also offers practical insights for policymakers and stakeholders seeking to align port development with long-term sustainability and resilient coastal economic systems.

Table 1. Critical comparison of prior literature reviews on smart ports and maritime sustainability, identifying thematic focus, methodological approaches, key findings, limitations, and the specific gaps addressed by the present study.

Reference (Year)	Focus Area	Key Contribution	Limitation	Gap Addressed in This Study
Walker (2016) [9]	Environmental certification programs for ports and maritime transport	<ul style="list-style-type: none"> Introduces the Green Marine Environmental Program Develops performance indicators across environmental dimensions Establishes a structured performance scale Provides a standardized benchmarking framework for port environmental performance Emphasizes transparency, verification, and continuous improvement 	<ul style="list-style-type: none"> Focused primarily on environmental performance, with limited integration of social and economic dimensions Limited discussion on digitalization and smart port technologies Did not explicitly connect certification frameworks to blue economy systems Regional focus (North America) limits global generalization 	Moving from performance-based environmental certification toward a fully integrated conceptual framework that combines digitalization, governance mechanisms, energy transition, and socio-ecological considerations.
Bergqvist & Monios (2019) [7]	Green port concept, environmental sustainability in ports, governance, and operational practices	<ul style="list-style-type: none"> Provides a comprehensive overview of environmental challenges in ports and shipping Expands green port concept beyond emissions to include noise, waste, water pollution, and ecosystem protection Highlights multi-actor governance roles Integrates policy, operational, and technological perspectives Emphasizes importance of hinterland transport sustainability 	<ul style="list-style-type: none"> Primarily focused on environmental sustainability, with limited social integration Did not explicitly incorporate digitalization Lacks a holistic integrative framework linking multiple sustainability dimensions Did not connect port sustainability with the blue economy paradigm 	Developing an integrated framework that simultaneously links technological innovation, governance mechanisms, environmental sustainability, and social dimensions within a unified transition pathway toward blue economy-oriented port systems
Alamouh et al. (2020) [12]	Technical and operational measures for reducing emissions and improving energy efficiency in ports	<ul style="list-style-type: none"> Develops a comprehensive classification of port decarbonization measures Covers both port-side operations and ship–port interface measures Provides a holistic categorization framework Synthesizes abatement potential, best practices, and implementation challenges 	<ul style="list-style-type: none"> Strong focus on technical and operational measures, with limited integration of governance frameworks, social dimensions, and policy interactions Did not explicitly connect findings to blue economy concepts Limited emphasis on system-level transformation of ports Limited discussion on developing economies' adaptation pathways 	Advances the literature by integrating technical measures with governance frameworks, digital transformation, socio-environmental considerations, and blue economy linkages.
Liu et al. (2025) [10]	Green innovation in ports	<ul style="list-style-type: none"> Develops a structured analytical framework Identifies categories of drivers Classifies innovation domains Highlights major challenges 	<ul style="list-style-type: none"> Focuses mainly on green innovation, not broader blue economy integration Did not deeply integrate governance–technology–ecosystem interactions into a unified framework Limited dataset Less emphasis on developing economies' implementation pathways 	Advances the literature by extending beyond green innovation toward an integrated smart green port–blue economy nexus, incorporating governance mechanisms, digital transformation, socio-ecological systems, and cross-sectoral maritime linkages
Alamouh & Ismail (2025) [14]	Port generation development models and integration of energy transition for decarbonization	<ul style="list-style-type: none"> Reviews the evolution of port generations Identifies a critical gap that energy transition is not explicitly integrated into port development models Proposes a conceptual framework linking port generations with energy transition Highlights the emergence of smart ports integrating AI, IoT, and automation Positions ports as future energy hubs supporting maritime decarbonization 	<ul style="list-style-type: none"> Focus is primarily on energy transition, not broader environmental or ecosystem integration Limited discussion on blue economy linkages Lack empirical validation Did not integrate social and governance dimensions 	Advances the literature by extending beyond energy transition to incorporate governance frameworks, digital transformation, environmental management, and socio-ecological integration within a blue economy perspective

Table 1. Cont.

Reference (Year)	Focus Area	Key Contribution	Limitation	Gap Addressed in This Study
Kurniawan et al. (2026) [11]	Integration of wastewater treatment technologies and governmental policies for marine pollution mitigation within the blue economy	<ul style="list-style-type: none"> Introduces the concept of wastewater–policy synergy linking technological solutions with governance frameworks Provides a comprehensive classification of marine pollution sources, including land-based and sea-based contributors Analyzes multi-level governance structures in addressing marine pollution Synthesizes conventional vs. advanced wastewater treatment technologies and their effectiveness Highlights SDG integration within blue economy strategies Examines policy fragmentation challenges and institutional coordination gaps 	<ul style="list-style-type: none"> Focuses primarily on pollution and wastewater systems, not port systems specifically Limited discussion on port digitalization, smart technologies, or logistics transformation Did not explicitly address smart green port evolution pathways Limited integration of port-centric economic and operational dimensions Emphasis is more on the environmental-policy nexus than on full maritime system transformation 	Advances the literature by extending the analysis toward port-centric transformations, integrating smart technologies, energy transition, governance mechanisms, and socio-ecological considerations.
Castro et al. (2026) [13]	Role of Artificial Intelligence (AI) in enabling sustainability, resilience, and system-level transformation in port ecosystems	<ul style="list-style-type: none"> Provides a system-level perspective linking AI to sustainable port ecosystems Combines bibliometric performance analysis and science mapping Identifies dominant AI application streams Develops thematic evolution phases of AI research Highlights AI as a systemic enabler, not just a technical tool 	<ul style="list-style-type: none"> Captures research trends, not real-world implementation performance Limited empirical validation of AI effectiveness in ports Focused mainly on AI dimensions, with less coverage of blue economy sectors 	Extends beyond a technology-centric and AI-focused perspective by integrating technological, governance, environmental, and socio-economic dimensions within a unified framework of smart green ports transitioning toward blue economy-oriented systems
This study	Integrated transition from smart green ports to blue economy-oriented sustainable maritime systems, incorporating technological, governance, environmental, and socio-economic dimensions	<ul style="list-style-type: none"> Develops an integrated conceptual framework linking smart green ports to blue economy systems Synthesizes technology, governance, environmental, and social dimensions into a unified analysis Identifies global transformation patterns in port sustainability pathways Expands discussion beyond technology to include policy instruments, ecosystem protection, and community engagement Incorporates recent developments to capture emerging trends 	<ul style="list-style-type: none"> Potential selection bias due to inclusion of recent and non-indexed sources (policy reports, institutional websites) Heterogeneity of studies limits direct comparability 	This study addresses the lack of integrated analytical frameworks in existing literature by systematically linking technological innovation, governance mechanisms, environmental management, and socio-economic dimensions within a single transition pathway. It advances current knowledge by explicitly connecting smart green port development to blue economy principles, providing a holistic and policy-relevant understanding of sustainable maritime ecosystems.

Therefore, this review examines the evolving role of ports in advancing sustainable maritime infrastructure and supporting the transition from green port initiatives toward the broader blue economy framework. Specifically, this study synthesizes the recent literature on key technological and operational pathways, including renewable energy integration, smart port technologies, green logistics optimization, and alternative fuel infrastructure. In addition, the review explores environmental and social dimensions of sustainable ports, including marine pollution management, biodiversity conservation, and community engagement, as well as the policy and governance frameworks that guide sustainable maritime development. By integrating these perspectives, this paper provides a comprehensive understanding of how ports can function as critical enablers of low-carbon maritime systems and sustainable coastal development.

To guide the analysis and ensure a structured synthesis of the literature, this study is framed around the following research questions (RQ):

(RQ1) How has the concept of green ports evolved toward integrated blue economy-oriented port systems?

- (RQ2) What are the key technological pathways, such as renewable energy integration, alternative fuels, and digitalization, that enable sustainable maritime infrastructure in ports?
- (RQ3) How do policy frameworks and governance mechanisms influence the implementation of green and smart port strategies across different regions?
- (RQ4) What environmental and social dimensions, including marine pollution mitigation, biodiversity conservation, and community engagement, are addressed in sustainable port development?
- (RQ5) What are the major challenges and barriers to achieving low-carbon and resilient port systems, and how can these be addressed through integrated strategies?
- (RQ6) How do green port initiatives contribute to broader blue economy objectives, including sustainable ocean resource management and coastal development?

These research questions provide a structured framework for analyzing the selected literature and identifying key trends, gaps, and future directions in sustainable port development. In addition, this review assumes that integrating technological innovation, policy frameworks, and ecosystem-based management is essential to transforming ports into key enablers of the blue economy. To strengthen the analytical integration of this review, Table 2 presents a synthesized framework linking the six research questions with key technological, governance, environmental, and socio-economic dimensions, as well as their corresponding contributions to blue economy outcomes.

Table 2. Integrated framework linking research question (RQ), drivers, enabling systems, barriers, and blue economy outcomes in sustainable port transition.

Framework Layer and Related RQ	Component	Key Elements	Interconnections
Drivers (RQ1 & RQ6)	External pressures shaping port transition	Climate change & decarbonization pressure, digital transformation, policy & regulatory push, market demand for green shipping	Drive the need for technological adoption, policy development, and sustainability integration
Enabling system: Technological & energy (RQ2)	Infrastructure transformation	Renewable energy systems (solar, wind, microgrids), alternative fuels (liquefied natural gas, hydrogen, electrification), smart technologies (artificial intelligence, internet of things, automation)	Supports low-carbon operations, energy efficiency, and digital optimization across port systems
Enabling system: Governance & policy (RQ3)	Institutional and regulatory framework	International (International Maritime Organization, Sustainable Development Goals), regional (EU, ASEAN), national strategies; Incentives (carbon pricing, public-private partnerships)	Enables implementation of technologies and aligns stakeholders toward sustainability goals
Enabling system: Environmental & social (RQ4)	Sustainability integration	Emission reduction, marine pollution control, biodiversity protection, community engagement, corporate social responsibility	Ensures ecological protection and social acceptance of port development
Cross-cutting barriers (RQ5)	System constraints	Financial limitations, technological gaps, regulatory fragmentation, institutional capacity, stakeholder resistance	Influence effectiveness of all enabling systems and slow transition processes
Outcome: Blue economy (RQ6)	Integrated impacts	Low-carbon maritime transport, ecosystem protection, sustainable coastal development, industrial symbiosis, ocean-based economic activities	Result from interaction of all components and represent the transition toward blue economy systems

2. Methodology

2.1. Literature Search Strategy

A systematic literature review was conducted to synthesize current knowledge on green ports and their role in advancing sustainable maritime infrastructure within the blue economy framework. The review approach was designed to ensure transparency, reproducibility, and comprehensive coverage of relevant academic literature.

The literature search was primarily performed using the SCOPUS database, which is widely recognized for its extensive indexing of high-quality peer-reviewed journals in environmental science, maritime studies, and sustainable infrastructure. To complement this search and capture recent publications not yet indexed, Google Scholar was used as a supplementary source. In addition, targeted searches were conducted on official institutional websites (such as port authorities, international organizations such as the IMO, and governmental agencies) to obtain up-to-date information on policy developments and real-world port implementations.

The search query was constructed using three thematic groups combined with Boolean operators. The first group captured port-related concepts, including “green port*”, “smart port*”, “sustainable port*”, “port sustainability”, and “maritime infrastructure”. The second group focused on sustainability and energy transition aspects, including “decarbonization”, “renewable energy”, “alternative fuels”, “electrification”, and “energy transition”. The third group addressed broader systemic and governance contexts, including “blue economy”, “marine sustainability”, “coastal development”, “maritime policy”, and “port governance”. The search query performed in SCOPUS was structured as follows:

- (i) TITLE-ABS-KEY (“green port*” OR “smart port*” OR “sustainable port*” OR “port sustainability” OR “maritime infrastructure”);
- (ii) TITLE-ABS-KEY (“decarbonization” OR “renewable energy” OR “alternative fuels” OR “electrification” OR “energy transition”);
- (iii) TITLE-ABS-KEY (“blue economy” OR “marine sustainability” OR “coastal development” OR “maritime policy” OR “port governance”).

2.2. Screening and Selection of Studies

The first search returned 2684 documents, the second returned 406,889, and the third returned 7201. The retrieved publications underwent a systematic screening and selection process to ensure relevance and quality. All records obtained from the database search were exported and compiled, and duplicate entries were removed before further analysis.

The inclusion criteria applied during the initial screening phase were:

- (i) English language.
- (ii) Keywords from a minimum of two thematic groups using Boolean operators (AND).
- (iii) Studies directly related to port systems or maritime sustainability.

This screening yielded 610 documents. Subsequently, full-text eligibility screening was conducted based on the following exclusion criteria:

- (i) Publications outside the timeframe of 2016–2026.
- (ii) Studies that do not focus on green ports, smart ports, or sustainable maritime infrastructure.
- (iii) Research that does not address decarbonization strategies, renewable energy integration, digitalization, or alternative fuel systems in port environments.
- (iv) Publications that do not analyze policy frameworks, governance mechanisms, or blue economy integration in maritime systems.
- (v) Articles that do not originate from a peer-reviewed journal with clear environmental and/or technological relevance.

The screening process, conducted on 18 February 2026, followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, with a complete diagram presented in Figure 1. Following full-text assessment, a total of 181 studies were selected from the SCOPUS database for inclusion, which forms the primary analytical basis of the study. In addition, a total of 38 supplementary references (not more than 20% of the total references) were additionally targeted searches performed from Google Scholar and official institutional websites to capture up-to-date information on policy developments and real-world port implementations. These supplementary sources were used only to support contextual or practice-context discussion.

