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ICT Investment and Carbon Emission Efficiency in Regional Port Groups: Evidence from Chinese Coastal Provinces

Abstract
Growing concerns about climate change have intensified scrutiny of port operations as significant contributors to global emissions, prompting ports worldwide to reconcile environmental sustainability with operational efficiency. Yet how digital investments specifically influence environmental performance in regional maritime systems remains insufficiently understood. Existing research has examined ICT's economic impacts and operational efficiency separately. However, limited empirical attention has been directed towards the relationship between digital transformation and carbon emission efficiency. This gap is particularly notable regarding the differential effects of ICT components and the role of governance structures. This study examines nine Chinese coastal provinces from 2008 to 2019, decomposing ICT capital into hardware, communication equipment, and software components. Using two-way fixed effects models and instrumental variables approaches, we analyse their impacts on carbon emission efficiency within regional port groups. Results indicate that ICT investment significantly enhances carbon emission efficiency, with hardware demonstrating the strongest effect, followed by communication equipment and software. The relationship operates through both direct channels and indirect pathways via functional specialisation. Digital infrastructure enables ports to develop clearer divisions of labour and achieve economies of scale, thereby reducing emissions per unit of throughput. Furthermore, port integration exhibits an inverted U-shaped moderating effect, with optimal integration levels varying across ICT components. These findings advance understanding of environmental returns to digital investment in port infrastructure, offering empirical guidance for policymakers navigating governance challenges in sustainable maritime development.
Keywords: ICT Investment; Carbon Emission Efficiency; Port Specialization; Port Integration; Sustainable Maritime Transport; Green Ports; Digital Transformation

1. Introduction

Global climate change has emerged as one of the most pressing challenges confronting humanity, profoundly reshaping how industries approach sustainable development and environmental governance (Lei & Xu, 2024, 2025). Within this context, the maritime transport sector, particularly port operations, has been identified as a significant contributor to global carbon emissions. Ports account for approximately 3% of worldwide greenhouse gas emissions through diverse maritime and logistics activities (Jin, Huang, & Lei, 2024; Jin, Li, & Lei, 2024). As crucial nodes in global supply chains, ports face mounting pressure to reconcile two seemingly competing imperatives: reducing their environmental footprint while maintaining the operational efficiency necessary for economic competitiveness. This dual challenge has become particularly acute in rapidly industrialising economies where port infrastructure experiences intensive utilisation and faces stringent environmental regulations. Concurrent with these environmental pressures, rapid advancements in digital technologies, particularly Information and Communication Technology, have demonstrated remarkable potential for transforming traditional industries towards more sustainable operations. These technologies offer a promising pathway for ports to simultaneously enhance efficiency and environmental performance (R. Liu et al., 2019). The convergence of environmental urgency and technological capability creates a compelling rationale for investigating how digital investments can enable ports to achieve carbon emission reductions without compromising operational effectiveness.

Building upon this rationale, the digital transformation of ports represents a major paradigm shift in how maritime infrastructure operates and manages resources, moving beyond incremental improvements to systemic restructuring of operational processes (Heilig, Lalla-Ruiz, & Voß, 2017). Traditional port operations, historically characterised by manual processes and fragmented information systems, are increasingly being supplanted by smart port initiatives that strategically leverage digital technologies to achieve enhanced operational efficiency and improved environmental performance. This transformation manifests through multiple technological channels, including automated equipment control, real-time monitoring systems, integrated information platforms, and intelligent energy management systems (Alzahrani, Petri, Rezgui, & Ghoroghi, 2021; Min, 2022; C. Zhou et al., 2025). The existing literature on port efficiency has evolved correspondingly. Early studies focused on simple operational metrics for individual port performance, such as crane efficiency and throughput optimisation. More recent evaluations incorporate environmental considerations including carbon emissions and energy efficiency (Alamoush, Ballini, & Ölçer, 2020; Bichou, 2006; Ha, Yang, Notteboom, Ng, & Heo, 2017; Martínez-Moya, Vazquez-Paja, & Maldonado, 2019). Meanwhile, research on ICT investment has established its positive contributions to economic development across various sectors and geographies. Growing attention has been directed towards its environmental implications, though findings regarding ICT's impact on carbon emissions remain mixed and context-dependent (Stanley, Doucouliagos, & Steel, 2018). In the port sector specifically, studies have demonstrated that ICT integration shows promise in optimising resource utilisation, reducing vessel waiting times, and implementing more efficient energy management systems. These benefits are particularly evident in contexts where ports handle massive cargo volumes and face significant environmental pressures (Li, Haralambides, & Zeng, 2022).

Despite this growing body of research examining both port efficiency and ICT applications independently, a significant research gap persists. Limited understanding exists regarding how digital investments specifically impact port carbon emission efficiency, particularly within the organisational context of regional port groups operating under integrated governance structures. While existing studies have explored ICT's role in economic development and documented its general environmental impacts across various industries, limited empirical attention has been directed towards its specific effects on port sustainability outcomes. This gap is particularly noteworthy given three important developments in contemporary port management. First, port operations are increasingly characterised by regional integration, with individual ports consolidating into coordinated clusters under unified governance frameworks. Yet how this integration shapes the effectiveness of digital investments remains underexplored. Second, substantial investments are being channelled into port digitalisation globally, but the differential impacts of various ICT components—such as hardware, software, and communication equipment—on environmental performance lack systematic empirical investigation. Third, while port specialisation has been recognised as an important determinant of operational efficiency, its potential role as a pathway through which digital technologies influence environmental outcomes has received insufficient scholarly scrutiny. These gaps are especially pronounced in emerging economies where port systems are simultaneously pursuing rapid digitalisation, regional integration, and environmental sustainability, creating complex interactions that existing research frameworks have not adequately addressed.

Against this backdrop, this research seeks to answer several exploratory questions that probe the complex relationships between digital transformation and port environmental performance. How does ICT investment influence carbon emission efficiency in regional port groups operating under integrated governance structures?

Do different components of ICT investment, specifically hardware, software, and communication equipment, exert differential impacts on environmental outcomes, and if so, what mechanisms account for these variations? To what extent does port specialisation serve as an intermediate pathway through which digital investments affect carbon emission efficiency? How does the degree of port integration shape the relationship between ICT investment and environmental performance, and does this conditional effect exhibit linear or nonlinear patterns? These questions are designed to uncover not merely whether digital investments matter for port sustainability, but how they matter, through what pathways, and under what organisational conditions their effects are amplified or attenuated.

Addressing these questions, this study advances existing literature through four interconnected contributions from theoretical, methodological, empirical, and policy perspectives. Theoretically, it extends digital transformation and sustainability research by providing systematic evidence on environmental returns to ICT investment in port infrastructure, a sector where such evidence has been notably absent despite its significant contribution to global emissions. The disaggregation of ICT capital into hardware, communication equipment, and software components advances understanding of which forms of digital capital most effectively promote environmental efficiency and through what mechanisms these effects operate. Methodologically, we introduce port specialisation as an intermediate pathway, demonstrating that digital infrastructure enhances environmental sustainability partially through enabling organisational specialisation and functional differentiation within regional port systems. Furthermore, we identify an inverted U-shaped conditional effect of port integration. This finding contributes to ongoing debates regarding optimal governance structures by revealing that integration benefits environmental performance only up to a threshold, beyond which excessive consolidation may diminish returns. Empirically, our analysis of nine Chinese coastal provinces provides granular evidence on digital transformation in the world's largest port system. The findings offer insights into how emerging economies can leverage technology for sustainable infrastructure development while navigating the complexities of regional integration and specialisation. From a policy standpoint, our findings offer concrete guidance for port authorities and policymakers on ICT investment prioritisation strategies, optimal integration scope determination, and specialisation approaches that maximise environmental returns while maintaining operational efficiency.

