Print ISSN: 1738-3110 / Online ISSN 2093-7717
JDS website: http://accesson.kr/jds
http://doi.org/10.15722/jds.24.02.202602.109

The Future of Port Logistics: Evaluating Integrated Smart-Energy Solutions for Yeosu Port's Sustainability

Min Jung KANG[1], **Seonok PARK**[2]

Received: January 15, 2026. Revised: January 25, 2026. Accepted: February 05, 2026.

Abstract

Purpose: This research evaluates how Yeosu–Gwangyang Port (YGPA) integrates smart automation with energy self-sufficiency to establish a scalable sustainability model for maritime hubs, advancing a unified paradigm that aligns technological modernization with environmental imperatives **Research design, data, and methodology:** Using a diagnostic case study approach, the paper examines the port's infrastructure transition based on multi-source data, including internal performance metrics, national policy directives, and real-time operational datasets on renewable energy generation and terminal throughput. **Results:** The findings show that the convergence of terminal automation and localized renewable energy production yields a synergistic effect. Systematic carbon monitoring combined with on-site energy generation reduces the port's environmental footprint and buffers it against energy price volatility. Digitalized energy-management systems further enhance operational resilience while supporting long-term decarbonization pathways. **Conclusions:** Sustainable port management requires a "techno-ecological" framework that bridges climate action and high-tech infrastructure. By integrating automation, renewable energy deployment, and structured carbon management, the Yeosu model provides actionable insights for ports seeking to strengthen energy resilience, environmental performance, and competitive positioning. Overall, long-term maritime competitiveness necessitates the holistic integration of smart logistics and sustainable energy systems.

Keywords: Smart Automated Port; Energy Self-sufficient Port; Carbon-neutral port; Sustainable Port Development; Digital Transformation; Renewable Energy; Yeosu-Gwangyang Port

JEL Classification Code: M10 M30 M31 M15 M39

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1. Introduction

Global port industries are undergoing a profound transformation shaped by three reinforcing megatrends: rapid digitalization, structural energy transition, and the worldwide movement toward carbon neutrality. These shifts are driven by escalating climate-related disruptions, heightened volatility in global energy markets, increasing operational costs, and progressively stringent environmental regulations imposed by international institutions such as the IMO(International Maritime Organization) and the UNFCCC(United Nations Framework Convention on Climate Change) (United Nations, n.d.). As pivotal nodes in global supply chains, ports handle vast flows of goods and

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1 First Author. Professor, Department of Business Administration, Mokpo National University, Muan, South Korea.
Email: 7minjeong@hanmail.net
2 Second and Corresponding Author. Second Author. Postdoctoral Researcher, Jeonbuk National University, South Korea.
Email: solikek@hanmail.net

energy-intensive operations, positioning them as both major contributors to environmental pressures and essential actors in shaping decarbonized maritime futures (European Sea Ports Organisation[ESPO], 2025).

Consequently, ports are no longer viewed primarily as physical logistics hubs but as strategic infrastructures that must integrate digital intelligence, energy resilience, and low-carbon systems. Within this evolving paradigm, three conceptual frameworks—smart automated ports, energy self-sufficient ports, and carbon-neutral ports—have emerged as cornerstone strategies for enhancing port competitiveness, resilience, and sustainability. Smart automated ports employ next-generation technologies such as AI, IoT, autonomous systems, and digital twins to enhance operational accuracy, reduce human error, and ensure real-time adaptive decision-making. Energy self-sufficient ports seek to minimize external energy dependency by producing, storing, and managing their own renewable energy, thus strengthening operational reliability and contributing to long-term energy security. Meanwhile, carbon-neutral ports pursue comprehensive reductions in greenhouse gas emissions across all operational scopes, aligning port systems with global Net Zero trajectories (Intergovernmental Panel on Climate Change[IPCC], 2022).

Importantly, these three paradigms operate not in isolation but as interdependent pillars of sustainable port transformation. Automation enhances energy efficiency; renewable generation supports decarbonized equipment and operations; and carbon neutrality frameworks reinforce ports' transitions toward intelligent, energy-efficient infrastructure (World Economic Forum, 2020).

The efficacy of these digital interventions in achieving genuine sustainability is further elucidated by Bjerkan and Seter (2021), who propose a comprehensive typology of twenty-six distinct tools and technologies across management, energy, and operational domains. Their analysis underscores a critical knowledge-practice gap, noting that while technologies such as shore-side electricity (cold ironing) are extensively discussed in literature, there remains an insufficient empirical foundation to guide port authorities in prioritizing these investments. This suggests that the transition toward a sustainable maritime node is contingent not merely on the presence of advanced hardware, but on the ability of decision-makers to utilize empirical data to bridge the divide between technological potential and operational reality. Consequently, by focusing on a concrete, data-driven case study of a major industrial-support hub, this research seeks to provide the empirical grounding that Bjerkan and Seter (2019) identify as vital for moving beyond conceptual models toward actionable, climate-resilient port governance.