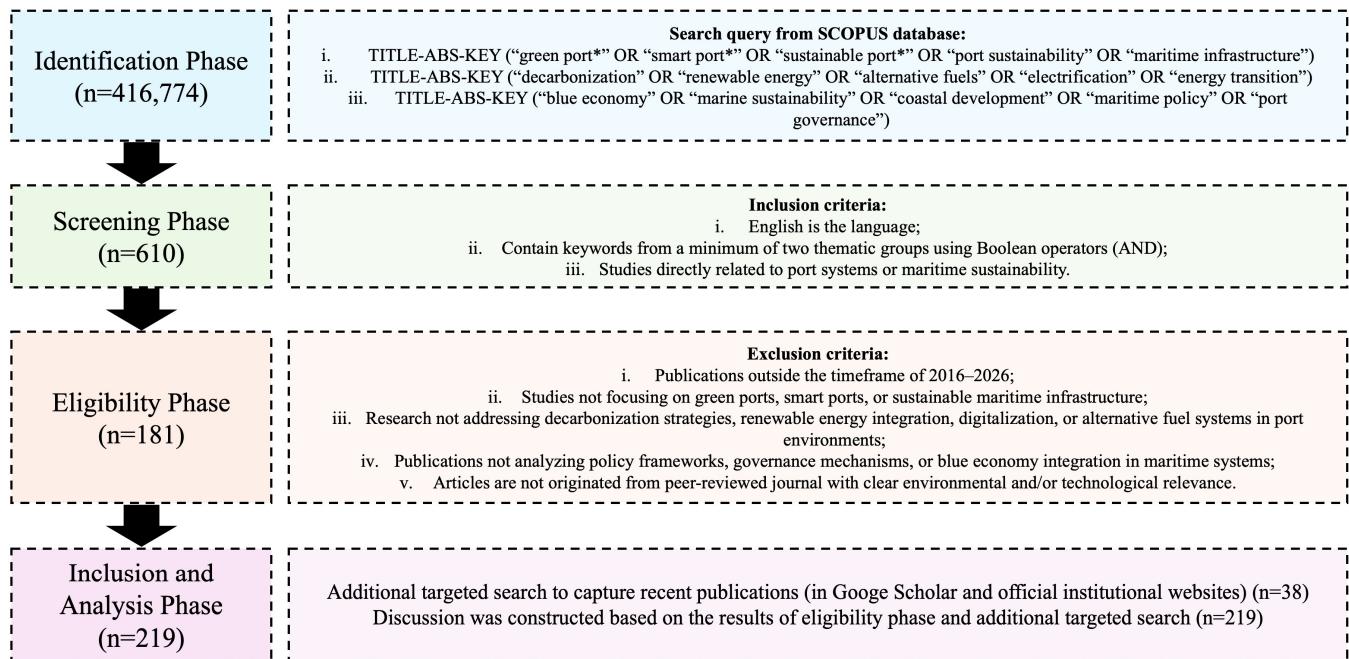


Figure 1. Overview of the literature search and selection process (PRISMA), including SCOPUS-based query design, inclusion and exclusion criteria, and final dataset construction ($n = 219$) for analyzing the transition from smart green ports to blue economy-oriented systems.

3. Conceptual Framework

Ports are increasingly recognized as critical infrastructure within smart coastal cities, where maritime logistics, digital technologies, and sustainable energy systems intersect [15]. As global trade continues to expand, ports must balance economic efficiency with environmental protection and social responsibility. Consequently, the traditional concept of port management has evolved toward integrated sustainability frameworks that link maritime infrastructure with broader urban and coastal development strategies.

In this study, conventional ports are understood as traditional port systems primarily focused on cargo handling, logistics efficiency, and economic throughput, with limited integration of environmental sustainability measures, digital technologies, or ecosystem-based management approaches. These ports typically operate under linear development models, prioritizing operational performance and trade facilitation over broader environmental and social considerations.

Building on this baseline, smart green ports are defined as integrated port systems that combine environmental sustainability principles with advanced digital technologies to optimize operational efficiency, reduce environmental impacts, and support low-carbon maritime logistics. This concept extends beyond green port approaches by incorporating smart technologies, including artificial intelligence, the Internet of Things (IoT), and

data-driven management systems, to enable real-time monitoring, predictive analytics, and energy optimization [13,16]. The blue economy refers to the sustainable use of ocean resources for economic growth, improved livelihoods, and ecosystem health [11]. It further expands this transformation by positioning ports within interconnected socio-ecological systems rather than isolated logistics hubs. Within this framework, ports serve as strategic nodes linking maritime transport to ocean-based industries, including fisheries, offshore renewable energy, coastal tourism, and marine biotechnology, while ensuring environmental protection and long-term ecological resilience.

3.1. Evolution of the Green Port Concept

The concept of a green port has evolved from a narrow focus on pollution control toward a comprehensive, sustainability-oriented paradigm [17]. Early green port initiatives were primarily reactive and focused on compliance with international environmental regulations, particularly in waste management and pollution mitigation [18]. However, contemporary scholarship conceptualizes green ports as maritime hubs that integrate environmental protection, economic performance, and social responsibility within port operations and governance structures [15].

Modern green ports increasingly incorporate advanced technological solutions to improve operational efficiency and reduce environmental impacts. These technologies include Onshore Power Supply (OPS) systems that enable ships to connect to port electricity, thereby reducing greenhouse gas emissions while at berth [19]. In addition, digital innovations such as digital twins, real-time monitoring systems, and intelligent energy management platforms enable ports to optimize resource use, improve operational efficiency, and support data-driven environmental management [20]. Another defining characteristic of green ports is the integration of circular economy principles [21]. Through industrial symbiosis within port clusters, waste streams and by-products generated by one industry can be reused as inputs for other industrial processes [22,23]. This circular approach minimizes resource consumption, reduces environmental externalities, and enhances the sustainability of port-related industrial ecosystems [24]. As a result, green ports increasingly function as circular industrial hubs within coastal urban systems.

3.2. Green Ports as Enablers of the Blue Economy

The relationship between green ports and the blue economy is rooted in the principle of decoupling maritime economic growth from environmental degradation [25,26]. Within this framework, ports serve as operational gateways connecting maritime transport networks to sustainable ocean-based industries [27]. By integrating environmentally responsible infrastructure and operational practices, green ports help protect marine ecosystems while supporting economic activities such as fisheries, aquaculture, coastal tourism, and offshore renewable energy [28–30].

Environmental management practices implemented in green ports, including strict ballast water management [31], oil spill prevention [32], and emission reduction strategies [33], play a crucial role in safeguarding marine biodiversity and coastal ecosystems. These efforts help preserve the natural capital required for sustainable blue economy sectors to thrive. At the same time, ports increasingly support the development of blue growth industries, such as offshore wind farms [34], marine biotechnology [35], and ocean-based renewable energy infrastructure [36]. From a systems perspective, green ports function as strategic nodes within interconnected coastal economies, enabling sustainable resource management and facilitating low-carbon maritime transport.

3.3. Smart Port Systems and Multi-Level Governance

The operationalization of green ports within the blue economy increasingly relies on the development of smart port systems, where digital technologies enable more efficient and environmentally responsible port operations [37]. Smart ports integrate technologies such as the IoT, artificial intelligence (AI), big data analytics, and blockchain to support real-time monitoring, predictive maintenance, and optimized logistics management [13,16,38]. However, the successful implementation of green and smart port strategies requires multi-level governance frameworks that coordinate actions across international, national, and local levels. Global institutions such as the International Maritime Organization (IMO) provide overarching regulatory mandates, such as the IMO 2050 greenhouse gas reduction strategy, that guide maritime decarbonization efforts [39]. These global commitments must then be translated into national policies, regional strategies, and local port management practices [40].

Effective governance, therefore, requires collaboration among governments, port authorities, industry stakeholders, and local communities to ensure that sustainability goals are aligned with economic development objectives [41]. Within this governance structure, ports increasingly function as innovation platforms that facilitate the integration of digital infrastructure, renewable energy systems, and sustainable logistics networks. To illustrate how these governance frameworks are implemented in practice, Table 3 presents a comparative analysis of regulatory approaches adopted by leading maritime nations. The comparison highlights how policy instruments, technological innovation, and institutional arrangements collectively support the transition to sustainable, digitally enabled port systems that contribute to the broader objectives of the blue economy.

Table 3. Comparative Analysis of Global Green Port Regulation.

Country	Key Policy/Initiative	Focus Area	Difference with Conventional Port	Impact on Blue Economy	Reference
Australia	Singapore–Australia Green and Digital Shipping Corridor	Green Corridors, Ammonia Pilot	Transforming port functionalities into clean energy export centers, shifting away from a reliance on mining commodity exports	Large-scale trade decarbonization and hydrogen export.	[42]
Canada	Green Marine Certification (Port of Vancouver)	Habitat Restoration, Noise Reduction	Regulatory requirements for underwater noise reduction to ensure marine mammal conservation.	Balancing trade growth with the protection of marine mammals.	[43]
China	14th Five-Year Plan for Green Transportation	Smart Ports, Onshore Power (OPS)	Mandatory shore power requirements for vessels at berth.	Reducing coastal pollution to support sustainable fisheries.	[20]
Germany	National Strategy for Green Shipping (Port of Hamburg)	Alternative Fuels, Digital Monitoring	Integration of Smart Port systems to optimize vessel routing for fuel efficiency.	Strategic leadership in European sustainable logistics.	[44]
Indonesia	National Blue Agenda Actions Partnership (NBAAP)	Maritime Digitalization, Waste Reception	Prioritizing port reception facilities for waste management and the digital integration of logistics through the Inaportnet system.	Circular economy in archipelagic logistics and marine conservation.	[45]
Netherlands	Rotterdam Port Authority Carbon Neutral 2050	CCS (Carbon Capture), Hydrogen Hub	The transition from fossil fuels to CCS infrastructure.	Decarbonizing maritime industry while maintaining economic lead.	[46]

Table 3. Cont.

Country	Key Policy/Initiative	Focus Area	Difference with Conventional Port	Impact on Blue Economy	Reference
Norway	Green Shipping Programme	Battery-Electric Ferries, Hydrogen Technology	Focusing on the full electrification of ferry fleets and the integration of renewable energy at berthing facilities.	Protection of fjords (Natural Capital) for blue tourism.	[47]
Singapore	Maritime Singapore Green Initiative (MSGI)	Green Bunkering (LNG), ESI Incentives	Fiscal incentives for vessels adopting low-emission fuels, such as LNG and biofuels, within port jurisdictions.	Sustainable shipping hub and marine ecosystem protection.	[48]
USA	Clean Air Action Plan (CAAP)-Port of LA/Long Beach	Zero-Emission Equipment, Truck Regulation	Zero-emission standards for port trucks and cargo handling equipment.	Improving air quality for coastal communities and tourism.	[49]
Vietnam	National Green Port Strategy 2030–2045	Legal Infrastructure Corridors	Compulsory ‘Eco-Port’ certification standards for greenfield terminal projects in ecologically sensitive coastal zones	Efficiency and environmental resilience in developing economies.	[50]

The comparative analysis of ten leading maritime nations demonstrates that the concept of the green port has evolved from a regulatory compliance requirement into a strategic instrument supporting the blue economy. This transformation is not uniform and reflects differentiated pathways shaped by economic capacity, institutional maturity, and national strategic priorities. Three major patterns of global port transformation [51] can be identified.

First, advanced maritime economies are increasingly transitioning toward energy-integrated port systems that support maritime decarbonization [52]. Countries such as the Netherlands, Australia, and Norway illustrate this shift by investing in carbon capture and storage infrastructure, hydrogen and ammonia fuel supply chains, and the electrification of ferry fleets. These initiatives reposition ports from traditional commodity logistics hubs into clean-energy platforms that support low-carbon maritime transport. In contrast, emerging economies tend to adopt more incremental approaches, focusing on digitalization, waste management, and regulatory development, reflecting financial and technological constraints while still aligning with sustainability objectives.

Second, policy frameworks commonly combine incentive-based instruments and regulatory enforcement mechanisms to accelerate sustainability transitions [53]. For example, some maritime economies promote voluntary adoption through fiscal incentives and smart port technologies that optimize vessel routing and energy efficiency, as seen in Singapore. Others implement stricter regulatory measures, including mandatory onshore power-supply requirements and zero-emission standards for port equipment, as observed in China and the United States. This divergence highlights that effective governance approaches are highly context-dependent and must be aligned with national institutional structures and market conditions.

Third, recent policy developments increasingly incorporate ecological protection and digital governance into port sustainability strategies [17]. Measures such as underwater noise mitigation, ecosystem protection programs, and eco-port certification standards indicate that port sustainability is now assessed not only by atmospheric emissions but also by the protection of marine ecosystems and biodiversity. This reflects a broader paradigm shift toward ecosystem-based management, where ports are increasingly recognized as

socio-ecological systems that must balance environmental stewardship with economic performance and technological innovation. Overall, ports are evolving into multi-functional platforms that not only enable decarbonized maritime transport but also support sustainable ocean resource management and resilient coastal development within the broader framework of the blue economy.

4. Sustainable Maritime Infrastructure

Maritime infrastructure constitutes a critical component of global trade systems and coastal urban economies. Ports, terminals, shipyards, navigation systems, and related facilities enable maritime connectivity, facilitate efficient logistics operations, and support the economic development of coastal regions [54]. As maritime transport continues to expand in response to growing international trade, these infrastructures increasingly function as strategic nodes linking global shipping networks with regional supply chains and urban logistics systems [55].

In recent years, growing environmental concerns, climate commitments, and technological innovation have spurred the development of sustainable maritime infrastructure (SMI). SMI refers to the design and operation of maritime facilities that integrate environmental protection, energy efficiency, digital technologies, and resilient logistics systems to ensure long-term economic and ecological sustainability [56]. By combining technological innovation with sustainable operational practices, SMI seeks to minimize environmental impacts while maintaining high levels of logistical efficiency and economic competitiveness [57].