The remainder of this paper is organised as follows. Section 2 reviews relevant literature on port efficiency measurement, ICT investment impacts, and environmental performance in maritime contexts, identifying specific gaps that motivate our research design. Section 3 presents the theoretical framework underlying our hypotheses, drawing on theories of technological adoption, organisational specialisation, and governance structures to develop testable propositions regarding the relationships among ICT investment, port integration, specialisation, and carbon emission efficiency. Section 4 describes the research methodology, including our panel data structure covering nine Chinese coastal provinces from 2008 to 2019. This section also details variable measurement approaches for ICT capital stock and carbon emission efficiency, as well as econometric specifications designed to address potential endogeneity concerns. Section 5 presents empirical results from our main effects analysis, mechanism tests, conditional effect analyses, and robustness checks, discussing the implications of our findings for understanding digital transformation in port systems. Finally, Section 6 concludes with a synthesis of key findings, policy recommendations for port digitalisation strategies, acknowledgement of study limitations, and directions for future research on sustainable port development.

2. Literature Review

Port efficiency, as a core indicator for measuring port economic performance, has evolved considerably over time. This evolution spans from single operational dimensions to comprehensive performance evaluation, from independent ports to regional port groups, and from economic efficiency to environmental efficiency. Early research primarily focused on operational efficiency measurement of individual ports as decision-making units, employing single indicators such as throughput optimisation and container crane operational efficiency for assessment (Tabernacle, 1995; Talley, 1988). With the refinement of evaluation methodologies, researchers began adopting multi-input-multi-output frameworks. These approaches utilised Data Envelopment Analysis models and Malmquist productivity indices, incorporating berth numbers, terminal length, and yard area as input indicators while using total throughput as output indicators (Pang, 2006). Driven by environmental sustainability concepts, research gradually integrated environmental dimensions into port efficiency evaluation systems. Slack-based measure models were employed to address undesirable outputs and evaluate ports' environmental emission reduction efficiency (J. Liu, Wang, & Guo, 2021; Na, Choi, Ji, & Zhang, 2017). Recent research has further constructed comprehensive green development efficiency evaluation systems encompassing social welfare, environmental regulation, and economic growth. Utilising super-efficiency models and difference-in-differences methods, these studies assess green development efficiency in port cities, finding that port integration significantly promotes green development (Ma, Li, Jia, & Kuang, 2025). However, whether port efficiency improvements necessarily lead to carbon emission reductions remains contested. Research on Yangtze River inland ports reveals positive correlations between port total factor productivity and urban carbon emissions, particularly pronounced in medium-to-high emission cities. This impact exhibits threshold effects of port scale, suggesting that port efficiency enhancement requires complementary low-carbon governance mechanisms to achieve genuine environmental improvement (Ding & Choi, 2024; Luo et al., 2024). Concurrently, research perspectives have expanded from individual ports to port group systems. Scholars have explored relationships between ports and hinterland connections, inter-port network efficiency, and port-hinterland radiation efficiency. Regional port group efficiency is defined as maximising resource utilisation and economic benefits under integrated operations within provincial spatial domains. Two-stage network models have been employed to separately evaluate production stage and hinterland service stage efficiency and their impacts on overall efficiency (Jia, Ma, Wu, Lu, & Kuang, 2023; Wu, Wang, & Wang, 2022; Ye, Jiang, & Qi, 2020; X. Zhang & Deng, 2013).

Turning to the role of digital technologies, the environmental impact of Information and Communication Technology investment presents complex and sometimes contradictory results in existing research. These divergences partially stem from differences in research contexts, measurement methods, and mechanisms of action. While conclusions regarding ICT investment promoting economic growth have been validated in research on OECD-EU countries and South Asian nations (Fernandez-Portillo, Almodovar-Gonzalez, & Hernandez-Mogollon, 2020; Usman, Ozturk, Hassan, Zafar, & Ullah, 2021), its environmental impacts exhibit multifaceted characteristics. Some studies find that ICT development reduces carbon emissions through technological innovation and energy structure optimisation. ICT application promotes environmental behaviours and significantly reduces carbon emissions, while demonstrating spatial heterogeneity in reducing carbon intensity (Haini, 2021; Nakatani, 2021; Sun & Kim, 2021; Zheng & Wang, 2021). However, other research indicates that ICT exhibits rebound effects leading to increased consumption of high-energy products, or finds that internet usage increases energy consumption while reducing energy intensity (Joyce, Finnveden, Hakansson, & Wood, 2019; Ren, Hao, Xu, Wu, & Ba, 2021). In the port sector, digital technology applications demonstrate potential for enhancing operational efficiency and environmental performance. Ports utilise digital platforms to integrate intelligent transportation systems, Internet of Things, cloud computing, and big data analytics to improve logistics and operational efficiency. Smart port sensors, actuators, and intelligent platforms show significant potential in improving monitoring, control, and planning processes (Allam & Newman, 2018; Ferretti & Schiavone, 2016; Yang et al., 2018). Empirical evidence from major European ports indicates that intelligent transportation systems and sensor computing positively impact port monitoring and enhance port competitiveness (Ferretti, Parmentola, Parola, & Risitano, 2017; Parola, Risitano, Ferretti, & Panetti, 2017). The EU Commission's Horizon 2020 "Future Ports" programme highlights that port IoT technology develops intelligent infrastructure and optimises digital information flow among stakeholders by collecting big data from cargo and passenger movements. Cloud services support knowledge storage and monitoring analysis through automated data processing, while port ICT investment creates new infrastructure for managing port communications, marketing strategies, and multi-user maritime information systems (Hollen, van den Bosch, & Volberda, 2015; Parola, Pallis, Risitano, & Ferretti, 2018; Parola, Satta, Penco, & Profumo, 2013). Despite digitalisation optimising port services and reducing waiting times, insufficient investment due to high costs and uncertain outcomes limits its potential (Pruyn & van Hassel, 2022). Recent systematic reviews indicate that digitalisation serves as a key driving force for green port transformation. Digital technology integration significantly enhances green ports' energy efficiency levels, pollution control capabilities, and real-time management capacity, while also facing challenges such as information silos and inconsistent technical standards (Z. Zhang et al., 2024). Research on port efficiency determinants finds that port charges, infrastructure development, trunk line location, container mix, work practices, crane efficiency, and economies of scale significantly influence operational capacity. Port efficiency also correlates with hinterland GDP, population, inter-port and intra-port competition intensity, and average wage levels, while port specialisation and scale are identified as key efficiency drivers (Pérez, González, & Trujillo, 2020; Tongzon, 1995; Yeo & Song, 2005; Yuen, Zhang, & Cheung, 2013). Regarding environmental sustainability, research emphasises the importance of air pollution monitoring for implementing environmental measures and internalising port emissions. Clean energy technology applications, smart grids and renewable energy, and cleaner low-carbon technologies for port emission sources are identified as critical for improving energy efficiency and emission reduction. ICT applications such as IoT monitoring of logistics and fuel consumption, Electronic Data Interchange and one-stop e-commerce portals facilitate terminal-shipping company communication. Port community systems and vessel traffic management reduce vessel turnaround time and port carbon emissions (Kang & Kim, 2017; Ozturk, Jaber, & Imran, 2018; Ramos, Carballo, Alvarez, Sanchez, & Iglesias, 2014). Recent research utilising panel data from Chinese coastal port cities finds that digital economy development significantly reduces ship-related PM2.5 emission pollution, with more pronounced emission reduction effects observed in larger-scale ports. This reveals that digital infrastructure can serve as an important pathway for enhancing port green performance (Ding, Song, Zhu, & Ji, 2025).

Despite these substantial achievements in port efficiency measurement, economic and environmental impacts of ICT investment, and port digital transformation, several research gaps merit further exploration. First, while research on ICT capital investment in carbon emissions and energy consumption domains is relatively mature, studies on port group carbon emission reduction remain limited. This is particularly noteworthy given that ports and shipping account for approximately 3% of global greenhouse gas emissions. Second, existing port green efficiency research primarily focuses on single port measurements, influencing factor analysis, or literature reviews of digital technology applications for low-carbon operations. Relatively few studies conduct empirical investigations into specific relationships between digital investment strategies and port operational efficiency. Third, although some research explores influencing factors of port efficiency and overall impacts of digitalisation on port performance, in-depth examination of differential effects of different ICT investment components and their mechanisms of action remains insufficient. Finally, port integration and specialisation, as important characteristics of regional port group development, lack systematic examination of their intermediate and conditional roles in the process through which ICT investment influences port environmental performance. Addressing these gaps, this study adopts the regional port group concept, using provincial domains as spatial carriers to investigate the impact of digital investment on port group carbon emission efficiency under integrated operations (Jia et al., 2023). The research disaggregates ICT capital into hardware, communication equipment, and software components to explore their differential impacts on port efficiency. It incorporates port group specialisation levels into the analytical framework to systematically examine pathways through which digital investment affects regional port group carbon emission efficiency. Furthermore, it investigates the conditional effect of port integration degree in this relationship, thereby providing new empirical evidence for understanding how digital transformation promotes port sustainable development.