A significant evolution in maritime management theory has seen the focus shift from treating port digitalization and decarbonization as separate trajectories to a more integrated 'Twin Transition' approach. Under this new perspective, intelligent technologies are no longer viewed merely as efficiency tools, but as the primary catalyst for operationalizing environmental mandates. While earlier research often examined terminal automation and sustainable energy systems in isolation, the practical convergence of Cyber-Physical Systems (CPS) and Digital Twin (DT) technology has fundamentally redefined carbon-neutral operations. These advanced frameworks empower port authorities to perform predictive energy load optimization and track carbon footprints in real-time—a crucial capability for aligning regional port operations with global net-zero ambitions.

The conceptual architecture of the proposed "Twin Transition" is visualized in Figure 1, illustrating the fundamental shift from viewing digitalization and decarbonization as parallel trajectories to treating them as a singular, integrated mandate. Rather than operating in silos, the three pillars—smart automation, energy self-sufficiency, and carbon neutrality—function as mutually reinforcing elements of a techno-ecological governance model. As depicted in the framework, advanced Cyber-Physical Systems (CPS) and Digital Twin (DT) technologies act as the primary catalysts, operationalizing environmental mandates by enabling real-time predictive optimization of energy loads and carbon footprints. This integrative visualization highlights how localized energy production is synchronized with automated cargo handling, effectively bridging the empirical gap between conceptual sustainability models and the operational realities of regional industrial-support hubs like Yeosu-Gwangyang Port. Unlike conventional port digitalization frameworks that prioritize operational efficiency in isolation, the proposed Twin Transition model conceptualizes digital intelligence as the primary governance infrastructure for climate action, thereby repositioning automation not as an auxiliary tool but as the central coordinating mechanism for energy resilience and carbon neutrality.

However, a significant research gap persists: most existing models are based on European or North American 'Landlord' port structures, leaving a deficit in empirical frameworks for Asian Public or Hybrid port models that are rapidly integrating smart-green infrastructures (Notteboom et al., 2021). Furthermore, the strategic alignment between localized energy production (Energy Self-sufficiency) and automated cargo handling has not been fully operationalized in the context of regional logistics hubs. By examining the Yeosu–Gwangyang Port, this study addresses this gap, providing a unique case of how a major industrial-support port can synchronize its energy-intensive operations with digital-green mandates.

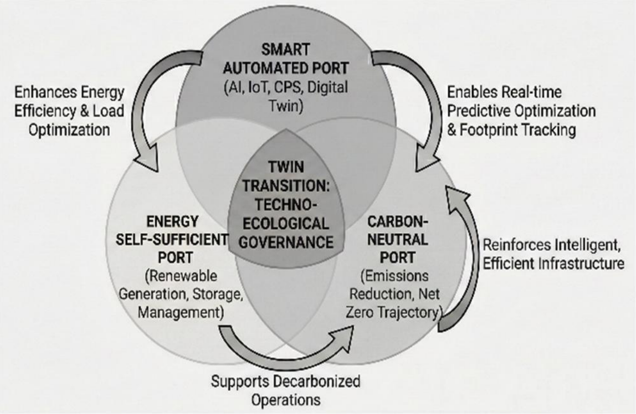


Figure 1: Integrated Framework for the Twin Transition in Port Management: Synchronizing Digital Intelligence with Energy Resilience.

2. Literature Review

2.1. Smart Automated Ports

Smart automated ports are characterized by their ability to generate measurable performance gains across operational, safety, environmental, and economic dimensions through the deployment of digitally orchestrated technologies. Empirical evidence synthesized in Table 1 indicates that the automation of key cargo-handling systems—such as automated guided vehicles (AGVs), automated stacking cranes (ASCs), and remotely operated quay cranes—can raise terminal productivity by approximately 30–50%, primarily by stabilizing workflows and minimizing operational variability (World Economic Forum [WEF], 2020). These efficiency gains are further reinforced by real-time optimization of berth allocation and yard utilization, which enables continuous 24/7 operations under standardized performance conditions.

A defining feature of smart automated ports is the automation of major cargo-handling equipment. Studies further report that AGVs, ASCs, and remotely operated quay cranes substantially reduce human error by over 70% and lower workplace accidents by up to 90%, reinforcing the safety gains associated with automation (WEF, 2020). Such improvements stem from automation's ability to eliminate operational variability, stabilize workflow, and enable continuous operations under standardized performance conditions.

The multidimensional performance impacts associated with smart automated port technologies are summarized in Table 1.