Global sustainability agendas and maritime decarbonization policies strongly influence the development of sustainable maritime infrastructure. Initiatives such as the IMO greenhouse [58] gas reduction strategy and the United Nations Sustainable Development Goals (SDGs) [42] have accelerated efforts to reduce emissions from maritime transport and port operations. As a result, ports are increasingly adopting integrated solutions that combine renewable energy systems [59], smart technologies [60], energy-efficient logistics networks [60], and alternative fuel infrastructure [61]. These transformations are reshaping ports into digitally enabled, low-carbon infrastructure within smart coastal city systems. Rather than functioning solely as logistics hubs, modern ports increasingly serve as platforms for energy transition, technological innovation, and sustainable maritime logistics. The following subsections examine these dimensions in detail, highlighting how technological innovation and infrastructure development contribute to the transition toward low-carbon and resilient maritime systems.

4.1. Renewable Energy Integration

Ports serve as critical nodes in global maritime supply chains, supporting international trade and logistics distribution while connecting maritime transport with regional and urban economies. However, their strategic role is associated with substantial energy consumption and greenhouse gas emissions from both maritime and land-based operations [62,63]. Major emission sources include ships at berth that rely on auxiliary engines for onboard power and port-side operations involving cargo-handling equipment, terminal vehicles, and energy-intensive logistics activities [64,65]. As maritime traffic and port throughput continue to expand, these emissions are expected to increase, intensifying pressure on port authorities to improve environmental performance and adopt low-carbon operational strategies.

Renewable energy integration has therefore emerged as a central pathway to decarbonizing port operations. By incorporating renewable energy sources into port energy systems, ports can reduce dependence on fossil fuels, improve energy efficiency, and en-

hance long-term operational sustainability [66] (Figure 2). In recent years, many ports have begun deploying renewable energy technologies such as solar photovoltaic systems, wind power, and marine-based energy sources to support port facilities and provide electricity to berthed vessels [67,68]. These initiatives contribute not only to emission reduction but also to improved energy resilience and lower operational costs.

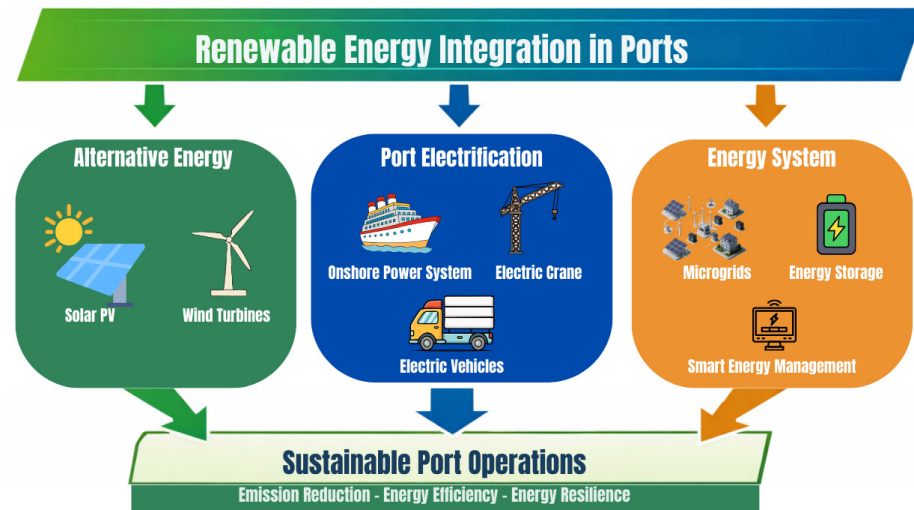


Figure 2. Renewable energy integration framework for sustainable port operations.

One of the most effective decarbonization measures in port environments is the implementation of shore-to-ship power systems, commonly referred to as OPS [69]. These systems enable vessels to connect directly to onshore electricity while at berth, allowing auxiliary diesel engines to be shut down and significantly reducing emissions of carbon dioxide, nitrogen oxides, sulfur oxides, and particulate matter by approximately 30–50% in specific case studies, depending on the electricity mix and operational conditions [70,71]. When powered by renewable energy sources, OPS systems provide a particularly effective means of reducing the environmental footprint of maritime operations in port areas. Furthermore, integrating OPS with energy storage technologies and port microgrids can enhance energy reliability while maximizing the utilization of locally generated renewable electricity [72].

To further improve energy autonomy and operational efficiency, ports increasingly adopt hybrid energy systems that combine renewable energy generation, grid connections, and energy storage technologies [73]. These systems can operate under both on-grid and off-grid configurations, allowing ports to balance electricity demand, manage surplus renewable energy, and enhance the stability of local power systems [74,75]. Hybrid energy architectures are particularly relevant in large port complexes where energy demand fluctuates significantly due to cargo-handling operations, vessel arrivals, and logistics activities [76]. In addition, operational optimization strategies, such as scheduling cranes, yard equipment, and terminal vehicles, can help align energy consumption patterns with the availability of renewable energy, thereby improving overall system efficiency [77]. Effective renewable energy integration also requires advanced energy management and forecasting systems. Accurate electricity demand forecasting is essential for planning renewable energy infrastructure and ensuring a reliable energy supply within increasingly electrified port environments [78]. Forecast-based energy planning enables port authorities to evaluate the technical and economic performance of various system configurations [63], including different grid connections, storage capacities, and renewable generation scenarios.

Despite these opportunities, integrating renewable energy into port systems also presents several technical challenges. Issues related to power quality, grid stability, voltage

fluctuations, and current harmonics may arise when renewable energy sources are interconnected with national power grids [79,80]. Addressing these challenges requires appropriate system design, advanced control strategies, and regulatory frameworks that support the integration of renewable technologies within port energy infrastructures.

The successful deployment of renewable energy systems in ports also depends on collaboration among multiple stakeholders, including port authorities, shipping companies, energy providers, and government institutions. Coordinated policy frameworks, shared investments, and technological partnerships can accelerate the adoption of renewable energy solutions and facilitate the broader decarbonization of maritime transport systems [81,82]. In many coastal cities, port energy systems are increasingly integrated with urban smart grids and renewable energy infrastructures [83], reinforcing the role of ports as key components of sustainable urban energy systems. Table 4 summarizes the major renewable energy technologies currently applied in port environments, highlighting their advantages, energy potential, implementation challenges, and representative ports.

Overall, renewable energy integration represents a fundamental pillar of sustainable maritime infrastructure. By combining renewable energy generation, electrification technologies, hybrid energy systems, and intelligent energy management strategies, ports can significantly reduce emissions while maintaining operational efficiency and energy resilience. These developments not only support international decarbonization targets established by the IMO but also position ports as innovation hubs for the transition toward low-carbon maritime logistics and sustainable coastal development [65,84].

Table 4. Summary of Renewable Energy Technologies for Decarbonization of Port Operations.

Renewable Energy Source	Advantages	Energy Potential	Development Challenges	Typical Applications	Ports of Implementation
Floating Solar Photovoltaic (PV) [85–88]	Efficient use of water surface, reduced land use, improved panel efficiency due to cooling effect	Very high potential in calm port basins, docks, and sheltered coastal waters	Mooring system design, corrosion, wave and tidal stability, higher initial cost	Floating solar arrays on port basins, hybrid PV–battery systems for port microgrids, power supply for cold storage and reefer containers, charging of electric port equipment	Port of Avilés (Northern Spain), Port of Amsterdam in Netherlands, Port of Barrow in Cumbria, Port de Sète in France, Port of Constanta in Romania
Solar Photovoltaic (PV) [89–91]	Clean, abundant, low operating cost, easy integration	High potential in tropical and coastal regions with strong solar irradiance	Intermittency, space limitations, efficiency reduction due to salt corrosion	Rooftop solar on terminals and warehouses, port lighting, administrative buildings, auxiliary power	Port of Los Angeles (USA), Port of Long Beach (USA), Port of Valencia in Spain, Ports of Tenerife in Spain, Port of Barcelona in Spain, Port of Rotterdam in Netherlands, Port of North Sea (Belgium and The Netherlands), Port of Solomon Islands, Ports of Fiji, Port of Colombo in Sri Lanka, Port of Marseille in France, Port of Helsinki in Finland, Port of Antwerp in Belgium, Port of Batangas in Philippines, Ports of Associated British (UK), Ports of Auckland in New Zealand, Ports of Stockholm in Sweden, Port of Hamburg in Germany, Singapore’s Jurong Port, Port of Genoa in Italy
Tidal Energy [3,92]	Highly predictable, stable output, long-term reliability	Significant potential in narrow straits and areas with strong tidal currents	High capital cost, limited suitable locations, environmental impact concerns	Power supply for remote ports, navigation aids, port microgrids	Ports of Gladstone in Australia
Wave Energy [93–95]	Large and untapped energy resources, suitable for open seas	Promising for ports exposed to strong wave conditions	Technology is still developing, maintenance challenges, harsh marine environment	Supplementary power for port facilities, offshore port structures	Port of Los Angeles (USA), Port of Tanger-Med (Morocco), Port of Pecém in Ceará, Brazil
Wind Energy [3,84,96]	High energy yield, mature technology, suitable for coastal areas	Strong potential in offshore and coastal ports with consistent wind patterns	Visual impact, noise concerns, high initial investment, grid integration	Onshore/offshore wind turbines supplying port electricity, hybrid renewable systems	Port of Gothenburg in Sweden, Port of Rotterdam in Netherlands, Ports of Associated British (UK), Ports of Tenerife in Spain, Port of Helsinki in Finland, Port of Genoa in Italy, The Port of Tianjin in China

4.2. Smart Port Technologies

Smart ports have emerged as technologically advanced maritime hubs designed to manage the increasing operational complexity of global supply chains by integrating digital technologies into port infrastructure and operations. As critical nodes within smart coastal city systems, smart ports leverage digital infrastructure to improve logistics efficiency, operational transparency, and environmental sustainability [97]. By adopting Industry 4.0 technologies, such as the IoT [98], AI [99], big data analytics, cloud computing, and automation [16], ports can optimize resource allocation, enhance operational efficiency with some case studies reporting energy savings of up to 10% under optimized operational conditions, and strengthen their competitiveness within global logistics networks.

At a conceptual level, smart ports are characterized by extensive digitalization and connectivity across port functions, enabling data-driven decision-making and real-time visibility along the maritime supply chain [100,101]. Technologies such as IoT sensors, RFID systems, and connected monitoring devices support continuous tracking of port assets, cargo flows, and environmental conditions [68]. These capabilities allow port operators to anticipate congestion, minimize operational delays, and improve asset utilization within increasingly complex logistics systems [68,102].

AI plays a particularly important role in enabling intelligent port operations. AI-driven models support predictive analytics for vessel arrival estimation, berth and yard planning, traffic flow optimization, and predictive maintenance of port equipment [103]. When combined with real-time data generated through IoT systems, AI enables proactive asset management and enhances the resilience and reliability of port logistics networks [104,105].

Data integration and analytics represent another fundamental component of the smart port ecosystem. Large volumes of operational data are collected and processed across cloud and edge computing infrastructures, enabling port operators to monitor operations in real time and conduct long-term strategic analyses [106,107]. Big data platforms enable advanced analytics for operational optimization, while machine learning algorithms can identify patterns in cargo flows, equipment usage, and energy demand. These capabilities support more informed decision-making and improve the efficiency and reliability of port logistics systems [84,108].

From a system architecture perspective, smart ports are typically organized using layered digital frameworks. These architectures commonly consist of sensing layers (IoT sensors and monitoring devices), communication layers (high-speed networks such as 5G), data processing layers (cloud and edge computing platforms), and application layers that support analytics, optimization, and decision-making [109,110].

Automation technologies further enhance the operational capabilities of smart ports. Equipment such as automated stacking cranes (ASCs) [111], autonomous guided vehicles (AGVs) [112], and intelligent terminal operating systems (TOS) [113] enable ports to automate cargo handling, yard management, and terminal operations. These systems improve operational safety, reduce labor-intensive activities, and increase throughput reliability [99,114]. In addition, digital platforms such as Port Community Systems facilitate efficient data sharing, streamline documentation processes, and improve coordination among port-related organizations [115]. Beyond improving operational efficiency, smart port frameworks increasingly integrate environmental sustainability objectives. Digital energy management systems, renewable energy monitoring platforms, and emission tracking tools enable ports to optimize energy consumption and reduce environmental impacts [116]. Real-time energy monitoring, combined with intelligent control strategies, supports peak demand reduction and facilitates the integration of renewable energy into port microgrids [117]. These technologies directly contribute to emission-reduction targets and support global decarbonization efforts in the maritime sector.

Overall, the convergence of digital infrastructure, IoT connectivity, AI-driven analytics, automation, and sustainability-oriented technologies is transforming ports into intelligent logistics platforms. By integrating these technologies within coordinated governance frameworks, smart ports can enhance operational efficiency, strengthen resilience, and support the transition toward low-carbon maritime logistics systems [102]. To illustrate how digital technologies interact within smart port systems, Figure 3 presents a multi-layer digital architecture that integrates sensing technologies, communication networks, data platforms, and intelligent applications.