3. Theoretical Framework and Hypotheses

3.1. ICT Investment Effects on Carbon Efficiency

ICT investment, functioning as high-quality capital formation, becomes deeply integrated with port group operations, thereby facilitating digital infrastructure development while simultaneously optimising operational processes throughout the system. This integration enhances loading efficiency, reduces vessel port time, and enables intelligent low-carbon operations, thereby decreasing energy consumption and carbon emissions. For instance, automated terminals achieve operational efficiency improvements of up to 30% while reducing labour requirements by approximately 70%. Through ICT technologies, ports can implement real-time energy monitoring and management systems, promptly identifying energy waste and optimising energy allocation to reduce carbon emissions (Cui, Cao, Feng, & Zhang, 2023). ICT investment also facilitates information sharing and collaborative operations between ports and upstream/downstream enterprises, reducing logistics redundancy and transportation-related carbon emissions. Smart port development demonstrates ICT's crucial role in port logistics chain integration. Furthermore, ICT technologies enable ports to establish comprehensive environmental monitoring systems, providing real-time air quality and carbon emission monitoring and facilitating timely emission reduction measures (B. Wang, Liu, Wang, Chen, & Wang, 2023). Therefore, robust ICT investment development contributes to improving port group carbon emission efficiency. Based on these theoretical foundations, we propose:

H1: Provincial ICT investment positively influences port group carbon emission efficiency (CEE) within the same province.

3.2. Port Specialisation as an Intermediate Pathway

ICT investment directly enhances port group specialisation levels (PSI) by improving information flow efficiency, optimising resource allocation, and promoting industrial agglomeration. Investment in hardware, software, and communication infrastructure establishes efficient information-sharing platforms, reducing information asymmetry and enabling more rational resource allocation among port group members, thereby promoting specialisation. Research demonstrates that ICT infrastructure effectively improves supply chain resource allocation efficiency (Davidson, De Filippi, & Potts, 2018). Digital technology applications optimise port group operational efficiency through real-time data analysis and intelligent scheduling (Martin & Trippl, 2017). For port groups, increased ICT capital stock enhances informatisation and intelligence levels, optimising resource allocation and encouraging clear division of labour based on individual port advantages. Smart port systems enable precise cargo handling and storage resource allocation, attracting specialised cargo transportation businesses and promoting port group specialisation. In turn, port group specialisation may enhance overall carbon emission efficiency through the concentration of resource and technological advantages, potentially leading to reductions in unit carbon emission costs. Competitiveness theory suggests that specialisation drives regional economic scale effects, reducing carbon consumption of production factors (Porter, 1991). Higher specialisation levels facilitate clean technology adoption and diffusion, improving carbon emission efficiency (Chen, Zhang, Song, & Wang, 2022). Therefore, we propose:

H2: ICT investment promotes provincial port group carbon emission efficiency (CEE) through enhancing port group specialisation levels (PSI).

3.3. Port Integration as a Conditional Factor

In early integration stages, ports operate independently with fragmented resource allocation, potentially leading to redundant ICT infrastructure investments and inefficient resource utilisation. Research indicates that sustainable port development requires comprehensive consideration of environmental, social, and economic factors, with port integration facilitating resource optimisation and enhancing overall competitiveness (Lim, Pettit, Abouarghoub, & Beresford, 2019). As integration deepens, enhanced coordination enables more effective deployment of digital infrastructure across the port network. Conversely, excessive levels of integration may potentially generate monopolistic effects, which could suppress innovation incentives and diminish the marginal benefits derived from ICT investment. Studies highlight the lack of coordination between port integration and regional ecological protection (Y. Zhou, Li, Duan, & Deng, 2023). Highly centralised port management may improve short-term efficiency but weakens long-term innovation drive and limits low-carbon technology adoption. This suggests a nonlinear relationship whereby integration initially amplifies but eventually attenuates ICT investment's positive effects on environmental performance. Therefore, we propose:

H3: Port integration exhibits an inverted U-shaped conditional effect on the relationship between ICT investment and provincial port group carbon emission efficiency (CEE).

4. Methodology and Data

4.1. Sample and Data Sources

4.1.1. Carbon Emission Efficiency Measurement

Although existing literature has predominantly concentrated on efficiency measurements of individual ports, a notable gap exists in understanding regional port group efficiency within the context of integrated operational frameworks. Following previous research (Jia et al., 2023; Y. Zhou et al., 2023), this study employs a super-efficiency network SBM model considering undesirable outputs. We utilise MaxDEA software to calculate the temporal efficiency variations of nine provincial-level regional port groups under integrated operations, based on selected input-output indicators (as shown in Table 1).

The selection of input-output variables for our super-efficiency network SBM model is grounded in established port efficiency measurement literature. The production stage specification follows resource-based perspectives conceptualising ports as capital-intensive facilities transforming infrastructure inputs into throughput outputs while generating environmental externalities (Bichou, 2006). Berth numbers and terminal length as inputs reflect the essential role of quayside infrastructure in determining production capacity, consistent with prior port efficiency studies (Ha et al., 2017). Cargo and container throughput as desirable outputs represent core port services, following standard practice in port performance measurement (Tongzon, 1995). CO_2 emissions as undesirable output incorporates environmental considerations, building on environmental economics literature modelling production processes as jointly generating desirable goods and undesirable pollutants (Na et al., 2017). The hinterland service stage specification reflects systems theory recognising ports as nodes connecting maritime and terrestrial networks (X. Zhang & Deng, 2013). Transportation infrastructure variables across multiple modes capture multimodal hinterland connectivity, while regional economic outputs reflect port-hinterland integration (Ye et al., 2020). This two-stage framework with linking variables has theoretical foundation in network efficiency literature (Jia et al., 2023).

Table 1. Input-Output Indicators for Port Group Efficiency Measurement

Stage	Indicator Type	Specific Indicator	Unit
Production Stage	Input	Number of production berths (≥10,000 tons)	Count
	Input	Total number of production berths	Count
	Input	Length of production terminals	Meters
	Undesirable Output	CO_2 emissions	Tons
Linkage Factors	Intermediate Output	Cargo throughput	10,000 tons
	Intermediate Output	Container throughput	10,000 TEU
Hinterland Service Stage	Intermediate Output	Highway cargo turnover	10,000 ton-kilometers
	Intermediate Output	Waterway cargo turnover	10,000 ton-kilometers
	Input	Railway cargo turnover	100 million ton-kilometers
	Input	Per capita transportation and communication expenditure/total consumption expenditure	Ratio
	Input	Total import and export	10,000 USD
	Desirable Output	Per capita GDP of direct hinterland	Yuan
	Desirable Output	Tertiary industry output of direct hinterland	100 million Yuan

Note: This two-stage efficiency evaluation model incorporates linkage factors that connect the production and hinterland service stages.

Provincial port group carbon emission efficiency measurement conceptualizes each provincial port group as a decision-making unit (DMU), dividing operational processes into production and hinterland service stages using a super-efficiency network SBM model that considers undesirable outputs for dual-stage efficiency measurement. In the production stage, infrastructure resources such as the number of production berths and terminal length serve as inputs, while cargo throughput and container throughput represent desirable outputs, and CO_2 emissions constitute undesirable outputs. The hinterland service stage uses highway, railway, and waterway cargo turnover as transportation resource inputs, along with the ratio of per capita transportation and communication expenditure to total consumption expenditure as regional logistics cost input. Regional outputs are characterized by direct hinterland import-export trade volume, per capita GDP, and tertiary industry output value, representing the economic linkage between regional port groups and their hinterlands.