Table 1: Expected Operational and Environmental Benefits of Smart Automated Port Technologies

Category	Indicator	Expected Benefit
Operational Efficiency	Terminal Productivity	Increase by 30–50%
	Berth and yard utilization	Improved through real-time optimization
	24/7 Continuous Operations	Enabled under standardized conditions
Safety & Reliability	Human error	Reduction by over 70%
	Workplace Accidents	Reduction by up to 90%
	Equipment failure incidents	Significant decrease via predictive maintenance
Environmental Performance	CO_2 emissions	Reduction by approximately 20–30%
	Energy consumption per move	Reduction through workflow optimization
Economic Benefits	Equipment maintenance costs	Reduction by approximately 15%
	Equipment Lifespan	Extension by approximately 25%
	Labor cost volatility	Stabilized through automation

Source: WEF (2020), IMO (2023)

Table 1 further indicates that the impacts of smart automation extend beyond productivity gains by revealing structural efficiency mechanisms embedded in automated port systems. Rather than functioning solely as throughput enhancers, these technologies operate as systemic enablers that synchronize operational stability, emissions performance, and asset lifecycle optimization within a single techno-operational architecture.

Integrated digital operation platforms constitute another core component of smart automated ports. IoT-powered monitoring systems capture real-time operational data—such as equipment performance, cargo status, traffic flow, and vessel movements—which are analyzed by AI-driven algorithms to optimize berth allocation, yard planning, and cargo sequencing. Digital twins provide dynamic, data-synchronized virtual replicas of port environments, enabling scenario-based simulations that support risk mitigation, congestion management, and resource optimization. These systems enhance operational resilience by allowing ports to preemptively adjust workflows in response to disruptions such as extreme weather, equipment failure, or surges in cargo volume.

Furthermore, smart automated ports incorporate advanced safety and environmental management mechanisms. Automated hazard detection systems, AI-based collision-prevention tools, and continuous air-quality monitoring improve the port's capability to manage operational risks while minimizing environmental impacts. Research indicates that ports implementing smart automated environmental systems can achieve 20–30% reductions in CO_2 emissions, 15% reductions in equipment maintenance costs, and 25% extensions in equipment lifespan (International Maritime Organization [IMO], 2023).

Collectively, these developments position smart automated ports as a transformative model that integrates operational efficiency, worker safety, environmental performance, and technological innovation into a cohesive competitive strategy. The increasing complexity of automated port ecosystems further necessitates a higher level of digital trust among diverse stakeholders. The integration of blockchain technology into port community systems (PCS) provides an immutable ledger for tracking cargo status and automated service contracts. This transparency reduces the administrative burden of manual documentation and mitigates the risks associated with data tampering, thereby enhancing the overall reliability and appeal of the port as a secure node in the global supply chain (Carlan et al., 2017).

2.2. Energy Self-Sufficient Ports

Energy self-sufficient ports refer to ports that secure stable and sustainable operations by producing and managing the energy required for port activities independently, minimizing reliance on external power grids. This concept extends beyond simple energy savings or cost efficiency and is increasingly understood as a strategic infrastructure transition responding to climate change and global energy supply instability (United Nations, n.d.). Due to their large-scale energy demand and extensive spatial resources, ports are regarded as ideal testbeds for implementing and scaling energy self-sufficiency strategies (European Sea Ports Organisation [ESPO], 2025).

At the international level, the concept of energy self-sufficient ports is closely aligned with the United Nations Sustainable Development Goal (SDG) 7. SDG 7 aims to ensure universal access to affordable and reliable energy, increase the share of renewable energy, and improve energy efficiency. Energy-intensive infrastructures such as ports are considered key implementation actors in achieving these objectives (United Nations, n.d.). In particular, renewable energy-based self-generation systems and advanced energy management frameworks are emphasized as critical measures for enhancing the long-term resilience of port operations (World Economic Forum, 2020).

Previous studies identify three core components in the development of energy self-sufficient ports. First, improving energy efficiency in port buildings and facilities is a foundational step. Aging port infrastructure typically exhibits high levels of energy loss, and efficiency measures such as high-performance lighting, HVAC systems, and improved insulation significantly reduce baseline energy demand (Yeosu Gwangyang Port Authority[YGPA], 2025).

Second, the deployment of distributed renewable energy generation systems—most notably solar photovoltaic installations—is essential. Port areas, including parking facilities, warehouses, and terminal rooftops, offer favorable conditions for solar energy deployment, enabling on-site electricity production (ESPO, 2025). In recent years, ports have increasingly moved beyond self-consumption models to generate economic value through the issuance and trading of Renewable Energy Certificates (RECs) (World Port Sustainability Program, n.d.).

Third, the advancement of energy management and demand-side control systems plays a critical role. Smart energy management platforms, incorporating real-time monitoring and demand response mechanisms, help mitigate the intermittency of renewable energy sources and optimize overall energy efficiency across port operations (World Economic Forum, 2020).

In summary, energy self-sufficient ports represent a comprehensive approach that integrates energy efficiency improvements, renewable energy production, and advanced energy management systems. This integrated model strengthens both the environmental sustainability and economic stability of port operations, positioning energy self-sufficiency as a core strategy for future-oriented port development (ESPO, 2025).