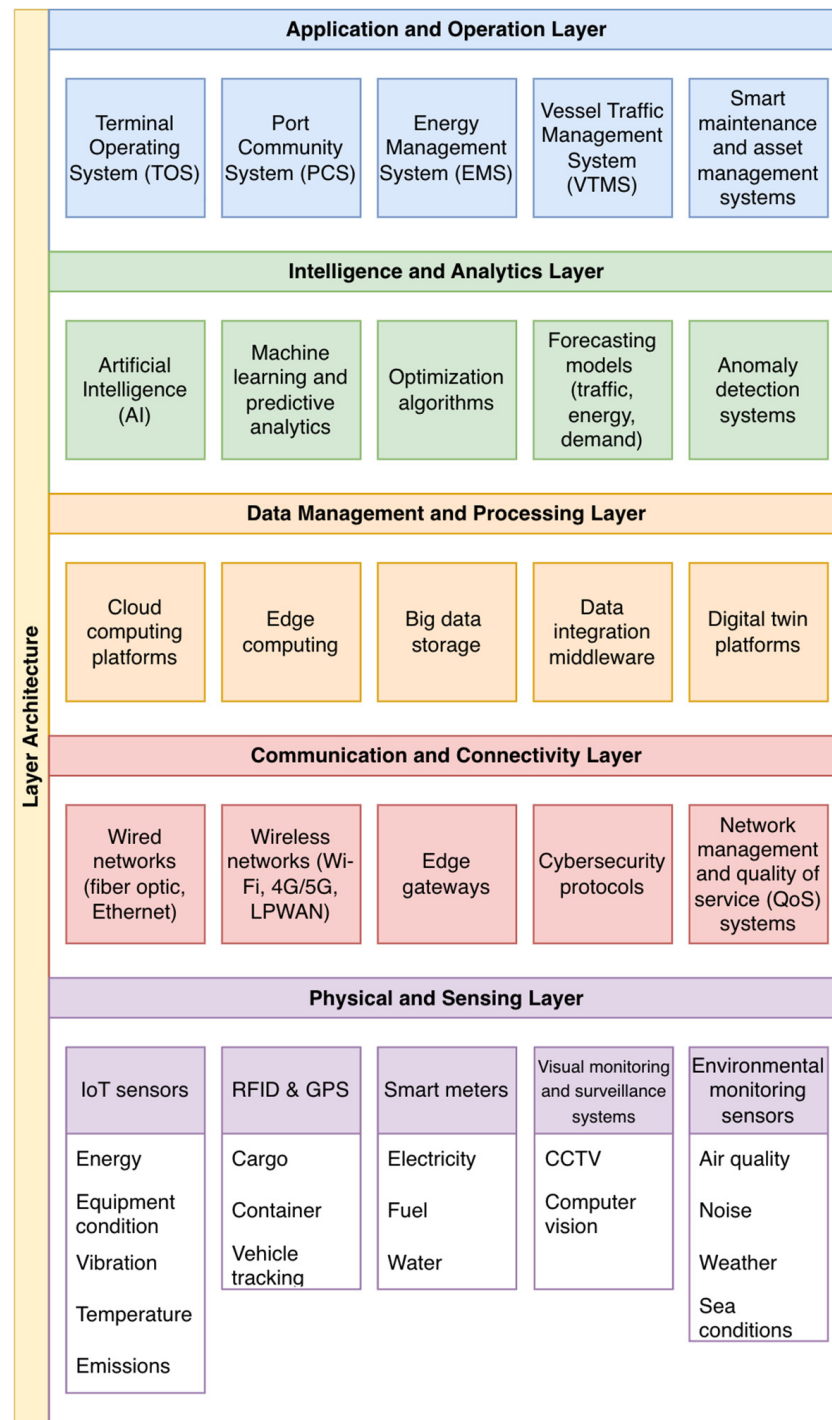


Figure 3. The framework of digital technologies in smart ports.

Figure 3 illustrates a hierarchical architecture of smart port systems in which multiple digital layers interact to enable intelligent, data-driven port operations [118]. Each layer performs a specific function while remaining interconnected with other components of the digital ecosystem. The architecture demonstrates how physical infrastructure, communication networks, data platforms, and intelligent analytics collectively support efficient, automated, and sustainable port management.

Layer 1—Physical and sensing layer forms the foundation of the framework and includes the physical assets and sensing technologies deployed throughout the port environment. IoT sensors are used to monitor equipment condition, vibration, temperature, emissions, and energy consumption. In addition, RFID and GPS technologies enable the tracking of cargo, containers, and vehicles within terminal areas. Smart meters measure electricity, fuel, and water usage across port facilities, while CCTV and computer-vision cameras support surveillance and operational monitoring. Environmental sensors also collect information on air quality, noise levels, weather conditions, and sea states. The primary role of this layer is to generate continuous streams of real-time data reflecting operational activities, infrastructure conditions, and environmental parameters within the port system [109,110].

Layer 2—The communication and connectivity layer enables the reliable transmission of data captured at the physical layer to higher-level digital systems. This layer integrates wired communication infrastructure, such as fiber-optic networks and Ethernet connections, with wireless technologies, including Wi-Fi, 4G/5G networks, and low-power wide-area networks (LPWAN). Edge gateways are commonly used to preprocess data close to the source, reducing latency and improving processing efficiency. Cybersecurity mechanisms are also embedded within this layer to ensure data protection, system integrity, and secure communication across interconnected devices. Through these functions, the communication layer ensures seamless connectivity, interoperability, and real-time data exchange within the port's digital ecosystem [109,110].

Layer 3—The data management and processing layer acts as the central hub for storing, integrating, and processing operational data generated throughout the port system. Cloud computing platforms provide scalable storage and computational capabilities, while edge computing enables low-latency processing for time-sensitive applications. Big data infrastructures support the handling of high-volume and high-velocity data streams generated by sensors and operational systems. In addition, data integration middleware facilitates interoperability among heterogeneous digital platforms operating within the port environment. Digital twin technologies further enhance system visibility by creating virtual representations of port assets and operational processes. This layer, therefore, plays a critical role in organizing and processing multisource data to support system-wide monitoring and analytical applications [106,107].

Layer 4—The intelligence and analytics layers represent the analytical core of the smart port architecture. At this stage, processed data are transformed into actionable insights through advanced analytical methods. Artificial intelligence, machine learning algorithms, and predictive analytics models are applied to forecast vessel arrivals, optimize berth allocation, predict equipment failures, and estimate energy demand patterns [103]. Optimization algorithms and anomaly detection tools further support proactive maintenance strategies and operational risk management. By converting raw operational data into predictive insights, this layer enables intelligent decision-making and enhances overall port performance [98,119].

Layer 5—The application and operation layer represents the interface between digital technologies and operational decision-making within the port environment. This layer includes operational platforms such as TOS, Port Community Systems (PCS), Energy

Management Systems (EMS), Vessel Traffic Management Systems (VTMS), and digital asset management tools. Through interactive dashboards, monitoring platforms, and decision-support systems, analytical outputs generated in lower layers are translated into operational actions. Consequently, this layer enables port authorities and terminal operators to implement intelligent control strategies that improve operational efficiency, safety, and environmental performance [99,120].

Taken together, this five-layer architecture illustrates how digital infrastructure, communication networks, data platforms, and intelligent analytics interact to create an integrated smart port ecosystem. By linking physical infrastructure with advanced digital technologies, this framework enables ports to improve operational transparency, optimize logistics processes, and support sustainable maritime infrastructure within increasingly complex global supply chains.

4.3. Green Logistics and Supply Chain Optimization

Green logistics in the maritime sector is a systemic approach to reducing environmental impacts across the entire logistics chain, with particular emphasis on minimizing greenhouse gas emissions from shipping, port operations, and port–hinterland transportation. As global cargo volumes continue to increase and ports become more deeply embedded within regional and multimodal logistics networks, they have evolved into critical nodes where environmental, technological, and economic considerations converge [121,122]. However, port activities remain significant sources of environmental pressure through air and water pollution, noise emissions, and ecosystem disturbances associated with infrastructure development and dredging [123].

In this context, green logistics strategies aim to optimize maritime supply chains by integrating environmentally responsible operational practices, low-emission transport solutions, alternative-fuel infrastructure, and clean-energy technologies. These strategies must be supported by coherent regulatory frameworks, technological readiness, economic feasibility, and organizational capacity [123]. From this perspective, green logistics in port systems can be understood as a structured effort to improve the environmental performance of vessel calls, cargo handling processes, terminal operations, and port–hinterland connectivity through the application of low-emission technologies and data-driven operational management [124]. It has been shown in selected case studies, such as the Port of Singapore, to reduce fuel consumption by approximately 10–15% through data-driven route optimization [15], while similar approaches in the Port of Rotterdam demonstrated comparable efficiency (15%) under specific forecasting lock jams operational conditions [125].

From a systems perspective, ports should be viewed not as isolated operational units but as integral nodes within interconnected regional and multimodal logistics networks. The environmental performance of maritime transport is therefore strongly influenced by the efficiency of port–hinterland connectivity and the coordination of maritime, road, and rail transport systems [126]. Network-level optimization enables the identification of emission hotspots and supports coordinated mitigation strategies across multiple ports and transport corridors [81].

Several optimization approaches have been proposed to support low-carbon logistics in maritime supply chains. Routing optimization focuses on identifying transport routes that minimize emissions by accounting for factors such as travel distance, modal choice, and energy efficiency [127]. Scheduling optimization improves temporal coordination among vessels, terminals, and inland transport modes, reducing idle time and unnecessary energy consumption [128]. In addition, cargo consolidation strategies increase vehicle and vessel utilization rates, thereby reducing per-unit emissions and improving overall logistics efficiency [129].

Digital technologies increasingly act as key enablers of green logistics by improving data availability, analytical capabilities, and operational transparency [130]. Real-time tracking and tracing technologies enhance visibility over cargo and vehicle movements, enabling more accurate emission monitoring and responsive operational adjustments [104,131]. Furthermore, digital twin platforms and AI-supported logistics systems enable simulation-based evaluation of routing, scheduling, and consolidation strategies prior to physical implementation, thereby reducing operational risks and improving environmental performance [102,130].

The integration of emission monitoring systems and transparent data platforms also strengthens accountability and supports sustainability-oriented decision-making throughout the maritime logistics chain [132]. Nevertheless, achieving low-carbon logistics often involves trade-offs between cost, time efficiency, operational reliability, and environmental performance [123,129]. Emission-minimizing strategies may increase operational costs or extend transit times, highlighting the need for multi-objective optimization frameworks that balance economic and environmental priorities [133].

Overall, effective green logistics implementation requires not only technological innovation but also integrated policy frameworks, stakeholder collaboration, and coordinated network-level planning. Such approaches enable ports to function as strategic hubs within sustainable maritime logistics systems, supporting both environmental objectives and long-term economic resilience [134,135]. An integrated conceptual framework for green logistics and supply chain optimization is presented in Figure 4, highlighting the role of regulatory support, digital enablers, sustainable infrastructure, and optimization methods in improving environmental performance across port-centric logistics systems.

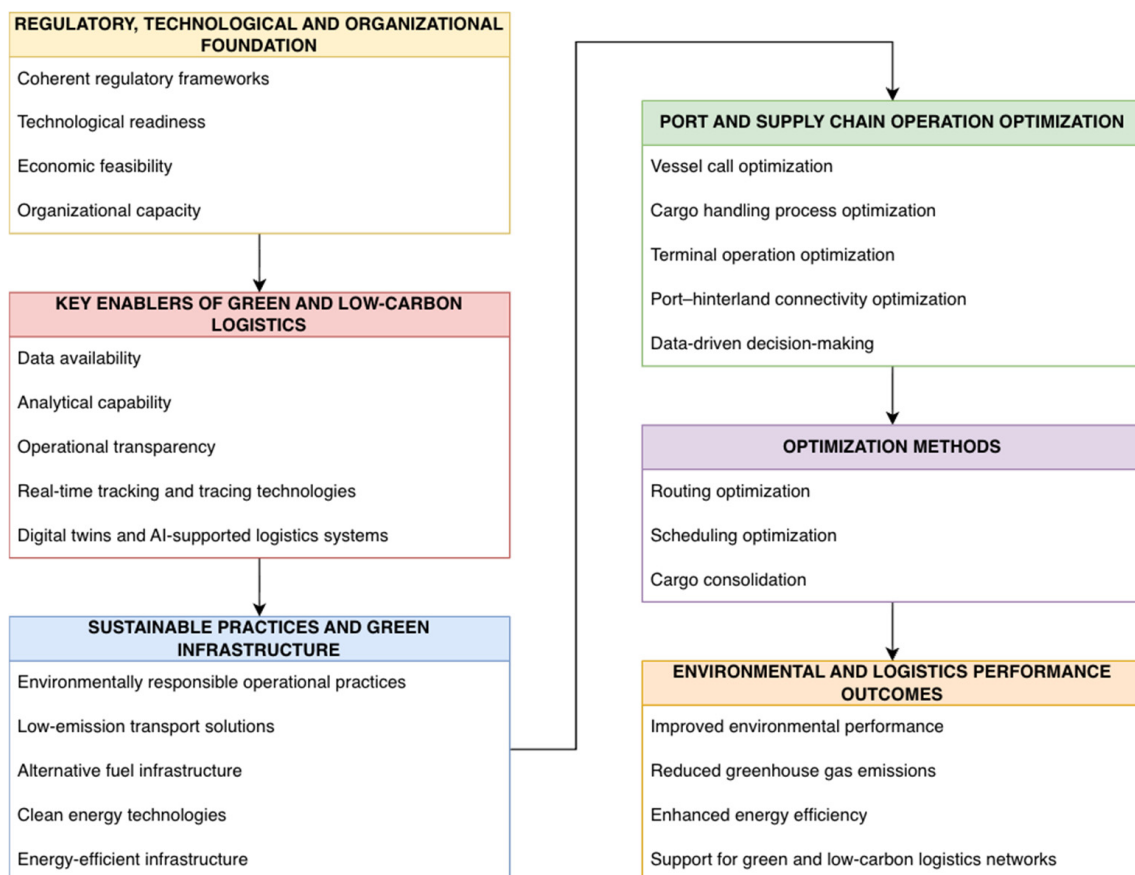


Figure 4. Conceptual diagram of green logistics & supply chain optimization.

4.4. Infrastructure for Alternative Fuels

Maritime- and land-based transportation systems are among the largest and fastest-growing contributors to global energy consumption and greenhouse gas emissions, particularly in port regions where shipping activities, cargo handling operations, and hinterland transport converge [72]. Emissions from vessel maneuvering, auxiliary engines operating at berth, cargo-handling equipment, and port–hinterland logistics have been shown to degrade local air quality significantly and generate substantial health-related external costs for nearby communities [136]. These environmental pressures have intensified the need to develop sustainable port ecosystems that reduce emissions while maintaining operational efficiency and economic competitiveness [137,138]. As a result, alternative fuels and low-carbon energy systems have emerged as critical components of maritime decarbonization strategies rather than optional technological upgrades [139,140].