Regarding carbon emissions measurement, we acknowledge that our CO_2 emission data encompasses provincial-level emissions from port-related activities and broader maritime logistics operations. While ports represent one component of total emissions, this approach is justified by three considerations. First, modern port groups function as integrated logistics hubs where port activities generate extensive indirect emissions through regional supply chain operations and hinterland transportation networks. Second, China's statistical system lacks consistent port-specific emission data across provinces during 2008-2019, whereas provincial data ensures reliability and comparability. Third, our fixed effects specification controls for time-invariant differences in port emission shares across provinces, with identification coming from temporal variation in port throughput and logistics intensity directly influenced by ICT investment.

Combining the two-stage input-output indicator system, we utilized MaxDEA software to calculate carbon emission efficiency for nine regional port groups from 2008-2019. Our data compilation draws primarily from authoritative sources including the China Port Yearbook, China Marine Statistical Yearbook, China Statistical Yearbook, as well as comprehensive annual reports published by provincial transportation departments and respective port group authorities. Carbon emissions are calculated following established methodology using the standard coal consumption method (Men, Gan, & Chen, 2014).

Provincial regional port group carbon emission efficiency (CEE) demonstrates relatively robust overall performance: the sample mean is 0.9023, with a maximum value of 1.59, minimum of 0.15, standard deviation of 0.343, and range of 1.44. The median of 0.94 slightly exceeds the mean, indicating moderate efficiency distribution across provinces. Despite significant inter-provincial differences, the standard deviation remains moderate, indicating no extreme efficiency polarization has occurred. The calculated carbon emission efficiency results reveal distinct spatial and temporal patterns across China's coastal port groups. The efficiency distribution shows that eastern coastal provinces generally outperform northeastern and southern regions, reflecting differences in technological advancement, management capabilities, and economic development levels. The temporal trend indicates a general improvement trajectory, with most port groups achieving higher efficiency levels by the end of the study period. These efficiency patterns provide crucial context for understanding how ICT investments differentially impact port groups with varying baseline performance levels. The heterogeneity in efficiency outcomes also justifies our focus on identifying the key drivers of performance variation, particularly the role of digital transformation in enhancing environmental sustainability.

4.1.2. ICT Investment Variables

This study employs ICT Productive Capital Stock (PCS) as the core explanatory variable to better reflect actual investment utilization and service efficiency (Q. Xu, Zhong, & Cao, 2022). Following established methodology, ICT investment is disaggregated into hardware, software, and communications components, with real investment stock calculated using the perpetual inventory method (Shabani & Shahnazi, 2019).

Our ICT investment measures are constructed at the provincial level rather than port-specific, reflecting both data constraints and theoretical considerations. Provincial ICT infrastructure development directly supports port operations through telecommunications networks, data platforms, and digital talent pools that enable port digitalization. Regional digital ecosystems facilitate port ICT adoption through spillover effects, shared technical services, and coordinated policy frameworks. Our two-way fixed effects specification controls for time-invariant provincial characteristics, with identification from temporal variation in regional digital infrastructure affecting port efficiency through documented mechanisms.

ICT investment data is derived from total fixed capital formation in China's regional input-output tables, with missing data points interpolated using average growth rates (Ceccobelli, Gitto, & Mancuso, 2012). Hardware and communications equipment investments are separated based on annual consumption rates from established industry reports (Zhong, Cao, & Zou, 2022).

Component-specific depreciation periods are set at 4, 5, and 7.5 years for hardware, software, and communications respectively, with corresponding depreciation rates of 31.19%, 31.50%, and 26.44% (B. Xu, Sendra-Garcia, Gao, & Chen, 2020). Due to the absence of systematic ICT price indices in China, this study applies established harmonization methods to estimate Chinese ICT investment price indices using U.S. BEA's Hedonic Price Index data (Schreyer, 2002).

The base period ICT investment stock for 2010 is calculated using:

$$K_{2010} = \frac{I_{2011}}{g + \delta} \tag{1}$$

where K_{2010} represents 2010 ICT investment stock, I_{2011} denotes 2011 real investment, g is average growth rate, and δ is depreciation rate.

The perpetual inventory method incorporates a hyperbolic time-efficiency function to capture ICT investment's productivity dynamics, with a survival function representing normal distribution retirement patterns to calculate periodic ICT investment stock.

4.1.3. Mediating Variables

Port specialization helps reduce inter-port competition. Following previous research, this study adopts the Port Specialization Index (PSI) (W. Wang, Wang, & Jin, 2018; Q. Zhang, Yan, & Yang, 2021):

$$PSI_i = \frac{n_i}{n_i - 1} \times \sum_{j=1}^{n_i} \left(t_{ij} - \bar{t}\right)^2 \ and\ \bar{t} = \frac{\sum_{j=1}^{n_i} t_{ij}}{n_i} \tag{2}$$

where PSI_i represents the PSI of province i, and t_{ij} denotes the proportion of port throughput for cargo type j to total port throughput in province i. PSI values range from 0 to 1, with higher values indicating greater specialization in specific cargo types.

The selection of port specialization as a mediating variable is grounded in industrial economics literature demonstrating that functional specialization enables economies of scale and resource optimization. Empirical studies show that specialized port facilities achieve superior operational performance through focused expertise and dedicated infrastructure (Pérez et al., 2020). Prior research on port efficiency has identified specialization as a significant determinant of port competitiveness (W. Wang et al., 2018). The theoretical linkage between ICT investment and specialization reflects that digital infrastructure facilitates information flows and coordination mechanisms necessary for functional differentiation in spatially distributed port systems.

4.1.4. Moderating Variables

The establishment of port groups following resource integration serves as a fundamental starting point for this research. Post-integration, individual ports within each province achieve cross-administrative interest adjustment and redistribution, evolving into integrated "regional port clusters" under unified port group management entities. The formation of port groups has fostered closer operational and financial connections among subordinate ports than ever before. Longer establishment periods of port groups facilitate the elimination of fragmented management and promote unified operational control, enabling orderly competition and differentiated services based on new functional positioning. Therefore, this study incorporates the "degree of port integration" as a moderating factor, measured by the standardized number of years since port group establishment using Z-score normalization.

The selection of port integration as a moderating variable reflects organizational theory on administrative consolidation costs and benefits. Research documents that fragmented port governance creates coordination failures and duplicated investments undermining infrastructure investment effectiveness (Lim et al., 2019). Studies of Chinese port integration provide empirical evidence that while moderate consolidation improves resource allocation and coordination, excessive centralization may generate bureaucratic rigidity and reduce local innovation incentives (Ma et al., 2025; Y. Zhou et al., 2023). This literature suggests that integration's moderating effect on ICT investment returns may be nonlinear, with optimal benefits at intermediate integration levels.

4.1.5. Control Variables

This study employs several control variables to account for regional variations. Industrial structure is measured by the ratio of tertiary to secondary industry added value. Urbanization level is represented by the proportion of urban population to total resident population. R&D intensity is calculated as the ratio of internal R&D expenditure to GDP. Government intervention is measured through relative fiscal expenditure, defined as the ratio of local government budgetary expenditure to regional GDP, which helps minimize measurement bias due to absolute economic scale differences. In our empirical regression analysis, we applied standardization treatment to the original port group establishment years using Z-score standardization to convert it into a standardized variable with mean = 0 and standard deviation = 1. The standardized variable values represent the degree of deviation of each province's port integration duration from the sample average level. Positive values indicate above-average levels, while negative values indicate below-average levels. Therefore, negative values such as -0.92 can reasonably appear, representing observations that fall below the sample mean rather than actual negative years.

The study examines nine coastal provinces that completed full or partial port resource integration before 2019: Guangxi, Hainan, Hebei, Jiangsu, Liaoning, Shandong, Shanghai, Tianjin, and Zhejiang. The research period spans from 2008 to 2019. Data sources include the China Port Yearbook, China Marine Statistical Yearbook, China Urban Statistical Yearbook, China Statistical Yearbook, China Electronic Information Industry Statistical Yearbook, China Energy Statistical Yearbook, China Regional Economic Statistical Yearbook, the National Bureau of Statistics website, and the EPS Global Statistical Data Analysis Platform. Natural logarithms are applied to certain variables to reduce heteroscedasticity and volume differences. Table 2 presents descriptive statistics for all variables.