The implementation of these technological systems is further validated by a comprehensive taxonomic framework that identifies seven distinct categories and nineteen subcategories of technical and operational interventions (Alamoush et al., 2020). Central to this framework is the role of Information Measures, which necessitate the establishment of rigorous emission inventories and continuous monitoring as the essential baseline for any smart optimization strategy. This research highlights that the drive for energy efficiency and renewable integration is often motivated not only by environmental mandates but also by the critical requirement for energy security. By deploying smart grids and localized generation, ports can ensure an uninterrupted power supply—a prerequisite for 24/7 automated operations—while simultaneously enhancing their license to operate through improved corporate social responsibility (CSR) and green reputation. Ultimately, Alamoush et al. (2020) argue that since no single measure can achieve full decarbonization, the strategic value of a port lies in its ability to identify the most effective combination of portside and ship-port interface measures, such as shore-side electricity and optimized land transport synchronization.

2.3. Carbon-Neutral Ports

Carbon-neutral ports refer to ports that systematically reduce greenhouse gas (GHG) emissions generated throughout port operations and achieve net-zero emissions by removing or offsetting unavoidable residual emissions (UNFCCC, 2024.). The concept of carbon neutrality has become an internationally recognized benchmark for climate change mitigation, and ports—characterized by high energy consumption and concentrated emission sources—are increasingly regarded as critical spaces for implementing decarbonization strategies (United Nations, n.d.).

At the scientific level, the definition of carbon neutrality has been established by the Intergovernmental Panel on Climate Change (IPCC). The IPCC defines net zero as a state in which anthropogenic greenhouse gas emissions are balanced by anthropogenic removals and emphasizes that achieving global net-zero emissions by around 2050 is essential to limit the increase in global mean temperature to 1.5°C above pre-industrial levels (IPCC, 2022). This scientific consensus provides a compelling rationale for structural decarbonization across all industrial sectors, including ports.

In the port sector, the acceleration of carbon-neutral initiatives has been strongly influenced by environmental regulations issued by the International Maritime Organization (IMO). The IMO 2020 sulphur regulation, which limits the sulphur content of marine fuels to 0.5%, has contributed to improved air quality in port areas. Furthermore, the IMO's 2050 Net Zero strategy establishes an institutional framework requiring significant reductions in greenhouse gas emissions across the maritime and port sectors (IMO, 2023). As a result, ports are increasingly expected to function not merely as logistical nodes but as hubs for low-carbon energy supply and emissions management.

Previous studies emphasize that achieving carbon-neutral ports requires comprehensive management of Scope 1, Scope 2, and Scope 3 emissions. Scope 1 includes direct emissions from port-owned equipment and vehicles; Scope 2 encompasses indirect emissions from purchased electricity; and Scope 3 covers emissions generated by vessels at berth, hinterland transportation, and port-related activities conducted by external stakeholders (World Port Sustainability Program, n.d.). Given the multi-actor nature of port environments, effective management of Scope 3 emissions is widely recognized as indispensable for realizing meaningful carbon neutrality in ports (European Sea Ports Organisation [ESPO], 2025).

Accordingly, key strategies for carbon-neutral ports include the deployment of onshore power supply (OPS), electrification of cargo-handling equipment and port vehicles, and expanded use of renewable energy-based electricity. OPS enables vessels at berth to switch from onboard auxiliary engines to shore-based electricity, thereby significantly reducing both local air pollutants and greenhouse gas emissions in port areas (ESPO, 2025). Electrified cargo-handling equipment offers higher energy efficiency than conventional fossil-fuel-based machinery, and when integrated with renewable energy sources, its carbon reduction potential is further amplified (World Economic Forum, 2020).

International case studies, particularly from European ports, indicate a growing trend toward the voluntary adoption of carbon-neutral targets, with system boundaries expanding beyond terminal operations to encompass entire port areas and port communities. ESPO's environmental reports demonstrate the diffusion of integrated carbon management frameworks that incorporate port authorities, terminal operators, shipping lines, and logistics stakeholders (ESPO, 2025).

In addition, the World Port Sustainability Program (WPSP) plays a central role in global port decarbonization governance by facilitating collaboration among ports, standardizing emissions accounting methodologies, sharing mitigation strategies, and accelerating the diffusion of low-carbon technologies (World Port Sustainability Program, n.d.).

In summary, carbon-neutral ports represent a transformative concept that extends beyond technological solutions to encompass institutional arrangements, operational practices, and collaborative governance structures. As such, carbon neutrality is expected to function as a critical benchmark shaping future port competitiveness and sustainability performance (United Nations, n.d.).