Among the available options, LNG has been widely adopted as a transitional fuel in maritime transport due to its lower emissions of carbon dioxide (20–25%), sulfur oxides, and particulate matter than conventional heavy fuel oil and marine diesel oil [72]. LNG is particularly attractive from an operational perspective due to its relatively mature bunkering infrastructure, high energy density, and compatibility with existing propulsion systems via dual-fuel engine technologies [138]. Nevertheless, LNG remains a fossil-based fuel and poses environmental challenges related to methane slip and long-term alignment with net-zero emission targets [141]. Consequently, LNG is increasingly regarded as an interim solution that can facilitate short-term emission reductions while enabling the gradual transition toward zero-carbon energy carriers.

In contrast, hydrogen has gained significant attention as a promising zero-carbon energy carrier, particularly when produced through renewable-powered electrolysis. Hydrogen can support a wide range of port and maritime applications, including fuel-cell-powered vessels, cargo-handling equipment, heavy-duty vehicles, and stationary power generation systems [142,143]. The adoption of hydrogen technologies may enhance energy diversification and reduce dependence on fossil fuels in energy-intensive port operations. However, large-scale hydrogen deployment remains constrained by challenges related to storage complexity, safety considerations, infrastructure investment requirements, and the current high cost of green hydrogen production [144].

Another important pathway for maritime decarbonization is electrification, particularly through the deployment of OPS systems. OPS allows vessels to switch off auxiliary engines while at berth and draw electricity directly from the port grid, thereby significantly reducing emissions of carbon dioxide, nitrogen oxides, sulfur oxides, and particulate matter [72]. Despite these environmental benefits, the large-scale implementation of OPS faces several barriers, including high capital investment requirements, limited capacity of port electrical infrastructure, and the lack of global standardization in voltage and frequency systems [145]. To address these challenges, electrification strategies are increasingly combined with port microgrids and intelligent energy management systems that balance electricity demand, integrate renewable energy, and improve overall system efficiency [61].

Comparative assessments of LNG, hydrogen, and electrification indicate that each decarbonization pathway has distinct advantages and limitations in terms of emission-reduction potential, technological maturity, and infrastructure requirements [141,146]. While LNG provides relatively immediate emission reductions with moderate infrastructure adjustments, hydrogen and battery-electric systems offer greater long-term decarbonization potential when supported by clean energy supply chains. Hybrid configurations, such as dual-fuel engines combined with OPS systems or battery-assisted propulsion, have therefore emerged as practical transitional solutions that improve operational flexibility while lowering environmental impacts [72]. These findings highlight the importance of

context-specific decision frameworks that consider factors such as port size, traffic patterns, energy availability, and regulatory conditions [137,141].

Ultimately, integrating alternative fuels and electrification technologies with renewable energy sources such as solar, wind, and green hydrogen represents a critical step toward achieving net-zero emissions in port systems [147]. Renewable-powered port microgrids can support the decarbonization of both stationary and mobile energy demand while improving energy resilience and reducing dependence on fossil-fuel markets [137]. Through the coordinated deployment of alternative fuels, electrification technologies, renewable energy integration, and intelligent energy management systems, ports can increasingly serve as key enablers of sustainable, low-carbon maritime logistics. Table 5 summarizes the key characteristics, advantages, and limitations of major alternative fuel pathways currently considered for maritime and port decarbonization.

Table 5. Comparison of alternative fuel pathways for maritime and port decarbonization.

Fuel/Technology	Emission Reduction Potential	Maturity	Infrastructure Requirements	Advantages	Key Challenges	Applications	References
Liquefied Natural Gas (LNG)	Moderate CO ₂ reduction (20–25%); major reduction in SO _x and particulate matter	High	LNG bunkering terminals, cryogenic storage tanks, pipelines	Mature technology, high energy density, existing bunkering infrastructure	Methane slip, still fossil-based	Container ships, tankers, bulk carriers	[148]
Hydrogen	Near-zero emissions when produced via renewable electrolysis	Emerging	Hydrogen production plants, high-pressure storage, fuel cells, bunkering infrastructure	Zero-carbon fuel potential, versatile applications	Storage complexity, high cost, safety concerns	Fuel-cell vessels, port equipment	[149]
Battery-Electric Systems/ Electrification (OPS)	Zero emissions at berth or short-range operations	Moderate	Shore power systems, charging stations, upgraded port grid	Immediate emission reduction, high energy efficiency	Limited range, infrastructure costs	Ferries, port equipment, short-sea shipping	[70]
Ammonia (NH ₃)	Potentially zero CO ₂ emissions	Emerging	Ammonia production plants, cryogenic or pressurized storage, bunkering systems	Carbon-free fuel, relatively high energy density, global ammonia trade network	Toxicity, NO _x formation, safety management	Deep-sea vessels (future designs)	[150,151]
Methanol (CH ₃ OH)	Lower CO ₂ emissions; near-carbon-neutral if produced from renewable sources	Emerging to moderate	Methanol bunkering infrastructure, storage tanks, modified engines	Liquid at ambient conditions, easier storage and handling	Lower energy density, production pathway dependence	Container ships, tankers	[152]

To connect sustainable maritime infrastructure with broader blue economy objectives, it is important to recognize that integrating renewable energy systems, smart port technologies, green logistics, and alternative fuel infrastructure goes beyond emission reduction and operational efficiency. Collectively, these developments contribute to the formation of low-carbon, resource-efficient, and environmentally responsible port ecosystems that support sustainable coastal development. Renewable energy integration and electrification reduce air and water pollution, thereby protecting marine ecosystems and improving environmental quality in port-adjacent coastal areas. Smart port technologies enhance system-wide efficiency and transparency, enabling more sustainable management of maritime traffic and reducing congestion-related environmental impacts. Meanwhile, green logistics and the adoption of alternative fuels support cleaner supply chains and facilitate the decarbonization of maritime transport networks. From a blue economy perspective, these infrastructure transformations enable ports to function not only as logistics hubs but also as strategic enablers of sustainable ocean-based industries. By supporting offshore renewable energy deployment, low-emission shipping, and environmentally responsible supply chains, sustainable maritime infrastructure strengthens the resilience of coastal economies while minimizing ecological degradation.

5. Environmental and Social Dimensions

The transition toward sustainable port systems involves not only technological innovation but also broader environmental and social considerations. Ports operate at the interface between maritime transport networks, coastal ecosystems, and surrounding communities, making environmental management and stakeholder engagement critical components of sustainable port development.

The recent literature identifies several key drivers shaping the transition toward sustainable ports. According to Liu et al. [10], three principal factors influence this transformation: economic and technological development, policy frameworks, and environmental conditions. Based on a review of 67 academic publications, the authors identified four primary domains of green innovation within port systems, including (i) infrastructure modernization and governance reforms to enhance environmental performance; (ii) improvements in logistics efficiency, automation of cargo handling operations, the implementation of emission-reduction strategies; (iii) adoption of alternative fuels, electrification of port equipment, integration of renewable energy sources, and the development of smart grid systems within port infrastructure; and (iv) the use of advanced technologies such as AI, IoT, and blockchain to enhance data-driven port management and operational transparency.

Despite these advancements, ports continue to face several persistent challenges. Increasing environmental pressures, uncertainties associated with clean energy transitions, regulatory inconsistencies across jurisdictions, and the ongoing trade-offs between operational efficiency and environmental sustainability remain key barriers. Addressing these challenges requires stronger policy integration, increased investment in clean energy infrastructure, the development of intelligent port systems, and enhanced collaboration among governments, port authorities, industry stakeholders, and local communities. Such coordinated efforts are essential for achieving reliable, efficient, and low-carbon port operations.

5.1. Marine Pollution and Emission Reduction Strategies

Marine pollution and atmospheric emissions remain among the most critical environmental challenges associated with maritime transport and port activities. Recent research indicates significant progress in emission reduction efforts across the maritime sector, including the adoption of low-carbon fuels, electric propulsion systems, innovative ship designs, and the optimization of vessel operating patterns [153].

A comprehensive analysis of alternative marine fuels suggests that LNG, green methanol, hydrogen, and ammonia each offer distinct decarbonization potential depending on vessel type and the chosen energy transition strategy [154]. Comparative assessments emphasize that fuel selection policies should incorporate life-cycle analyses that cover upstream fuel production and distribution, as well as downstream utilization, to ensure genuine emission reductions across the entire energy supply chain [155].

For short-distance maritime transport, such as coastal tourism vessels, hybrid propulsion systems combining battery power and green methanol have been proposed as efficient solutions, owing to their operational flexibility and enhanced emission-reduction potential [156]. At the port level, the implementation of shore power systems has demonstrated considerable potential to reduce emissions of nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter (PM), and volatile organic compounds (VOCs) when vessels are docked [157]. These systems contribute significantly to improved air quality in port cities, although their environmental effectiveness depends largely on the electricity generation mix and the availability of supporting power infrastructure.

Beyond emissions generated through fuel combustion, marine pollution may also arise from incidents such as oil spills. During the early stages of such events, volatile compounds

are released into the atmosphere, primarily consisting of volatile organic compounds (VOCs) and light polycyclic aromatic hydrocarbons (PAHs) [158]. In addition, studies on Ballast Water Management Systems (BWMS) indicate that several disinfection techniques, including chlorination, ozonation, and electrochemical treatment, can generate disinfection by-products (DBPs) [31]. These by-products may include transient toxic compounds such as trihalomethanes (THMs) and haloacetic acids (HAAs), which can accumulate within ballast water systems [159]. Consequently, stricter monitoring is required, particularly at discharge locations with environmentally sensitive conditions, such as specific tank configurations, discharge dispersion zones, and local water turbidity levels [160].

Risk assessment studies have further highlighted the potential ecological impacts of DBPs, indicating that without adequate mitigation measures, these compounds could introduce new forms of persistent marine pollution [31]. From a blue economy perspective, environmental management efforts should therefore be integrated comprehensively into policy frameworks, coastal zone management systems, and pollution control technologies. Such integration is essential to prevent the transfer of pollution between environmental compartments and to ensure sustainable maritime development [11].

5.2. Biodiversity and Ecosystem Protection in Port Regions

The global biodiversity crisis has intensified in recent decades, with anthropogenic activities such as habitat destruction, pollution, and climate change driving unprecedented declines in species populations. It is estimated that more than one million species could face extinction within the coming decades if current trends continue [161]. In coastal and port regions, biodiversity plays a crucial role in maintaining essential ecological functions. Marine and coastal organisms contribute to water purification, shoreline protection against erosion and wave action, carbon sequestration, and the maintenance of fisheries productivity [162]. These ecosystem services support environmental stability and provide economic benefits for communities that depend on coastal resources [163].

However, port-related activities impose considerable pressure on surrounding ecosystems. Infrastructure expansion, land reclamation, sediment dredging, intensive ship traffic, and industrial development in coastal areas can lead to habitat degradation and declining environmental quality in adjacent marine environments [164]. Since ports are typically located within ecological transition zones, they often overlap with ecologically valuable habitats, including mangroves, salt marshes, seagrass beds, and intertidal flats [165]. These ecosystems play important roles in maintaining biodiversity and enhancing coastal resilience.

Physical disturbances associated with port development may alter seabed morphology, increase water turbidity, and disrupt benthic communities [166]. Benthic organisms are essential components of marine ecosystems [167], providing habitats for numerous invertebrate and shellfish species that serve as critical links in marine food webs. In addition, underwater noise generated by vessel movements and port equipment can interfere with the communication and navigation systems of marine mammals such as whales and dolphins [168]. Such acoustic disturbances may result in behavioral changes, physiological stress, injuries, or even mortality in species highly sensitive to underwater noise [169].

Another significant environmental risk arises from the introduction of invasive alien species transported through ballast water or attached to ship hulls [170]. Once introduced into new ecosystems, invasive species may outcompete native organisms for food and habitat resources, potentially altering food web structures and destabilizing ecological balance [163]. Despite these risks, biodiversity considerations have historically been treated by many port authorities as regulatory obligations or additional operational costs rather than strategic components of sustainable port management [171]. Although global awareness of

ecosystem protection has increased, the integration of biodiversity conservation into port planning and operational practices remains uneven across regions.

Addressing these ecological challenges requires governance approaches that incorporate biodiversity conservation into port management strategies. Several theoretical frameworks provide useful perspectives for this integration. Natural capital theory recognizes ecosystems as valuable assets that provide both ecological and economic benefits, emphasizing that conserving and restoring habitats can generate long-term value for port operations and surrounding communities [172]. Stewardship theory highlights organizations' responsibility to act as custodians of natural resources by prioritizing long-term environmental sustainability over short-term economic gains [173]. Similarly, the ecosystem services framework emphasizes the strong dependence of human well-being on healthy ecosystems and biodiversity, making it a useful foundation for environmentally integrated port planning [174]. Complementing these perspectives, the Natural-Resource-Based View (NRBV) suggests that environmental management practices, including pollution prevention, habitat restoration, and efficient resource utilization, can generate competitive advantages for organizations operating within environmentally sensitive contexts [175].

Several international ports have already begun incorporating biodiversity conservation into their operational and planning strategies. The Port of Brisbane [176], for example, has implemented extensive habitat restoration initiatives, successfully increasing seagrass coverage by more than 100% since 1991. The port also protects approximately 352 hectares of mangrove habitat that serve as critical nursery areas for fish populations and provide natural coastal protection against erosion. Additionally, a 4.6 km intertidal seawall managed by the port has been designed to function as an ecological habitat, demonstrating how port infrastructure can be engineered to support both operational and ecological functions.

In Europe, the Port of Rotterdam [125] integrates biodiversity considerations into its long-term development strategy through its Nature Vision, which aligns with the broader Port Vision 2030 program. This initiative includes developing nature-friendly shorelines, implementing ecological vegetation management practices, and creating ecological stepping-stones to facilitate the movement of flora and fauna across fragmented habitats. The port also prioritizes controlling invasive species to preserve the ecological balance of its complex delta ecosystem. These initiatives illustrate the practical application of ecosystem-based management and eco-engineering principles in contemporary port governance.