Table 2. Descriptive Statistics of Variables

Variable	Abbreviation	Obs	Mean	SD	Min	Median	Max
Carbon emission efficiency	CEE	108	0.9023	0.343	0.15	0.94	1.59
ICT capital	LnICT	108	8.1519	2.011	1.97	8.34	11.43
Hardware capital	LnHW	108	6.2174	1.820	0.54	6.42	9.51
Communication capital	LnCW	108	7.5197	1.855	1.64	7.79	10.85
Software capital	LnSW	108	6.7150	2.538	0.13	6.77	10.51
Port specialisation	PSI	108	0.2618	0.213	0.03	0.21	0.82
Degree of port integration	PI	108	0.0000	1.000	-0.92	-0.32	2.72
Government intervention	Gov	108	0.1858	0.064	0.09	0.18	0.35
Industrial structure	Str	108	1.1680	0.521	0.59	1.01	2.85
R&D intensity	R&D	108	0.1843	0.098	0.02	0.19	0.42
Urbanization	Urba	108	0.6295	0.147	0.38	0.61	0.94

Note: Port Integration (PI) is processed using Z-score standardization; negative values indicate levels below the sample average.

4.1.6. Variable Transformation

This study adheres to established econometric principles in variable selection, with logarithmic transformation primarily applied to variables exhibiting substantial range spans and significant right-skewed distributions in their original values. ICT investment amounts and their respective components (hardware, communication equipment, software) demonstrate considerable magnitude differences across provinces. Direct model inclusion would likely induce heteroscedasticity and poor model fit issues. Logarithmic transformation compresses extreme values, promotes normal distribution tendencies, reduces heteroscedasticity, and enhances estimation robustness. In contrast, the dependent variable "port cluster carbon emission efficiency" calculated through DEA methodology, along with control variables (government intervention, industrial structure, etc.), exhibit concentrated distributions with similar magnitudes. Most values fall within the same order of magnitude, allowing direct model incorporation without introducing significant heteroscedasticity or scale imbalance issues, thus eliminating the need for logarithmic transformation.

4.2. Model Specifications

Given the balanced nature of our panel dataset, we employ a two-way fixed effects model specification that simultaneously accounts for both individual heterogeneity and temporal variations across the observation period. This approach addresses potential omitted variables that remain constant over time (individual effects) and those that vary uniformly across provinces (time effects). The basic model structure is expressed as:

$$CEE_{it} = \beta_0 + \beta_1 LnICT_{it} + \gamma X_{it} + \sigma_\mathrm{t} + \mu_\mathrm{i} + \varepsilon_{it} \tag{3}$$

where CEE_{it} represents port cluster carbon emission efficiency, $LnICT_{it}$, denotes the total ICT capital stock, X_{it} represents control variables, β_0 is the intercept term, σ_t represents time effects invariant to individual heterogeneity, μ_i represents individual effects constant over time, and ε_{it} is the random error term. Subscripts i and t denote different regions (provinces) and time periods, respectively.

4.3. Correlation and Multicollinearity Analysis

To examine the relationships among variables and assess potential multicollinearity concerns, this study conducts comprehensive correlation analysis and variance inflation factor (VIF) testing. Understanding the correlation structure is essential for interpreting our regression results and ensuring that multicollinearity does not compromise the reliability of our coefficient estimates.

Table 3. Correlation Matrix

Variable	CEE	LnICT	LnHW	LnCW	LnSW	PSI	PI	Gov	Str	R&D	Urba
CEE	1.000										
LnICT	0.233**	1.000									
LnHW	0.228**	0.990***	1.000								
LnCW	0.238**	0.992***	0.997***	1.000							
LnSW	0.196**	0.974***	0.942***	0.943***	1.000						
PSI	0.033	-0.012	0.081	0.064	-0.155	1.000					
PI	0.493***	0.054	-0.003	0.021	0.093	-0.234**	1.000				
Gov	-0.013	-0.297***	-0.363***	-0.344***	-0.205**	-0.356***	-0.747***	1.000			
Str	0.382***	0.113	0.027	0.047	0.208**	-0.529***	0.809***	0.738***	1.000		
R&D	0.506***	0.623***	0.599**	0.600***	0.617***	-0.284***	0.146	-0.346***	0.177*	1.000	
Urba	0.391***	0.461***	0.363***	0.378***	0.437***	-0.487***	0.349***	-0.025	0.351***	0.848***	1.000

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 3 presents the correlation matrix for all variables in our analysis. The results show that ICT investment and its components exhibit moderate positive correlations with carbon emission efficiency, with correlation coefficients ranging from 0.196 to 0.238, all significant at conventional levels. The correlations among ICT components are high, ranging from 0.942 to 0.997, indicating strong interrelationships among these investments. However, this high correlation is expected given that hardware, software, and communication investments typically develop in tandem within regional digital ecosystems. Control variables show generally modest intercorrelations, with the highest being 0.848 between R&D intensity and urbanisation, which warrants attention in our multicollinearity diagnostics.

To formally assess multicollinearity concerns, we compute variance inflation factors for all explanatory variables in our model specification. Table 4 presents the VIF results, which provide reassuring evidence that multicollinearity is not a significant concern in our analysis. All variables exhibit VIF values below the conventional threshold of 10, with the highest VIF being 9.66 for the R&D intensity variable. The mean VIF of 5.97 is within acceptable ranges, indicating that our coefficient estimates are not substantially affected by collinearity among regressors.

Table 4. Multicollinearity Diagnostics

Variable	VIF	1/VIF
LnICT	1.88	0.531
PI	6.63	0.151
Gov	8.85	0.113
R&D	9.66	0.104
Urba	6.26	0.160
Str	5.75	0.174
PSI	2.78	0.360
Mean VIF	5.97	-

Note: VIF denotes Variance Inflation Factor. Values above 10 typically indicate problematic multicollinearity.

5. Empirical Analysis

5.1. Main Effects Analysis

Table 5 reports the impact of ICT investment on carbon emission efficiency (CEE) across provincial port clusters. The empirical findings reveal that ICT investment and its constituent components exert statistically significant positive influences on port cluster carbon emission efficiency, with results demonstrating significance at the 1% level. Specifically, the regression coefficient of total ICT investment (LnICT) is 0.145 (β=0.145, t=3.83), indicating that increased ICT investment effectively improves port cluster carbon emission efficiency, supporting Hypothesis 1. This aligns with research findings that ICT applications in ports enhance operational efficiency and environmental performance (Yau, Peng, Qadir, Low, & Ling, 2020).

Table 5. Main Effects of ICT Investment on Carbon Emission Efficiency

Variable	(1) CEE	(2) CEE	(3) CEE	(4) CEE
LnICT	0.145***			
	(3.83)			
LnHW		0.168***		
		(3.66)		
LnCW			0.146***	

			(4.27)	
LnSW				0.057***
				(2.67)
R&D	1.807**	1.822**	1.935**	0.715
	(2.11)	(2.23)	(2.37)	(0.85)
Urba	-1.829**	-2.027***	-2.102***	-1.477**
	(-2.63)	(-2.88)	(-2.98)	(-2.18)
Gov	-1.432	-1.715	-1.804	-0.265
	(-1.23)	(-1.53)	(-1.53)	(-0.24)
Str	0.007	0.066	0.085	0.005
	(0.06)	(0.60)	(0.76)	(0.03)
_cons	0.793	1.041*	1.009*	1.362**
	(1.39)	(1.97)	(1.88)	(2.31)
Year	Yes	Yes	Yes	Yes
Individual	Yes	Yes	Yes	Yes
N	108	108	108	108
r2_within	0.263	0.271	0.280	0.196
F	6.300***	5.590***	6.180***	6.290***

Note: t statistics in parentheses, * p < 0.1, ** p < 0.05, *** p < 0.01

Further decomposition of ICT investment into hardware (LnHW), software (LnSW), and communications (LnCW) components reveals varying contributions to port cluster carbon emission efficiency improvement. Their regression coefficients are 0.168, 0.146, and 0.057, respectively, indicating that a 1% increase in LnHW, LnCW, and LnSW leads to 0.168%, 0.146%, and 0.057% improvements in CEE. Hardware investment demonstrates the most significant impact on carbon emission efficiency. This is attributed to ports' heavy reliance on modern hardware equipment, including automated loading systems, intelligent warehousing, and transportation equipment. These systems substantially improve port operational efficiency and reduce vessel dwell time, thereby decreasing fuel consumption and carbon emissions. Research notes that port limitations in ICT hardware infrastructure integration and national IT infrastructure, alongside challenges in funding, technical expertise, and facility maintenance, constrain port efficiency improvements (Onwuegbuchunam, Aponjolosun, & Ogunsakin, 2021).