The realization of a carbon-neutral port necessitates a departure from isolated technical interventions toward a sophisticated, integrated portfolio approach. Recent systematic evaluations of the maritime literature underscore that the inherent complexity of port ecosystems precludes the efficacy of any singular, 'one-size-fits-all' decarbonization measure. Instead, sustainable transitions are increasingly defined by the strategic combination of four primary pillars: clean energy sources, operational optimizations, advanced energy systems, and conservative measures (Fadiga et al., 2024). This multifaceted framework emphasizes that while individual technological innovations are necessary, their impact is maximized only when synchronized through robust regulatory frameworks and active stakeholder collaboration (Alamoush A.S. et al., 2020).

Furthermore, cluster analysis within the scholarly discourse identifies three critical research domains—energy systems, emissions management, and clean energy sources—which must be orchestrated in tandem to facilitate a viable decarbonization roadmap. The current lack of clarity on how to effectively combine these diverse measures represents a significant research gap that modern port authorities must address. Consequently, the transition toward a carbon-neutral state is not merely a technical challenge but a process of building 'techno-institutional' synergy, where digitized emissions tracking and energy-efficient operations are supported by a unified governance structure. By adopting this integrated path, ports can evolve from energy-intensive logistical nodes into sustainable maritime hubs that are resilient to the escalating pressures of global climate mandates collaboration (Alamoush A.S. et al., 2020).

3. Case Study: Yeosu–Gwangyang Port

3.1. Smart Automated Port in Yeosu Port

The automation of Yeosu–Gwangyang Port (YGPA) is being operationalized under the strategic umbrella of the 'K-Smart Port' initiative, a core component of the South Korean Ministry of Oceans and Fisheries' (MOF) 4th Basic Port Plan (2021–2030). Central to this vision is the Gwangyang Port Phase 3-2 Container Terminal project, which serves as the nation's primary testbed for a Total Automated Terminal. This policy-driven mandate seeks to transition the port from traditional labor-intensive operations to a digitally orchestrated ecosystem. By establishing a fully automated workflow-encompassing ship-to-shore, horizontal transport, and yard stacking-YGPA is establishing an empirical model for port modernization that aligns with the technical measures identified in global maritime literature (MOF, 2024; Alamoush et al., 2020).

A distinguishing feature of YGPA's smart strategy is its emphasis on the localization of core automated hardware. The Phase 3-2 project involves a significant investment to deploy domestically developed Automated Guided Vehicles (AGVs), Automated Stacking Cranes (ASCs), and remotely operated Quay Cranes (QCs). Current development reports indicate a localization target of over 90% for these key components, aimed at securing technological sovereignty and reducing reliance on foreign proprietary systems. This focus on indigenous technology development not only optimizes terminal productivity—projected to increase by over 30% compared to conventional berths—but also creates a synergistic effect with regional industrial clusters, reinforcing the port's role as a resilient node in the global supply chain (YGPA Operational Report, 2025; Tijan et al., 2021).

Furthermore, the intelligence of YGPA's automated framework is underpinned by the implementation of a Digital Twin-based Port Integrated Control System. This platform utilizes IoT sensor networks and AI-driven algorithms to create a high-fidelity virtual replica of terminal operations, enabling real-time predictive optimization of berth allocation and yard planning. Research within the Korean maritime academic community highlights that this digital orchestration is critical for mitigating operational variability and enhancing safety-targeting a 90% reduction in workplace accidents through AI-based collision prevention and hazard detection. This 'Information-led Automation' framework allows YGPA to achieve superior end-to-end visibility, effectively bridging the gap between port-side operations and hinterland logistics (MOF, 2024; Tijan et al., 2021).

The Yeosu-Gwangyang Port Authority (YGPA) is strategically focusing its resources on the advancement of state-of-the-art smart port infrastructure, aiming to establish and operate a world-leading, Korean-model smart port system. Central to this initiative is the Gwangyang Port Automated Terminal (Port Testbed) construction project, which gained significant momentum following the commencement of infrastructure works in 2023. By 2024, the project advanced to the design and construction phases for superstructure facilities, including architectural, electrical, and telecommunication systems. Concurrently, YGPA is pursuing comprehensive smartification across its infrastructure and operational systems. This includes the intelligentization of port safety management through the adoption of technologies such as drones, IoT-based smart safety equipment, and AI-driven video analytics.

Ultimately, the smart automation at Yeosu–Gwangyang Port represents a strategic move toward building techno-institutional resilience. Beyond internal efficiency gains, the adoption of automated infrastructure is a proactive response to escalating global competition and the need for standardized, high-performance logistics services. By integrating domestic hardware innovation with advanced digital control systems, YGPA is not merely adopting technology; it is redefining the port as a smart logistics hub that can preemptively adapt to market fluctuations and international environmental mandates. This integrated model provides a unique competitive advantage, positioning YGPA as a leading example of how legacy industrial ports can successfully navigate the complexities of the global digital transition (Fadiga et al., 2024; YGPA, 2025).