Similarly, the Port of Vancouver in North America implemented a comprehensive conservation approach through its Habitat Enhancement Program, which focuses on restoring and improving natural habitats within port areas. The port also operates the Enhancing Cetacean Habitat and Observation (ECHO) Program [177], an initiative aimed at reducing underwater noise levels and protecting endangered killer whales. In addition, the enforcement of the Species at Risk Act and strict monitoring of invasive species demonstrate the application of stewardship principles in modern port management. Table 6 summarizes the biodiversity conservation initiatives in major international ports.

Table 6. Biodiversity conservation initiatives in major international ports.

Port	Key Biodiversity Initiative	Ecosystem Focus	Outcomes	Reference
Port of Brisbane	Seagrass restoration	Coastal seagrass ecosystem	Increased seagrass coverage	[176]
Port of Rotterdam	Nature Vision program	Delta ecosystems	Habitat connectivity	[125]
Port of Vancouver	ECHO program	Marine mammals	Reduced underwater noise	[177]

These examples illustrate that biodiversity protection in port regions can be achieved through multiple approaches, including habitat restoration, environmentally sensitive infrastructure design, pollution control measures, and continuous ecological monitoring. Such initiatives reflect the increasing recognition that ports must balance economic development with environmental stewardship. The idea that ports should act as custodians of coastal ecosystems represents an important shift in perspective, from viewing ports solely as commercial hubs to recognizing them as institutions responsible for maintaining ecological health.

Given the growing environmental pressures associated with expanding maritime trade, ecosystem protection in port regions has become a critical component of sustainable maritime infrastructure and integrated coastal management [178]. Recognizing biodiversity as a strategic asset rather than a regulatory burden can enhance ecosystem resilience, strengthen climate adaptation capacity, and contribute to the long-term sustainability of port operations and coastal economies [179].

5.3. Community Engagement and Social Responsibility

Despite growing attention to community engagement, the social dimension of port sustainability remains underdeveloped compared to technological and environmental aspects. Ports operate at the interface between global trade networks and local communities, making stakeholder participation essential to ensuring that port expansion and operations align with broader societal expectations [180]. Community engagement in port planning and management is critical to fostering harmonious relationships between port authorities and local stakeholders. Numerous studies emphasize that modern ports must establish open dialogue platforms that allow residents, community organizations, and other stakeholders to participate in discussions regarding port development strategies [36]. Such participatory approaches help ensure that major decisions receive adequate public support and achieve social legitimacy. When communities are actively involved in consultation processes, they are generally more likely to support port development or expansion initiatives, thereby reducing the potential for social conflicts related to environmental concerns or logistics-related transportation issues [180]. However, the effectiveness of such participatory mechanisms depends not only on the existence of dialogue platforms but also on the depth and inclusiveness of engagement. In many cases, participation remains consultative rather than transformative, limiting local communities' ability to influence decision-making outcomes. This highlights the need to move beyond symbolic participation toward more inclusive governance frameworks that actively incorporate local knowledge and address power imbalances between stakeholders.

Beyond participatory decision-making, community engagement initiatives can also promote more equitable distribution of economic benefits generated by port activities. Research indicates that programs focusing on environmental education, vocational training, and the empowerment of local small and medium-sized enterprises (SMEs) can enhance local economic opportunities for populations living in port regions [181]. At the same time, Corporate Social Responsibility (CSR) initiatives implemented by port authorities and operators help strengthen institutional reputation while delivering tangible social and economic benefits to surrounding communities [180]. Nevertheless, the distribution of these benefits is often uneven, with local communities continuing to bear disproportionate environmental burdens, including air pollution, noise, and increased traffic congestion. This imbalance underscores the importance of adopting a justice-oriented perspective in port development, ensuring that economic gains are not achieved at the expense of community well-being. Collaborative governance frameworks further enhance the effectiveness of community engagement. Cooperation among local governments, port authorities, private operators,

and civil society organizations can improve the management of issues that directly affect residents, including air pollution, noise emissions, and traffic congestion associated with port logistics activities [182]. In addition, CSR initiatives focused on maritime education, workforce development, and youth empowerment have been shown to increase environmental awareness and foster long-term positive relationships between ports and local communities [183]. At the same time, the increasing adoption of digitalization and smart port technologies introduces new social dynamics, including workforce transformation, skill shifts, and potential job displacement due to automation. While these technologies improve efficiency, they also require proactive reskilling strategies and inclusive labor policies to prevent the exacerbation of social inequalities within port regions.

Studies examining CSR practices in port governance suggest that structured programs, such as local workforce training, community infrastructure investments, and funding for social development initiatives, can strengthen the social license to operate, defined as the level of public acceptance and trust toward port activities [184]. Importantly, the concept of social license to operate extends beyond compliance and reflects long-term trust-building between ports and communities. Ports that fail to secure this social acceptance may face resistance, project implementation delays, and reputational risks, ultimately undermining sustainability objectives. Furthermore, experiences from several European ports demonstrate that the use of transparent digital communication platforms can enhance stakeholder participation and facilitate more efficient responses to public concerns [97]. In Asian port regions, CSR initiatives emphasizing inclusive economic development have also demonstrated ports' potential to improve the livelihoods of low-income coastal communities [185].

Taken together, the environmental and social dimensions discussed in this section demonstrate that sustainable port development extends beyond technological solutions and must be grounded in ecosystem-based management and inclusive governance. From a blue economy perspective, effective pollution control, emission reduction strategies, and biodiversity conservation are essential for maintaining the ecological integrity of marine and coastal systems that support fisheries, aquaculture, and other ocean-based industries. By reducing environmental externalities and preserving critical habitats, ports can help sustain ecosystem services that underpin long-term economic productivity and resilience in coastal regions. At the same time, strengthening community engagement and social responsibility enhances the social sustainability of port systems by ensuring that economic benefits are distributed more equitably and that local stakeholders are actively involved in decision-making processes. This alignment between environmental protection and social inclusion reinforces the role of ports as key facilitators of sustainable coastal development. Furthermore, integrating environmental stewardship with community-centered governance supports the transition toward blue economy-oriented port systems, where economic growth is balanced with ecological preservation and social well-being.

6. Policy and Regulatory Landscape

The transition toward sustainable ports and maritime infrastructure is strongly influenced by policy and regulatory frameworks operating across multiple governance levels. These frameworks provide the institutional foundation for implementing environmental standards, promoting technological innovation, and aligning port development with global sustainability objectives, as illustrated in Figure 5. In recent years, maritime governance has increasingly emphasized decarbonization, environmental protection, and the integration of ports into broader sustainable ocean governance systems.



Figure 5. Multi-level governance framework for sustainable ports.

6.1. International Policy Frameworks

At the global level, international regulatory institutions play a central role in shaping sustainability policies within the maritime sector. The IMO has established several regulatory instruments to reduce greenhouse gas emissions and improve environmental performance in shipping. Notably, the IMO Initial Strategy on the reduction in GHG emissions from ships sets long-term targets to lower emissions across the maritime industry [186]. It encourages the adoption of alternative fuels, energy-efficiency measures, and low-carbon maritime technologies. Complementing these regulatory initiatives, the United Nations SDGs provide a broader policy framework linking maritime activities to sustainable development objectives. In particular, SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 9 (Industry, Innovation, and Infrastructure) highlight the importance of sustainable maritime infrastructure, environmental protection, and technological innovation within ocean-based economies [187]. Together, these global frameworks establish the strategic direction for maritime sustainability and encourage national governments and port authorities to implement policies that support low-carbon shipping and environmentally responsible port operations.

6.2. Regional and National Policy Initiatives

Regional policy frameworks further translate global sustainability objectives into more concrete regulatory and operational strategies. Within the European Union, initiatives such as the European Green Deal and the Fit for 55 policy package promote climate neutrality and support the transformation of transport systems, including maritime logistics [188,189]. These policies encourage the adoption of shore power systems, alternative fuels, and digitalized port operations, while establishing emission-reduction targets for maritime transport. European ports, including those in the Netherlands, Germany, and Spain, have implemented comprehensive sustainability strategies aligned with EU climate policies [190]. These initiatives typically focus on port electrification, renewable energy integration, and the development of green shipping corridors connecting major maritime trade routes.

In Southeast Asia, regional cooperation under the Association of Southeast Asian Nations (ASEAN) also promotes sustainable maritime development [191]. ASEAN initiatives aim to enhance regional maritime connectivity while encouraging green shipping corridors,

sustainable port infrastructure, and maritime digitalization. Countries such as Singapore, Indonesia, and Malaysia have begun incorporating sustainability principles into national maritime strategies by supporting clean energy integration, improving waste management systems, and adopting smart port technologies [192]. Table 7 lists previous policies that support the development of a sustainable port.

Table 7. Major policy instruments supporting sustainable port development.

Policy Level	Policy Framework	Key Objectives	Implications for Ports	Reference
Global	IMO Strategy on Reduction in GHG Emissions from Ships	Achieve net-zero greenhouse gas emissions from international shipping around 2050; reduce carbon intensity of marine fuels	Adoption of low-carbon fuels, energy-efficiency technologies, and port infrastructure supporting clean shipping	[186]
Global	UN Sustainable Development Goals (SDGs)	Promote sustainable infrastructure, climate action, and marine ecosystem protection	Encourage ports to adopt environmentally responsible operations and support sustainable ocean governance	[193]
Regional (EU)	European Green Deal	Achieve climate neutrality by 2050 and decarbonize the transport sector	Electrification of ports, renewable energy integration, and low-carbon maritime logistics systems	[189]
Regional (EU)	Fit for 55 Package & FuelEU Maritime	Reduce greenhouse gas emissions by at least 55% by 2030 and promote low-carbon maritime fuels	Deployment of alternative fuels, shore power, and emission monitoring in ports and shipping	[194]
Regional	EU Emissions Trading System (ETS) for Shipping	Introduce carbon pricing for maritime emissions to incentivize decarbonization	Financial incentives for ports and shipping companies to reduce emissions and invest in green technologies	[195]
Regional (ASEAN)	ASEAN Maritime Transport Cooperation & Green Shipping Initiatives	Enhance sustainable maritime connectivity and regional logistics integration	Promotion of smart ports, green shipping corridors, and sustainable port infrastructure in Southeast Asia	[196]
National	National Maritime Decarbonization Strategies (e.g., Singapore, Netherlands, Japan)	Integrate sustainability into national maritime development policies	Implementation of smart port technologies, alternative fuel infrastructure, and renewable energy systems	[197]

6.3. Economic Incentives and Governance Mechanisms

In addition to regulatory frameworks, economic incentives and financial mechanisms play an essential role in accelerating the transition toward sustainable port systems. Governments and international institutions increasingly promote green financing instruments such as climate funds, green bonds, and sustainability-linked loans to support investments in renewable energy infrastructure, electrification systems, and low-emission maritime technologies [198]. Fiscal incentives also contribute to the adoption of sustainable practices in maritime logistics [199]. Measures such as reduced port fees for low-emission vessels, tax benefits for green infrastructure investments, and carbon pricing mechanisms encourage shipping companies and port operators to reduce emissions and adopt environmentally friendly technologies.

Public–private partnerships (PPPs) are another important governance mechanism that supports sustainable port development [200]. Collaboration among governments, port authorities, private investors, and research institutions enables the implementation of large-scale infrastructure projects, including hydrogen bunkering facilities, renewable energy installations, and digital port management platforms. By distributing financial risks

and leveraging technological expertise, PPPs can accelerate the deployment of innovative solutions in maritime infrastructure.

Overall, the policy and regulatory landscape play a pivotal role in enabling the transition from smart green ports toward blue economy-oriented maritime systems by providing the institutional and financial conditions necessary for sustainable transformation. From a blue economy perspective, coherent and multi-level governance frameworks facilitate the alignment of environmental protection, economic development, and technological innovation within port systems. International policies set overarching decarbonization targets and sustainability principles, while regional and national frameworks translate these goals into actionable strategies tailored to specific socio-economic and environmental contexts. Importantly, the integration of economic incentives, regulatory instruments, and collaborative governance mechanisms supports the development of low-carbon maritime transport, sustainable coastal infrastructure, and ecosystem-based management practices. These policy-driven transformations enable ports to act as catalysts for sustainable ocean-based industries, including offshore renewable energy, sustainable fisheries logistics, and environmentally responsible maritime trade. Well-coordinated governance frameworks enhance regulatory certainty, attract long-term investments, and promote cross-sectoral integration, all of which are essential for building resilient and inclusive coastal economies. Therefore, effective policy and regulatory alignment represent a critical enabler in advancing the broader objectives of the blue economy.

7. Case Studies of Green Port Initiatives

The implementation of green port strategies varies across regions depending on economic capacity, technological readiness, regulatory frameworks, and environmental priorities. Examining real-world initiatives from both developed and developing regions provides valuable insights into how ports can adopt sustainable practices while maintaining operational efficiency and economic competitiveness. Table 8 summarizes some global examples of the green port initiative.

Table 8. Selected global examples of green port initiatives.

Port	Country	Key Green Initiatives	Technologies/Policies	Reference
Port of Rotterdam	The Netherlands	Hydrogen hub, CCS (Porthos), renewable energy integration	Smart port systems, circular industry clusters	[125]
Port of Singapore	Singapore	Maritime Singapore Green Initiative	LNG bunkering, digital port systems	[201]
Port of Los Angeles	USA	Clean Air Action Plan (CAAP)	Electrification, zero-emission trucks, shore power	[202]
Port of Long Beach	USA	Clean Air Action Plan	Zero-emission cargo handling equipment	[203]
Malaysian Ports	Malaysia	Green port guidelines	Energy efficiency, waste management	[204]
Indonesian Ports	Indonesia	Inaportnet digitalization	Waste reception facilities, smart logistics	[205]
African Ports	Various	Renewable energy and efficiency programs	Solar power, port modernization	[206]

7.1. Green Port Initiatives in Developed Regions

In developed maritime economies, several major ports have taken leading roles in implementing comprehensive sustainability strategies. The Port of Rotterdam (Netherlands) is widely recognized as a global pioneer in sustainable port development. The port has

adopted an ambitious strategy to achieve carbon neutrality by 2050 through initiatives such as CCS, hydrogen infrastructure development, and large-scale integration of renewable energy [15,207]. In addition, Rotterdam has implemented smart port technologies, digital monitoring systems, and circular industrial clusters that promote resource efficiency and industrial symbiosis among port-related industries.