Additionally, energy management systems, including smart grids and energy consumption monitoring equipment, enable real-time monitoring and energy use optimisation. Through effective energy management, ports can minimise unnecessary energy consumption, improve energy efficiency, and reduce carbon emissions. Communications investment also proves crucial in port cluster development. Research has found that integrating ICT equipment enables ports to optimise and safely manage operations, significantly improving operational efficiency and service quality (Serra & Fancello, 2020).

Investment in environmentally friendly hardware facilities, such as shore power systems and clean energy equipment, can directly reduce carbon emissions during port operations. Shore power systems allow docked vessels to shut down engines and use port electricity, significantly reducing emissions. Studies have found that cold ironing systems connecting berthed vessels to shoreside power grids substantially reduce greenhouse gas emissions (Yau et al., 2020). These findings demonstrate the crucial role of ICT investment and its components in promoting green development and improving carbon emission efficiency in port clusters.

5.2. Mediation Analysis

The total effect analysis indicates that ICT investment demonstrates a positive influence on port cluster carbon emission efficiency. To further explore the underlying mechanisms, we employ port specialisation level as a mediating variable to examine the indirect pathways through which ICT investment affects port cluster carbon emission efficiency, as presented in Table 6.

Table 6. Mediation Effects Analysis

Variable	(1) PSI	(2) CEE	(3) PSI	(4) CEE	(5) PSI	(6) CEE	(7) PSI	(8) CEE
LnICT	0.042^{***}	0.103^{**}						
	(2.66)	(2.56)						
LnHW			0.039^{**}	0.128^{***}				
			(2.31)	(2.79)				
LnCW					0.033^{**}	0.112^{***}		
					(2.30)	(3.32)		
LnSW							0.018^{**}	0.036
							(2.28)	(1.64)
PSI		1.020^{***}		1.040^{***}		1.029^{***}		1.173^{***}
		(3.41)		(3.69)		(3.58)		(4.04)
R&D	1.376^{***}	0.404	1.303^{***}	0.467	1.318^{***}	0.579	1.067^{***}	-0.537
	(3.90)	(0.47)	(3.65)	(0.60)	(3.65)	(0.75)	(3.44)	(-0.70)
Urba	-0.119	-1.707^{**}	-0.121	-1.902^{***}	-0.13	-1.968^{***}	-0.027	-1.446^{**}
	(-0.53)	(-2.60)	(-0.56)	(-2.79)	(-0.58)	(-2.92)	(-0.12)	(-2.32)
Gov	-1.570^{***}	0.169	-1.549^{***}	-0.104	-1.555^{***}	-0.203	-1.242^{***}	1.192
	(-3.28)	(0.14)	(-3.34)	(-0.09)	(-3.17)	(-0.17)	(-2.93)	(1.12)
Str	0.009	-0.002	0.03	0.035	0.035	0.049	0.005	-0.002
	(0.21)	(-0.02)	(0.72)	(0.34)	(0.84)	(0.48)	(0.10)	(-0.01)
_cons	0.025	0.768	0.11	0.926^{*}	0.105	0.901^{*}	0.189	1.140^{**}
	(0.13)	(1.47)	(0.59)	(1.89)	(0.56)	(1.81)	(1.00)	(2.13)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	108	108	108	108	108	108	108	108
r2_within	0.342	0.347	0.317	0.362	0.317	0.368	0.302	0.314
F	3.39^{**}	7.83^{***}	3.14^{**}	7.69^{***}	3.07^{**}	8.48^{***}	2.99^{**}	7.58^{***}

Note: t statistics in parentheses, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

In Model (1), the ICT coefficient is 0.042, significantly positive at the 1% level, indicating that ICT investment (LnICT) significantly positively affects port cluster specialisation level (PSI). This reflects digital investment's contribution to port cluster specialisation. Model (2) shows that ICT investment and PSI coefficients on CEE are 0.103 and 1.020, respectively, both significantly positive at 5% and 1% levels. This finding clearly demonstrates PSI's partial mediating role between ICT and CEE, with a mediating effect of 0.0428 (0.042×1.020), direct effect of 0.103, and mediating effect ratio of 0.295. Thus, ICT investment improves port cluster carbon emission efficiency by enhancing port cluster specialisation level, providing continuous structural optimisation and effectively promoting sustainable development in global supply chains. This verifies Hypothesis 2.

This finding has significant theoretical and practical implications, revealing the dual pathways through which digital investment promotes green port development. The mediating role of port specialisation reflects the structural optimisation effects of ICT investment. Nearly one-third of ICT's emission reduction effects need to be realised through port specialisation, highlighting the importance of aligning port functional positioning with digital technology investment. ICT investment achieves a transmission chain from technological input to organisational transformation to efficiency improvement by promoting port functional specialisation. Specialisation enables individual ports to concentrate resources on developing specific cargo handling capabilities, reducing redundant construction and resource waste. It improves overall operational efficiency through economies of scale and technical expertise, thereby reducing carbon emissions per unit of cargo handled.

Simultaneously, the 70.5% direct effect demonstrates that ICT investment itself possesses strong emission reduction potential. This direct effect operates primarily through direct technical pathways including equipment automation, energy management optimisation, and real-time monitoring. Hardware investment exhibits the most significant direct effect, directly reducing energy consumption and carbon emissions in port operations through automated loading and unloading systems, intelligent warehousing equipment, and clean energy facilities. Communication equipment investment directly reduces port carbon emissions by optimising vessel scheduling, reducing berthing waiting times, and improving coordination efficiency.

This dual pattern of direct and indirect effects provides clear policy guidance for port digital transformation. It indicates the need to emphasise both the direct application effects of ICT technologies and their indirect environmental benefits through organisational structure optimisation. To further enhance the robustness of our mediating effect analysis, this study employs Bootstrap confidence interval methods to verify the statistical significance of the mediating effects. Bootstrap methodology constructs empirical distributions through repeated resampling, enabling more accurate estimation of confidence intervals for mediating effects. This approach is particularly suitable for testing indirect effects with non-normal distributions.

After 5,000 Bootstrap resampling iterations, the indirect effects of total ICT investment, hardware investment, and communication equipment investment all passed Bootstrap validation, with confidence intervals excluding zero. This further confirms the mediating role of port specialisation level. However, the indirect effect of software investment shows some instability in Bootstrap testing, which may be attributed to the complexity of software investment effects and sample characteristics. The mechanism through which software investment influences port specialisation is more complex, potentially modulated by multiple factors including technology acceptance, employee training levels, and business process integration. These factors lead to increased volatility in Bootstrap test results within limited samples.

Models (3)-(4) empirically study ICT hardware investment's (LnHW) impact on provincial port cluster carbon emission efficiency through port cluster specialisation. In Model (3), the ICT hardware coefficient is significantly positive at the 5% level, indicating that ICT hardware investment effectively enhances port cluster specialisation level. Model (4) shows that hardware investment and PSI coefficients on CEE are both significantly positive at the 1% level, with a direct effect of 0.128 and PSI's mediating effect between hardware investment and CEE of 0.041 (0.039×1.040). Combined with baseline regression results, specialisation level serves as a partial mediator between hardware investment and CEE, with a mediating effect ratio of 0.241.

Models (5)-(6) examine PSI's mediating role between ICT communications investment (LnCW) and CEE. The results indicate that communications investment promotes port cluster specialisation development, thereby enhancing port cluster carbon emission efficiency. The partial mediating effect is 0.034 (0.033×1.029), direct effect is 0.112, and mediating effect ratio is 0.233.

Models (7)-(8) analyse PSI as a mediating variable to test software investment's mediating effect on CEE. Model (7) shows LnSW's impact coefficient on PSI is 0.018, significant at the 5% level, with PSI's mediating effect at 0.021 (0.018×1.173). Since the direct effect of 0.036 is insignificant, referring to previous research, this result represents a special case of mediation effects occurring under specific conditions (Preacher & Kelley, 2011). Combining with baseline results, software investment's (LnSW) total effect on CEE is 0.057, with PSI's mediating effect ratio at 0.368. This indicates that ICT software primarily influences carbon emission efficiency by enhancing port cluster specialisation level.