3.2. Energy Self-Sufficient Port: Yeosu–Gwangyang Port

Yeosu–Gwangyang Port is widely regarded as one of the leading domestic examples of a systematically implemented energy self-sufficient port. The Yeosu Gwangyang Port Authority (YGPA) established a strategic objective to produce and manage the energy required for port operations independently, thereby reducing reliance on external power grids, and developed a phased implementation strategy to achieve this goal (YGPA, 2025). This approach can be interpreted not only as a cost-reduction measure but also as a port-level energy security strategy aimed at mitigating risks associated with volatility in global energy markets

(World Economic Forum, 2020).

As a foundational step toward energy self-sufficiency, Yeosu–Gwangyang Port prioritized improvements in energy efficiency across port buildings. Aging port offices and operational facilities were comprehensively renovated through the installation of high-efficiency equipment and energy-saving retrofits, resulting in the acquisition of green building certification and a substantial reduction in annual electricity consumption (YGPA, 2025). Building-centered efficiency improvements are particularly effective as an initial strategy, as they generate visible and measurable outcomes within a relatively short time frame (United Nations, n.d.).

In parallel, the port pursued large-scale efficiency enhancements in port-wide facilities and infrastructure. Lighting systems throughout the port area were fully converted to LED technology, and high-efficiency, top-grade HVAC systems were introduced to fundamentally restructure the port's energy consumption profile (YGPA, 2025). These measures significantly reduced baseline energy demand and created favorable conditions for expanding the share of renewable energy in the overall energy mix (European Sea Ports Organisation [ESPO], 2025).

To assess the potential impact of integrated smart-energy solutions, it is imperative to first establish a quantitative baseline of Yeosu-Gwangyang Port's (YGPA) current environmental performance. An empirical analysis of YGPA's operational data highlights its energy consumption structure and carbon emission trajectory amidst growing reduction pressures. The empirical data covering the period from 2022 to 2024 illustrates distinct positive trends in resource efficiency and energy transition across different operational boundaries of the port authority. As detailed in Table 2, energy consumption within the office building infrastructure shows a clear downward trajectory; total usage decreased by approximately 29% by 2024 compared to 2022 levels, driven primarily by significant reductions in electricity demand. Concurrently, broader operational zones—including container terminals and the hinterland—demonstrated a robust shift toward sustainable energy sources amidst growing overall electricity demand. The renewable energy usage ratio improved substantially, rising from 57% in 2022 to reach 70% in 2024, indicating that renewable supply is scaling effectively to meet operational needs. Furthermore, resource management efforts at container terminals yielded tangible results in water conservation, with municipal water usage recording a notable drop after 2022 and stabilizing at lower levels. To enhance data reliability, all operational and environmental indicators reported by YGPA were cross-validated against national port energy statistics and annual disclosure formats mandated by the Ministry of Oceans and Fisheries (MOF, 2024). In addition, year-on-year trend consistency was verified to exclude anomalous fluctuations unrelated to policy or infrastructure interventions.

Table 2: Key Environmental Performance Indicators of Yeosu-Gwangyang Port (2022-2024)

Category	Indicator	Unit	2022	2023	2024
GHG Emissions (Office Building)	Total Emissions (Scope 1+2)	tCO_2eq	**533**	**494**	**382.326**
	Scope 1 (Direct Emissions)	tCO_2eq	**125**	**108.5**	**117.09**
	Scope 2 (Indirect Emissions)	tCO_2eq	**408**	**385.5**	**265.236**
Energy Usage (Office Building)	Electricity	TJ	**8.536**	**8.056**	**5.556**
	City Gas (LNG)	TJ	**0.207**	**0.115**	**0.082**
	Gasoline	TJ	**0.207**	**0.115**	**0.082**
	Gas/Diesel	TJ	**0.064**	**0.061**	**0.106**
	Total	TJ	**10.913**	**10.113**	**7.776**
Renewable Energy*	Electricity Consumption	GWh	**68**	**68.1**	**73.7**
	Renewable Energy Consumption	GWh	**38.5**	**44.3**	**51.6**
	Renewable Energy Usage Ratio**	%	**57**	**65**	**70**
Water Usage***	Municipal Water Usage	Ton	**8,196**	**6,597**	**6,689**

* Scope selected covers World Marine Center, Container Terminals, and Hinterland.

** Renewable Energy Usage Ratio : Renewable Energy Production relative to Electricity Consumption.

*** Calculated based on municipal water usage at Container Terminals.

Source: Yeosu Gwangyang Port Authority [YGPA](2025).