Similarly, the Port of Singapore, one of the world's busiest maritime hubs, has introduced a range of initiatives under the Maritime Singapore Green Initiative [15]. These programs include incentives for ships using cleaner fuels, investments in alternative-fuel bunkering infrastructure, such as LNG, and the deployment of smart port technologies to improve operational efficiency. Singapore has also prioritized digitalization and automation through data-driven port management systems that enhance logistics efficiency, reducing vessel waiting times by up to 20% and minimizing environmental impacts.

In the United States, the Ports of Los Angeles, Long Beach, and San Pedro have jointly implemented the Clean Air Action Plan (CAAP) [202,203], one of the most comprehensive port environmental programs globally. This initiative focuses on reducing air pollution through measures such as electrifying cargo-handling equipment, zero-emission truck programs, vessel speed reductions, and expanded shore power infrastructure. As a result, these ports have achieved significant reductions in nitrogen oxides, particulate matter, and greenhouse gas emissions while maintaining their role as major global trade gateways.

7.2. Green Port Initiatives in Developing Regions

While developed ports often benefit from greater financial resources and advanced technologies, developing regions are increasingly adopting sustainability initiatives adapted to local conditions. In Southeast Asia and Africa, green port initiatives are often introduced through phased, adaptive approaches rather than large-scale, capital-intensive transformations. In Malaysia, several ports have begun integrating sustainability principles into their operations through energy efficiency programs, improved waste-management systems, and the deployment of digital port services to optimize logistics processes [204]. Government-led initiatives have also promoted environmentally responsible shipping practices and infrastructure modernization.

In Indonesia, sustainability initiatives have focused on strengthening port waste reception facilities, improving maritime digitalization through systems such as Inaportnet [205], and promoting environmentally responsible port management practices. Given Indonesia's archipelagic geography, green port development is closely linked to improving maritime connectivity while minimizing environmental impacts on sensitive coastal ecosystems.

Across African ports, green initiatives are gradually emerging as governments and port authorities recognize the need to modernize port infrastructure while addressing environmental challenges. Several ports have begun implementing renewable energy projects, improving port energy efficiency, and adopting international environmental standards [206]. Although financial and technological constraints remain significant barriers, these initiatives reflect growing awareness of sustainable port development across emerging maritime economies.

These cases illustrate that sustainable port development in emerging economies often follows a staged trajectory, beginning with regulatory strengthening and digital integration, followed by infrastructure upgrades and renewable energy adoption. Unlike developed ports that pursue rapid decarbonization through advanced technologies such as hydrogen and carbon capture, developing regions tend to emphasize cost-effective and scalable solutions aligned with local institutional and financial capacities.

7.3. Lessons Learned and Best Practices

Several key lessons can be identified from these case studies. First, strong policy frameworks and long-term sustainability strategies are essential for guiding the transition toward greener port operations [208]. Second, technological innovation, including digitalization, electrification, and the integration of renewable energy, plays a critical role in reducing emissions and improving operational efficiency [209]. Third, collaboration among governments, port authorities, private investors, and research institutions is necessary to mobilize financial resources and accelerate technology deployment [182].

Finally, successful green port initiatives must integrate environmental objectives with broader social and economic considerations, including community engagement, workforce development, and regional economic integration (Figure 6). These examples demonstrate that while pathways toward sustainable ports may differ across regions, integrating environmental policies, technological innovation, and collaborative governance can significantly contribute to the development of resilient, low-carbon maritime systems aligned with the principles of the blue economy.

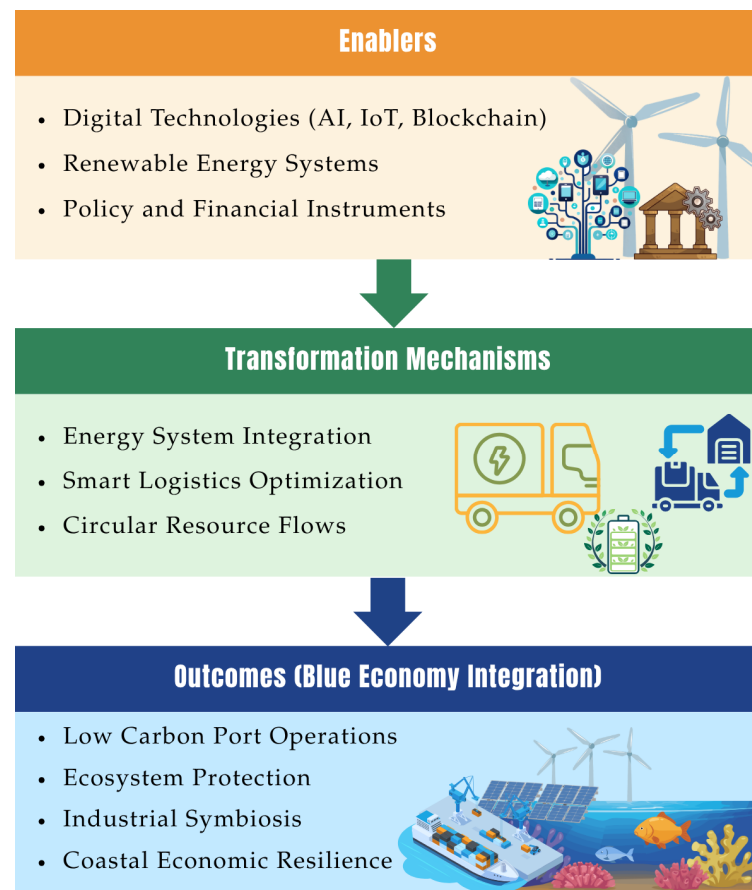


Figure 6. A structured transition pathway linking enabling factors, transformation mechanisms, and sustainability outcomes, illustrating how ports evolve from smart green systems toward integrated blue economy-oriented ecosystems.

8. Challenges and Barriers

Despite the growing adoption of sustainable port initiatives and the increasing integration of green technologies within maritime infrastructure, several structural challenges continue to hinder the widespread implementation of smart green port strategies and their alignment with blue economy objectives (Figure 7).

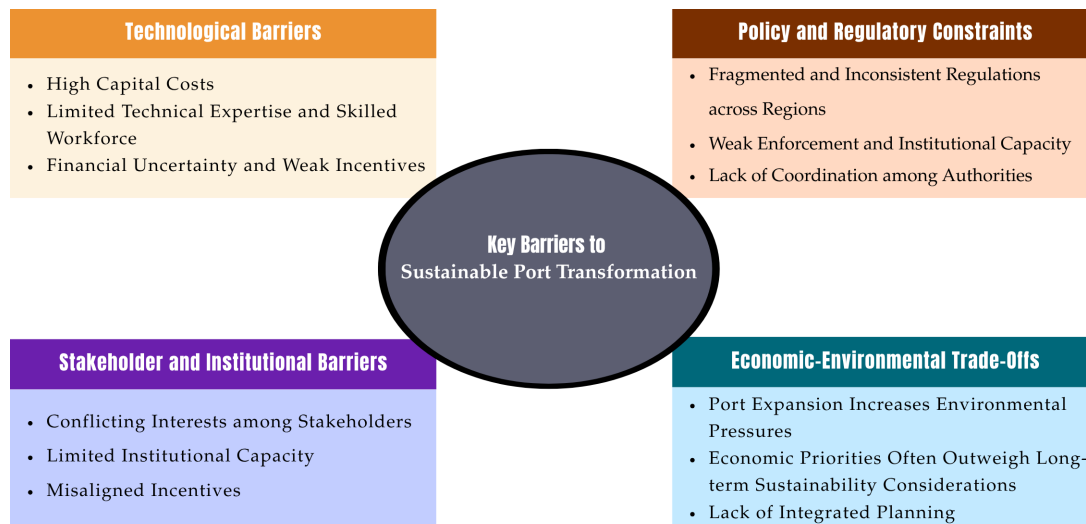


Figure 7. Multi-dimensional constraints affecting sustainable port transitions.

8.1. Technological Gaps and Investment Constraints

One of the most significant barriers to sustainable port development is the technology gap and the high capital costs of green infrastructure. Despite growing global momentum toward sustainable port development, maritime economies in developing regions face a distinct set of structural challenges that limit the pace and scale of transformation [68]. Unlike developed ports, which benefit from advanced infrastructure and strong institutional frameworks, many developing ports operate under financial constraints that limit large-scale investments in low-carbon technologies. Many decarbonization technologies, such as hydrogen-based fuel systems, large-scale integration of renewable energy, port microgrids, and electrified cargo-handling equipment, require substantial financial investment and advanced technical expertise. While developed maritime economies have begun deploying these technologies, many ports in developing regions face financial constraints, limited technical capacity, and uncertainty regarding long-term technological viability [68].

Infrastructure upgrades, such as onshore power supply systems, alternative-fuel bunkering facilities, and digital monitoring platforms, also entail considerable upfront costs [70]. These investments can create financial risks for port authorities and operators, particularly in contexts where regulatory incentives and market demand for green shipping remain uncertain. Technological and human capacity gaps further exacerbate these challenges. The adoption of smart port technologies, digital systems, and renewable energy integration requires not only capital investment but also technical expertise and skilled labor, which may be limited in developing regions. As a result, ports often rely on incremental improvements rather than transformative innovations.

8.2. Policy and Regulatory Inconsistencies

Another major challenge arises from inconsistencies within international and national maritime governance frameworks. Although global initiatives such as the IMO decarbonization strategy and regional environmental policies aim to guide the transition toward sustainable shipping, regulatory standards often vary across countries and regions. Fragmented regulatory frameworks, limited enforcement capacity, and weak coordination among stakeholders often hinder the effective implementation of sustainability policies. In many cases, environmental regulations exist but lack practical enforcement mechanisms, resulting in gaps between policy ambition and on-the-ground outcomes. This discrepancy reflects a broader structural issue in maritime governance, where policy ambition is often not matched by institutional capacity and cross-sectoral integration. As a result, sustain-

ability transitions are frequently slowed not by technological limitations but by governance inefficiencies and regulatory misalignment. This lack of harmonization creates uncertainty for port operators and shipping companies regarding compliance requirements, technology standards, and long-term investment planning [210]. Such uncertainty can discourage large-scale investments in low-carbon infrastructure, as stakeholders face risks associated with shifting regulatory expectations and inconsistent policy signals across jurisdictions. Consequently, ports may adopt short-term or incremental solutions rather than committing to transformative sustainability pathways.

Fragmented governance structures and overlapping responsibilities among maritime, environmental, and energy authorities may further complicate the implementation of coordinated sustainability policies [12,14]. This institutional fragmentation often leads to policy silos, where decarbonization, environmental protection, and digitalization initiatives are developed independently rather than as integrated strategies. The absence of cohesive governance frameworks undermines policy effectiveness and limits the potential for cross-sector synergies. Moreover, the uneven pace of regulatory development between developed and developing maritime economies exacerbates global disparities in port sustainability performance. While some regions implement stringent environmental standards, others struggle with basic regulatory enforcement, creating an uneven playing field and increasing the risk of carbon leakage within global shipping networks.

8.3. Stakeholder Resistance and Institutional Capacity Limitations

Stakeholder resistance and constraints on institutional capacity also influence the transition toward sustainable port systems. Ports operate within complex ecosystems involving multiple actors, including port authorities, terminal operators, shipping companies, logistics providers, government agencies, and local communities [211]. Differences in priorities, economic interests, and levels of environmental commitment can lead to resistance to sustainability initiatives, particularly when such measures are perceived as increasing operational costs or disrupting established business models. This resistance is not merely a matter of reluctance to change but reflects deeper structural tensions between short-term economic performance and long-term sustainability objectives. Stakeholders often prioritize immediate cost efficiency and competitiveness, which can conflict with the upfront investments required for low-carbon technologies and digital transformation. As a result, sustainability initiatives may face delays, partial implementation, or dilution in their effectiveness. In addition, many ports face institutional capacity limitations, including shortages of technical expertise, insufficient training programs, and limited organizational readiness to manage advanced digital systems and environmental monitoring technologies [212]. These capacity gaps are particularly pronounced in developing maritime economies, where limited access to financial resources and skilled labor constrain the adoption of complex technologies such as smart port systems, AI-driven logistics, and integrated energy infrastructure.

Furthermore, the lack of institutional readiness often results in fragmented or inefficient implementation of sustainability measures, even when policies and technologies are available. Without adequate training, knowledge transfer, and organizational restructuring, ports may struggle to operationalize sustainability strategies effectively [211]. Another critical challenge lies in the misalignment of incentives among stakeholders. While port authorities may pursue long-term sustainability goals, private operators and shipping companies may be driven by profit maximization and regulatory compliance rather than proactive environmental innovation. This divergence can hinder collaborative action and reduce the overall effectiveness of sustainability initiatives.

8.4. Trade-Offs Between Economic Growth and Sustainability

A further challenge lies in balancing economic growth with environmental sustainability. Ports serve as critical engines of economic development, facilitating international trade, industrial activity, and job creation [213]. However, expanding port infrastructure and increasing maritime traffic may intensify environmental pressures, including air emissions, marine pollution, habitat degradation, and disturbances to coastal ecosystems [178]. This tension reflects a fundamental structural dilemma in port development, where economic expansion is often directly linked to increased environmental externalities. As ports scale up operations to remain globally competitive, sustainability measures may be deprioritized or implemented only to meet minimum regulatory requirements, rather than as integral components of long-term strategic planning.