In examining ICT investment's impact on port cluster specialisation levels, we observe distinct heterogeneity. Hardware investment demonstrates the most significant effect on port cluster specialisation, with a regression coefficient of 0.039, indicating its crucial direct role in improving port operational efficiency and automation. Communications technology's contribution is slightly lower, with a regression coefficient of 0.033, reflecting its importance in ensuring smooth port operations and accurate information transmission. In contrast, software investment shows the weakest impact on port cluster specialisation, with a regression coefficient of only 0.018. This may be due to longer implementation periods required for software benefits and high dependence on employee technology acceptance and effective integration with business processes.

Port clusters can more effectively allocate resources through specialisation, concentrating on specific cargo types to achieve economies of scale, thereby reducing energy consumption and carbon emissions. The improvement in specialisation level not only optimises internal port operations but also amplifies the impact on regional carbon emission efficiency through port cluster synergy.

5.3. Moderation Analysis

5.3.1. Overall ICT Investment Moderation

Building upon the total effect analysis of ICT investment on port cluster carbon emission efficiency presented in Section 5.2, which provided empirical support for Hypothesis 1, we proceed to investigate the potential moderating role of port integration in this relationship. In our moderation analysis, we include interaction terms (PI×LnICT) and (PI^2×LnICT) but not the standalone PI^2 term. This specification focuses on how the marginal effect of the explanatory variable LnICT on outcome CEE varies quadratically with moderator PI, which is sufficient to capture the inverted U-shaped moderation structure. Including the pure PI^2 term would create high multicollinearity with PI and lead to over-parameterisation.

First, we test the linear moderating effect by introducing the first-order interaction term (PI×LnICT) to examine whether PI has a significant linear moderating effect on the positive relationship between ICT investment and port cluster carbon emission efficiency. As shown in Model (2) of Table 7, after introducing the first-order moderation term, the model's R^2 remains unchanged, with ICT investment (LnICT) maintaining a significant positive effect on CEE ($\beta = 0.163$, $t = 4.01$). However, PI's first-order moderation term is insignificant ($\beta = 0.013$, $t = 0.77$), indicating no apparent linear moderating effect.

Table 7. Moderation Effects: Total ICT Investment

Variable	(1) CEE	(2) CEE	(3) CEE
LnICT	0.150***	0.163***	0.158***
	(3.90)	(4.01)	(4.18)
LnICT×PI		0.013	0.052**
		(0.77)	(2.61)
LnICT×PI^2			-0.023***

			(-3.72)
PI	-0.019	-0.046	-0.070
	(-0.45)	(-0.94)	(-1.45)
R&D	1.773**	1.555*	1.867**
	(2.08)	(1.73)	(2.07)
Urba	-1.878**	-1.801**	-1.848***
	(-2.63)	(-2.49)	(-2.70)
Str	0.011	-0.028	-0.059
	(0.09)	(-0.21)	(-0.50)
Gov	-1.278	-1.013	-1.343
	(-1.02)	(-0.81)	(-1.24)
_cons	0.763	0.640	0.762
	(1.31)	(1.10)	(1.35)
Year FE	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes
N	108	108	108
r2_a	0.904	0.903	0.912
r2_within	0.264	0.267	0.3453
F	5.136***	4.432***	6.387***

Note: t statistics in parentheses, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

We then test port integration's "inverted U-shaped" moderating effect by introducing the second-order interaction term ($PI^2 \times LnICT$). After including this term, the model's R^2 increases significantly, indicating improved overall explanatory power (Model 3, Table 7). ICT investment maintains its significant positive effect ($\beta = 0.158$, $t = 4.18$), with PI's first-order moderation term significantly positive ($\beta = 0.052$, $t = 2.61$) and second-order term significantly negative ($\beta = -0.023$, $t = -3.72$). This verifies port integration's significant "inverted U-shaped" moderating effect on the positive relationship between ICT investment and carbon emission efficiency, supporting Hypothesis 3.

Further analysis of port integration's U-shaped moderating effect on ICT investment's impact on port cluster carbon emission efficiency is illustrated in Figure 1. When standardised port integration reaches 1.13, ICT investment's promoting effect on port cluster carbon emission efficiency peaks at 0.187, indicating that a 1% increase in ICT investment improves CEE by 18.7%. The insignificant linear moderation suggests that the relationship between port integration and ICT investment's impact on CEE is not unidirectionally increasing but constrained by port integration's marginal utility. At low integration levels, ICT investment's benefits are limited due to poor inter-port collaboration. As integration levels rise, resource allocation and information sharing efficiency significantly improve, enhancing ICT investment's promoting effect. However, when integration exceeds a certain threshold, coordination costs, resource conflicts, and management complexity may inhibit ICT investment's positive impact.

[Figure 1 about here]

5.3.2. Hardware Investment Moderation

We first examine port integration's linear moderating effect on hardware investment by introducing the interaction term ($PI \times LnHW$) into the baseline regression model. As shown in Model (2) of Table 8, after introducing the first-order moderation term, the hardware investment coefficient remains significantly positive at the 1% level (0.248), and the interaction term between hardware investment and port integration is significantly positive at the 5% level (0.054). This indicates that port integration plays a significant positive moderating role in hardware investment's impact on port cluster carbon emission efficiency.

Table 8. Moderation Effects: Hardware Investment

Variable	(1) CEE	(2) CEE	(3) CEE
LnHW	0.177^{***}	0.248^{***}	0.220^{***}
	(3.57)	(3.97)	(3.90)
LnHW×PI		0.054^{**}	0.073^{***}
		(2.08)	(2.72)
LnHW×PI^2			-0.021^{**}
			(-2.63)
PI	-0.030	-0.122^{*}	-0.118^{**}
	(-0.66)	(-1.92)	(-2.02)
R&D	1.780^{**}	1.113	1.483^{*}
	(2.22)	(1.30)	(1.71)
Urba	-2.120^{***}	-2.130^{***}	-2.147^{***}
	(-2.85)	(-2.91)	(-3.14)
Str	0.074	-0.002	-0.001
	(0.67)	(-0.02)	(-0.00)
Gov	-1.502	-1.075	-1.322
	(-1.27)	(-0.93)	(-1.31)
_cons	1.004^{*}	0.700	0.869^{*}
	(1.87)	(1.40)	(1.75)
Year FE	YES	YES	YES
Individual FE	YES	YES	YES
N	108	108	108
r2_a	0.905	0.908	0.913
r2_within	0.275	0.306	0.348
F	4.577^{***}	4.086^{***}	6.215^{***}

Note: t statistics in parentheses, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

To further examine port integration's moderating effect, we introduce the squared interaction term between hardware investment and port integration. Results in Model (3) of Table 8 show that this interaction term is significantly negative at the 1% level, indicating an "inverted U-shaped" moderating effect. At low port integration levels, port integration positively moderates hardware investment's impact on CEE; as integration levels increase, it weakens hardware investment's promoting effect, aligning with Hypothesis 3.

Analysis of the inverted U-shaped moderating effect (Figure 2) shows that when standardised port integration reaches 1.74, hardware investment's promoting effect on CEE peaks at 0.283, indicating that a 1% increase in hardware investment improves CEE by 28.3%. Research has found that regions face fragmentation issues in transport, with varying degrees of port digitalisation. Some ports still rely on traditional document exchange and manual management, despite system promotion, affecting transport and overall supply chain efficiency (Serra & Fancello, 2020). As the integration process advances, enhanced inter-port collaboration tends to emerge, thereby revealing the potential benefits of hardware facility resource sharing and the realisation of economies of scale effects across the integrated network. However, excessive integration may lead to technical incompatibility or maintenance complexity issues, reducing the promotional effect.