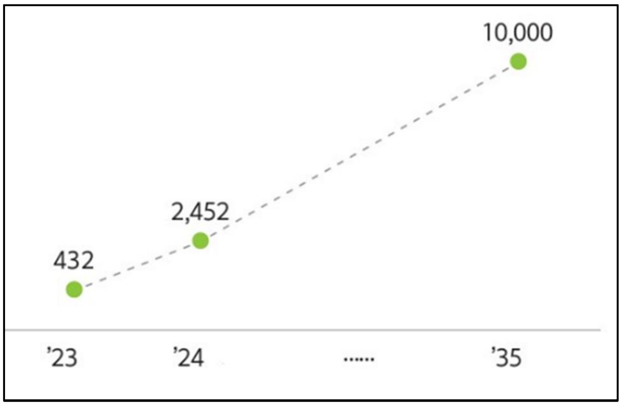
From a renewable energy perspective, Yeosu–Gwangyang Port established a self-generation system centered on solar photovoltaic power. Solar installations were deployed across port office parking areas, refrigerated and cold storage warehouses, and underutilized terminal spaces, enabling the port to produce a portion of the electricity required for daily operations on-site (YGPA, 2025). Notably, the port secured Renewable Energy Certificates (RECs) for the electricity generated and actively traded them, demonstrating that energy self-sufficiency can extend beyond environmental benefits to generate tangible economic value (World Port Sustainability Program, n.d.).

Overall, the case of Yeosu–Gwangyang Port illustrates a phased and integrated approach to energy self-sufficiency that combines energy efficiency improvements with on-site renewable energy production. This model enhances both operational stability and long-term sustainability, positioning the port as a benchmark for future-oriented energy transition strategies in the port sector (United Nations, n.d.)

3.3. Carbon-Neutral Port: Yeosu–Gwangyang Port

Aligned with its broader energy self-reliance agenda, Yeosu–Gwangyang Port has developed a structured medium- to long-term roadmap to advance carbon neutrality across port operations, with particular emphasis on the strategic acquisition of carbon credits. The Yeosu Gwangyang Port Authority (YGPA) articulated "Zero-Emission Port" as its guiding environmental vision and positioned greenhouse gas (GHG) emissions management as a central pillar of its sustainability strategy (YGPA, 2025). In line with the UNFCCC conception of carbon neutrality—defined as achieving net-zero emissions through a balance between emissions and removals (UNFCCC, 2024)—YGPA has adopted a hybrid mitigation framework that combines direct technological abatement with market-based instruments.

Within this framework, YGPA has established a cumulative target of securing 10,000 tCO_2eq in carbon credits by 2035. Figure 2 presents YGPA's medium- to long-term carbon credit acquisition trajectory, showing that 432 tCO_2eq were secured in 2023, followed by a sharp increase to 2,452 tCO_2eq in 2024, and a projected scale-up toward 10,000 tCO_2eq by 2035 (YGPA, 2025). This pattern indicates a deliberate stepwise expansion strategy, rather than a one-time offsetting approach, and underscores YGPA's intent to institutionalize carbon credit acquisition as a recurring component of its decarbonization pathway.



Source: Yeosu Gwangyang Port Authority [YGPA](2025).

Figure 2: YGPA's medium- to long-term carbon emission reduction targets (unit: tCO_2eq)

A major driver of the 2024 increase was the conclusion of a project-based memorandum of understanding (MOU) with a container terminal operator, under which emissions reductions generated from the electrification of 17 terminal cranes were formally registered as carbon credits. The replacement of diesel-powered cargo-handling equipment with electric alternatives represents a core Scope 1 mitigation measure, producing durable reductions in direct carbon dioxide emissions while also delivering ancillary benefits, such as lower noise levels and improvements in operational efficiency and workplace safety (IPCC, 2022).

YGPA's carbon credit initiative further incorporates an explicit economic rationale. The 2,452 tCO_2eq secured in 2024 are projected to generate approximately KRW 290 million in monetizable value, illustrating the feasibility of aligning emissions mitigation with financial performance (YGPA, 2025). Looking ahead, the authority plans to expand its carbon credit portfolio from 2025 onward through additional project pipelines, while simultaneously reinforcing its institutional readiness to participate in evolving emissions trading and regulatory regimes.

Parallel to these efforts, YGPA has intensified measures to curb Scope 2 emissions through increased reliance on renewable electricity. Power generated from on-site solar photovoltaic systems is progressively being integrated into port operations, thereby reducing dependence on grid-supplied electricity and lowering associated indirect emissions. This dual-track strategy illustrates how energy self-sufficiency initiatives can function in synergy with carbon neutrality objectives (World Economic Forum, 2020).

At the same time, preliminary actions addressing Scope 3 emissions have been introduced through strengthened regulatory compliance and environmental oversight. These include inspections of sulphur content in marine fuels used by foreign-flagged vessels and continuous air-quality monitoring within port precincts, which serve as indirect yet consequential interventions to mitigate emissions arising from vessel berthing and port calls (IMO, 2023). Such measures exemplify a cooperative governance model of decarbonization that extends responsibility beyond the port authority to encompass shipping lines and other port stakeholders (European Sea Ports Organisation [ESPO], 2025). In operational terms, YGPA has initiated Scope 3 engagement mechanisms through differentiated berth fee incentives for low-sulphur vessels, priority berthing schemes for environmentally certified shipping lines, and digital emissions reporting protocols integrated into the Port Community System (PCS). These instruments represent an embryonic form of cooperative carbon governance extending decarbonization responsibility beyond the port authority to shipping and logistics stakeholders.