Balancing these competing priorities requires integrated planning approaches that simultaneously consider economic efficiency, environmental protection, and social well-being. However, in practice, these dimensions are often addressed in isolation, leading to fragmented decision-making that fails to capture system-wide trade-offs and synergies [132]. This lack of integration can lead to unintended consequences, such as shifting environmental burdens across regions or sectors rather than achieving net sustainability gains. Sustainable port development, therefore, depends on governance frameworks that can manage these trade-offs while promoting long-term resilience in maritime systems. In this context, the concept of sustainable competitiveness becomes increasingly relevant, emphasizing that long-term economic performance is inherently dependent on environmental stewardship and social acceptance. Ports that fail to internalize environmental costs may achieve short-term growth but face long-term risks from regulatory pressure, environmental degradation, and a declining social license to operate.

Importantly, these constraints suggest that sustainability transitions in developing maritime economies are more likely to follow phased and adaptive pathways. Initial efforts typically focus on strengthening regulation, digitalization, and cost-effective environmental management practices, followed by the gradual integration of advanced technologies as institutional capacity and financial resources improve. This staged approach reflects the need to balance immediate economic priorities with progressive sustainability goals, allowing ports to incrementally align growth trajectories with environmental and social considerations.

9. Opportunities and Future Directions

Despite the challenges associated with transitioning to sustainable port systems, significant opportunities are emerging to accelerate the transformation of ports into key enablers of the blue economy. Advances in digital technologies, circular resource management, and integrated coastal development strategies provide promising pathways to improve environmental performance while maintaining economic competitiveness within the maritime sector, as summarized in Table 9 and discussed further below.

Table 9. Key opportunities and future research directions in sustainable port development.

Opportunity Area	Emerging Solutions	Potential Benefits
Digitalization	AI-based logistics optimization, blockchain documentation systems [103,207]	Improved efficiency and transparency
Renewable energy systems	Hybrid solar–wind–tidal energy systems [64,67,214]	Reduced carbon footprint
Circular economy	Industrial symbiosis, waste heat recovery, material recycling [154,215,216]	Resource efficiency

Table 9. Cont.

Opportunity Area	Emerging Solutions	Potential Benefits
Blue economy clusters	Offshore wind hubs, aquaculture logistics platforms [217]	Regional economic diversification
Net-zero infrastructure	Hydrogen bunkering, electrified port equipment [77,218]	Decarbonized maritime transport

9.1. Emerging Digital and Energy Technologies

One of the most important opportunities lies in advancing emerging digital and energy technologies, including AI, blockchain, and hybrid renewable energy systems [103,207]. AI-driven analytics can enhance port efficiency by optimizing vessel scheduling, cargo handling operations, and energy management, thereby reducing operational delays and associated emissions. Blockchain technology has also gained increasing attention for its potential to improve transparency, traceability, and security within maritime logistics networks, particularly in areas such as cargo documentation, emissions monitoring, and supply chain verification.

Beyond operational improvements, these technologies represent a broader shift toward data-driven and decentralized port systems, in which real-time information flows enable more adaptive, efficient, and transparent decision-making [207]. However, their effectiveness depends on integrating digital infrastructure among stakeholders, as fragmented data systems and a lack of interoperability can limit the full potential of digital transformation. Moreover, the adoption of advanced digital technologies introduces new challenges, including cybersecurity risks, high implementation costs, and the need for standardized data governance frameworks [103]. Without addressing these issues, digitalization may create new vulnerabilities while attempting to solve existing inefficiencies.

In parallel, hybrid renewable energy systems that combine solar, wind, tidal, and energy storage technologies offer ports the potential to develop resilient, low-carbon energy infrastructure [67]. These systems can support electrified port operations, alternative-fuel production, and distributed energy management in port environments. Importantly, the integration of such energy systems positions ports as emerging energy hubs within the blue economy, facilitating the coupling of maritime transport with broader renewable energy networks [214]. This transition enables ports not only to reduce their own carbon footprint but also to support the decarbonization of shipping and adjacent industrial sectors. However, the deployment of hybrid energy systems requires substantial capital investment, long-term planning, and supportive regulatory frameworks. In many cases, economic feasibility and grid integration challenges remain key barriers, particularly in developing regions [64]. Therefore, realizing this opportunity depends on coordinated policy support, public-private partnerships, and scalable implementation models.

9.2. Circular Economy in Port Ecosystems

Another promising opportunity involves integrating circular economy principles into port ecosystems. Ports can function as hubs for industrial symbiosis, where waste streams, energy flows, and by-products generated by port-related industries are reused or repurposed across interconnected sectors. For example, waste heat recovery, wastewater reuse, and material recycling within port clusters can reduce resource consumption while creating additional economic value [154,215,216]. Circular economy practices may also extend to ship recycling, sustainable construction materials for port infrastructure, and the recovery of valuable resources from maritime waste streams [219]. Such approaches

can significantly enhance resource efficiency and reduce environmental impacts across port operations.

Beyond resource efficiency, the circular economy reframes ports as integrated metabolic systems in which material and energy flows are continuously optimized across industrial networks. This systemic perspective highlights the potential of ports to act as catalysts for regional circularity, linking maritime activities with adjacent industrial clusters and urban systems. However, the implementation of circular economy practices in ports faces several structural barriers. These include the lack of coordination among stakeholders, insufficient infrastructure for waste collection and processing, and limited regulatory incentives to promote resource recovery and reuse [154,215]. In many cases, circular initiatives remain fragmented and project-based rather than being embedded within comprehensive port strategies.

Economic feasibility also represents a key challenge, as the initial investment required for circular infrastructure and technologies may not always be offset by immediate financial returns [154,216]. This is particularly relevant in developing maritime economies, where competing priorities often favor short-term economic gains over long-term resource efficiency. Furthermore, the success of industrial symbiosis depends on strong governance frameworks and data-sharing mechanisms that enable collaboration among diverse stakeholders. Without transparent information flows and coordinated planning, opportunities for resource optimization may remain underutilized. Therefore, advancing circular economy practices in port ecosystems requires integrated policy support, cross-sectoral collaboration, and the development of enabling infrastructure. By aligning economic incentives with environmental objectives, ports can transition from linear resource-consumption models to regenerative systems that support long-term sustainability within the blue economy framework.

9.3. Integration of Ports into Blue Economy Clusters

The integration of ports into broader blue economy clusters represents another key opportunity for sustainable coastal development. Ports can serve as strategic nodes that support interconnected maritime sectors such as fisheries, aquaculture, coastal tourism, and offshore renewable energy. Through infrastructure sharing, logistics support, and innovation platforms, ports can strengthen regional maritime economies while promoting sustainable ocean resource management. For example, ports may serve as service hubs for offshore wind farms, logistics centers for sustainable aquaculture supply chains, or innovation platforms supporting the marine biotechnology industry [217]. These integrated development models enhance economic diversification while reinforcing environmental stewardship in coastal regions.

Beyond their logistical role, ports can act as coordinating platforms that facilitate cross-sectoral integration and value chain optimization within the blue economy [35]. This expanded role requires ports to move from isolated operational entities toward ecosystem orchestrators that align economic activities with environmental and social objectives. However, the realization of blue economy clusters is highly dependent on governance capacity and the integration of spatial planning. In many cases, sectoral fragmentation and competing interests among maritime industries hinder effective coordination, limiting the potential for cross-sector synergies. Without integrated coastal and marine spatial planning frameworks, port-led cluster development may lead to resource conflicts, environmental pressures, or inefficient allocation of maritime space. In addition, the benefits of such integration are not evenly distributed, particularly in developing coastal regions where institutional capacity, infrastructure availability, and investment readiness remain limited.

This may result in unequal participation in blue economy opportunities, reinforcing existing regional disparities.

The success of port-based blue economy clusters, therefore, depends on multi-level governance, stakeholder alignment, and long-term strategic planning. Collaborative platforms that integrate public authorities, private-sector actors, and research institutions are essential for fostering innovation, managing trade-offs, and ensuring sustainable resource use.

9.4. Pathways Toward Net-Zero Ports

Achieving net-zero port operations is increasingly recognized as a strategic objective that will shape the future of maritime infrastructure. Pathways toward net-zero ports typically involve a combination of electrification, adoption of alternative fuels, integration of renewable energy, and energy efficiency improvements across port operations [77,218]. Measures such as onshore power supply systems, zero-emission cargo-handling equipment, green hydrogen production, and smart energy management platforms can significantly reduce greenhouse gas emissions in port environments. In addition, digital monitoring tools and carbon accounting systems can support evidence-based decision-making and facilitate compliance with evolving international climate targets. However, the transition toward net-zero ports is not merely a technological challenge but a systemic transformation that requires alignment among infrastructure, energy systems, regulatory frameworks, and market dynamics [64,67,214]. The scalability of these solutions depends on the availability of supporting energy infrastructure, such as grid capacity, hydrogen supply chains, and energy storage systems, which remain unevenly developed across regions.

Economic feasibility is also a critical constraint, as many low-carbon technologies entail high upfront investment costs and uncertain payback periods [153]. This creates financial risks for port authorities and private operators, particularly in the absence of stable policy incentives or carbon pricing mechanisms. As a result, the pace of transition may vary significantly across ports, reinforcing disparities between developed and developing maritime economies. Moreover, achieving net-zero targets requires coordinated action across the entire maritime value chain, including shipping companies, logistics providers, and energy suppliers. Without such alignment, emissions reductions at the port level may be offset by inefficiencies or emissions elsewhere in the transport system, limiting overall impact.

Looking forward, the successful realization of these opportunities will depend on coordinated policy frameworks, long-term investment strategies, and multi-stakeholder collaboration across the maritime sector. By integrating technological innovation, circular resource management, and ecosystem-based planning, ports can evolve from traditional logistics hubs into dynamic centers of sustainable maritime development, playing a critical role in advancing the global transition to a resilient, low-carbon blue economy.

10. Limitations of the Study

Despite the comprehensive approach adopted in this review, several limitations should be acknowledged. First, although a systematic literature search strategy was employed, the selection of studies inherently involves some subjectivity, particularly during the screening and eligibility stages. Decisions regarding relevance, inclusion criteria, and thematic focus may introduce selection bias, which could influence the representation of specific research areas.

Second, the review primarily relies on publications indexed in the major academic database SCOPUS, supplemented by Google Scholar and official institutional websites.

While this approach ensures broad coverage, it may not capture all relevant studies, particularly those published in non-indexed journals or regional databases.

Third, the inclusion of recent publications (2025–2026) and website sources, such as policy reports and official port authority documents, may introduce variability in methodological rigor and peer-review standards. However, these sources were included to reflect the rapidly evolving nature of port sustainability and maritime policy developments.

Finally, the qualitative nature of this review limits the ability to provide quantitative comparisons or meta-analytical conclusions regarding the effectiveness of specific technologies or policy interventions. Future research could address this limitation by incorporating bibliometric analysis or quantitative meta-analysis to further validate emerging trends. Despite these limitations, this review provides a comprehensive and up-to-date synthesis of current knowledge, offering valuable insights into the transition toward sustainable port systems within the blue economy framework.

11. Conclusions

This review examines the evolving role of ports in advancing sustainable maritime infrastructure and supporting the transition from traditional green port concepts toward a broader blue economy framework. The analysis highlights that ports are no longer viewed solely as logistics nodes but increasingly function as strategic platforms for integrating environmental sustainability, technological innovation, and socio-economic development within global maritime systems.

One of the key findings of this review is that the transformation of ports toward sustainability is driven by the convergence of multiple dimensions, including the integration of renewable energy, alternative-fuel infrastructure, digitalization through smart-port technologies, and green logistics optimization. The adoption of technologies such as onshore power supply systems, port electrification, hydrogen and LNG infrastructure, and renewable energy microgrids has demonstrated significant potential to reduce greenhouse gas emissions and improve energy efficiency in port operations. In parallel, the implementation of artificial intelligence, IoT, and data-driven management systems has enhanced operational efficiency, enabling ports to optimize resource allocation and reduce environmental impacts. Moreover, the integration of environmental management strategies, including marine pollution mitigation, biodiversity conservation, and ecosystem protection, reinforces the role of ports as key actors in sustainable ocean governance. Social dimensions, particularly community engagement and corporate social responsibility initiatives, also play a critical role in strengthening the social license to operate and ensuring that port development benefits surrounding communities.

Based on these findings, several policy and practice recommendations can be identified. First, governments and port authorities should strengthen policy integration across maritime, environmental, and energy sectors to create coherent regulatory frameworks that support sustainable port development. Second, increased investment in renewable energy infrastructure, alternative fuel systems, and digital port technologies is essential to accelerate the decarbonization of port operations. Third, collaboration among stakeholders, including port authorities, shipping companies, energy providers, research institutions, and local communities, should be enhanced through public–private partnerships and multi-stakeholder governance mechanisms. In addition, adopting circular economy principles in port ecosystems can improve resource efficiency, reduce environmental externalities, and create new economic opportunities.

Despite significant progress, several research gaps and future perspectives remain. Further studies are needed to evaluate the long-term economic feasibility and environmental performance of emerging decarbonization technologies, including hydrogen-based

fuels, hybrid renewable energy systems, and large-scale port electrification. In addition, more research is required to understand how digital technologies such as artificial intelligence, blockchain, and digital twins can be effectively integrated into port governance and logistics systems. Comparative studies across different regional contexts, particularly in developing economies, are also necessary to identify adaptable sustainability strategies that account for variations in institutional capacity, technological readiness, and financial resources. Furthermore, future research should explore integrated approaches that link port development with broader blue economy sectors, including fisheries, aquaculture, offshore renewable energy, and coastal tourism.

In conclusion, achieving sustainable and resilient maritime systems requires a holistic approach that integrates technological innovation, environmental stewardship, and inclusive governance. By embracing these principles, ports can evolve into key catalysts for the blue economy, supporting low-carbon maritime transport, protecting marine ecosystems, and fostering sustainable economic growth in coastal regions.

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