Taken together, the carbon neutrality agenda at Yeosu–Gwangyang Port reflects a phased transition strategy that integrates equipment electrification, renewable energy deployment, and carbon credit–based mitigation. By operationalizing both technological and market-oriented instruments, YGPA offers an empirically grounded reference case for domestic ports seeking to design pragmatic decarbonization pathways while preserving economic viability. More broadly, this case underscores the capacity of ports to function as proactive institutional actors in the pursuit of wider climate neutrality goals (United Nations, n.d.).

4. Conclusions

This study explored the theoretical frameworks and practical implementation of smart automated, energy self-sufficient, and carbon-neutral port strategies using Yeosu–Gwangyang Port (YGPA) as a comprehensive case study. The findings demonstrate that YGPA has successfully operationalized an integrated sustainability model built upon digital innovation, renewable energy deployment, and structured carbon management. By bridging the gap between climate action and high-tech infrastructure, the research underscores that modern port management must evolve from fragmented initiatives into a unified 'techno-ecological' paradigm. This transition is not merely a response to environmental mandates but a strategic necessity for maintaining long-term maritime competitiveness in an era of escalating energy volatility and digital disruption.

The evidence indicates that YGPA's three-pillar strategy yields a synergistic effect that transcends simple operational gains. Smart automation technologies, including AI-driven terminal operating systems and digital twins, have modernized workflows and strengthened systemic resilience against operational variability. Simultaneously, energy self-sufficiency initiatives—anchored in facility efficiency upgrades and large-scale solar generation—have enhanced the port's energy security and created tangible economic value through the trading of Renewable Energy Certificates (RECs). When integrated with carbon-neutral strategies such as equipment electrification and onshore power supply (OPS), these measures facilitate a structural reduction in greenhouse gas emissions across Scope 1, 2, and 3, effectively positioning the port as a proactive agent in global Net-Zero trajectories (Alamoush et al., 2020; MOF, 2024).

While this research aligns with the global scholarly consensus on the necessity of port decarbonization, it offers a distinct departure from the prevailing Landlord Port models centered on European contexts. The primary originality of this study lies in its analysis of an Asian public-led hybrid model that leverages unique regional industrial synergies. Specifically, YGPA's proximity to the Gwangyang steel complex and Yeosu petrochemical cluster allows for a Multi-Energy Hub strategy, where byproduct hydrogen and industrial-scale energy sharing transform the port into an active energy prosumer. This industrial-port symbiosis represents a significant advancement over existing literature that predominantly focuses on internal port operations in isolation, providing a scalable empirical framework for other industrial-support hubs worldwide.

In conclusion, the Yeosu model illustrates that the sustainable ports of the future must adopt holistic frameworks that synchronize technology, energy, and climate strategies. For policymakers and port authorities, the practical implication is clear: long-term differentiation in the global logistics market will be driven by a port's green brand and its ability to provide transparent, carbon-tracked services to international shippers. Future research should expand comparative analyses across diverse global port typologies to evaluate the generalizability of this integrated model. Furthermore, exploring the policy drivers of sustainable transformation and developing standardized techno-institutional governance structures will be essential for scaling YGPA's success across the global maritime supply chain, ensuring that ports remain resilient nodes in a decarbonized future (Fadiga et al., 2024).

Acknowledgements

This research was supported by the Glocal University Project of Mokpo National University, 2025.

Declarations

Ethics Approval and Consent to Participate

This study did not involve human participants or animal subjects.

Competing Interests / Conflicts of Interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

This work was supported by the Glocal University 30 Project of Mokpo National University (2025), funded by the Ministry of Education (MOE) and the National Research Foundation of Korea (NRF). The funder had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Author Contributions

Author Contributions
[Author 1 Min Jung Kang]: Conceptualization, Methodology, Formal
analysis, Investigation, Writing – original
draft, Review & editing, Visualization, Funding acquisition, Supervision
[Corresponding Author Seonok Park]:

Conceptualization, Methodology, Resources, Writing – original draft, Review & editing
All authors have read and approved the final manuscript.

Data Availability Statement

The data are not publicly available due to privacy or ethical restrictions but can be requested from the corresponding author.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the authors used ChatGPT-4 (OpenAI) & Gemini 3.0 to improve the clarity and readability of the manuscript and to generate initial ideas for the literature review structure. All AI-generated content was thoroughly reviewed, revised, and verified by the authors. The authors take full responsibility for the final content of the publication.

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