[Figure 2 about here]

5.3.3. Communication Investment Moderation

Building on previous results, we introduce the interaction between communications investment and port integration to test port integration's linear moderating effect. Model (2) in Table 9 shows that after introducing the first-order moderation term, the R^2 remains largely unchanged, with communications investment (LnCW) maintaining a significant positive effect on CEE (β = 0.181, t = 4.20). However, PI's first-order moderation term is insignificant (β = -0.077, t = -1.41), suggesting no clear linear moderating effect. This may be due to communications equipment's influence relying more on nonlinear pathways, such as network effects and collaborative efficiency.

Table 9. Moderation Effects: Communication Investment

Variable	(1) CEE	(2) CEE	(3) CEE
LnCW	0.152^{***}	0.181^{***}	0.163^{***}
	(4.37)	(4.20)	(4.40)
PI	-0.027	-0.077	-0.080
	(-0.61)	(-1.41)	(-1.55)
LnCW×PI		0.032	0.059^{**}
		(1.39)	(2.46)
LnCW×PI^2			-0.023^{***}
			(-3.06)
R&D	1.895^{**}	1.515^{*}	1.945^{**}
	(2.34)	(1.80)	(2.27)
Urba	-2.185^{***}	-2.139^{***}	-2.170^{***}
	(-3.02)	(-3.00)	(-3.30)
Str	0.093	0.049	0.044
	(0.83)	(0.42)	(0.42)
Gov	-1.606	-1.333	-1.695
	(-1.26)	(-1.04)	(-1.60)
_cons	0.976^{*}	0.796	0.957^{*}
	(1.78)	(1.52)	(1.88)
Year FE	YES	YES	YES
Individual FE	YES	YES	YES
N	108	108	108
r2_a	0.906	0.907	0.913
r2_within	0.283	0.297	0.356
F	5.047^{***}	3.882^{***}	6.035^{***}

Note: t statistics in parentheses, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Further analysis introducing the second-order interaction term (PI²×LnCW) shows significantly improved model fit (Model 3, Table 9). The regression results indicate that the interaction between communications investment and squared port integration is significantly negative at the 1% level, demonstrating an "inverted U-shaped" moderating effect. When port integration is low, it positively moderates communications investment's effect on CEE; as integration increases, this positive moderation weakens, supporting Hypothesis 3.

The inverted U-shaped moderating effect analysis (Figure 3) shows that communications investment's promoting effect on CEE peaks at 0.201 when standardised port integration reaches 1.28, indicating a 1% increase in communications investment improves CEE by 20.1%. Research notes that information and communications integration is crucial for port logistics integration (Alavi, Nguyen, Fei, & Sayareh, 2018). During initial integration stages, limited information flow between ports constrains communications equipment's effectiveness. As inter-port collaboration strengthens, network effects emerge, promoting information sharing and dynamic optimisation. However, excessive integration may introduce technical complexity and high coordination costs, weakening communications investment's positive impact.

[Figure 3 about here]

From a resource-sharing perspective, deeper integration strengthens inter-port resource sharing, enabling better resource allocation through communications systems. However, excessive integration may lead to resource misallocation, as ports have different circumstances and needs. In such cases, communications investment may fail to improve resource allocation effectively, potentially exacerbating resource waste through incorrect information transmission.

5.3.4. Software Investment Moderation

After examining moderation effects in hardware and communications components, we analyse port integration's moderating role in software investment. First, we introduce the interaction term (PI×LnSW) into the baseline regression model to test PI's linear moderating effect. As shown in Model (2) of Table 10, after introducing the first-order moderation term, software investment's coefficient remains positive at 5% significance (0.057), but PI's first-order moderation term is insignificant (β = -0.009, t = -0.64), indicating no clear linear moderating effect.

Table 10. Moderation Effects: Software Investment

Variable	(1) CEE	(2) CEE	(3) CEE
LnSW	0.063**	0.057*	0.046
	(2.62)	(1.98)	(1.64)
PI	-0.028	-0.004	0.006
	(-0.57)	(-0.06)	(0.10)
LnSW×PI		-0.009	0.010
		(-0.64)	(0.84)
LnSW×PI^2			-0.016***
			(-3.00)
R&D	0.637	0.868	1.383
	(0.76)	(1.01)	(1.54)
Urba	-1.560**	-1.696**	-1.750**
	(-2.22)	(-2.33)	(-2.59)
Str	0.001	0.049	0.064
	(0.01)	(0.27)	(0.40)
Gov	-0.021	-0.412	-1.025
	(-0.02)	(-0.34)	(-0.91)
_cons	1.347**	1.450**	1.571***
	(2.25)	(2.36)	(2.76)
Year FE	YES	YES	YES
Individual FE	YES	YES	YES
N	108	108	108
r2_a	0.895	0.894	0.902
r2_within	0.199	0.202	0.272
F	5.086***	4.269***	4.024***

Note: t statistics in parentheses, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Further analysis with the squared interaction term (Model 3, Table 10) shows no effective moderation of port integration on software investment's impact on CEE. Model (3) shows that while the (LnSW × PI) interaction term is not significant, the (LnSW × PI^2) term is significantly negative (-0.016, $p < 0.01$). However, the main effect of software investment (0.046) becomes non-significant in this specification. This pattern suggests that port integration's moderating effect on software investment operates primarily through the quadratic term, indicating that excessive integration suppresses software investment's emission reduction effects. The unclear overall inverted U-shaped relationship may be attributed to software investment's longer implementation periods and specific requirements for port integration levels.

This ineffective moderation may relate to several factors. Software architecture design may not adequately address port cluster integration needs. While integration requires systems supporting multi-port information sharing and resource coordination, many software architectures focus on single-port optimisation, failing to accommodate integration complexity. Research emphasises that technical adaptability is crucial for ICT investment's impact on regional economic and environmental performance (Du, Zhou, Bai, & Cao, 2023).

Integration demands specific software functionalities like real-time dynamic scheduling and cross-port resource allocation. Existing systems may lack these capabilities, leading to redundancy and inefficiency. Studies highlight collaboration as a key dimension of smart ports, emphasising seamless connectivity with supply chain partners through information systems (Belmoukari, Audy, & Forget, 2023). Without adapting to this dynamic complexity, software's moderating effect becomes limited.

5.4. Robustness Tests

5.4.1. Alternative Measures

To enhance confidence in the reliability and validity of our empirical findings, we implement comprehensive robustness analyses employing alternative proxy measures for our key independent variables. Following previous research, we use fixed investment amount (LnFI) as an alternative "flow" indicator (H. Zhang & Lin, 2021). Fixed investment amount serves as an effective proxy for ICT investment for several reasons. First, both fixed investment amount and productive capital stock represent investment flows, but fixed investment amount can reduce measurement errors arising from assumptions about depreciation rates, retirement patterns, and efficiency decay functions. Second, fixed investment data from official sources provides good data availability and authority, with ICT-related investments representing a significant portion of total fixed investments. Table 11's regression results show significant positive correlations between LnFI and CEE, consistent across hardware, communications, and software components, confirming our findings' robustness.

Table 11. Robustness Tests with Alternative Measures

Variable	(1) CEE	(2) CEE	(3) CEE	(4) CEE
LnFI	0.113^{***} (3.49)			
LnHFI		0.092^{***} (4.72)		
LnCFI			0.093^{***} (4.52)	
LnSFI				0.066^{***} (3.39)
Gov	-1.536 (-1.29)	-1.943^{*} (-1.82)	-2.022^{*} (-1.88)	-0.683 (-0.64)
Str	-0.016 (-0.13)	0.120 (1.19)	0.103 (1.01)	-0.062 (-0.45)
R&D	1.941^{**} (2.04)	1.658^{**} (2.10)	1.745^{**} (2.17)	1.162 (1.37)
Urba	-1.526^{**} (-2.38)	-1.737^{***} (-2.99)	-1.922^{***} (-3.14)	-1.449^{**} (-2.17)
_cons	1.009^{*} (1.76)	1.476^{***} (2.94)	1.472^{***} (2.90)	1.412^{**} (2.37)
Year FE	YES	YES	YES	YES
Individual FE	YES	YES	YES	YES
N	108	108	108	108

adj. R2	0.905	0.910	0.910	0.902
F	6.221	7.059	6.490	6.775

Note: t statistics in parentheses, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

5.4.2. Endogeneity Treatment

To address potential endogeneity, we employ instrumental variables (IV) methodology. Following established research, we select the number of post offices in 1984 as our instrumental variable, using two-stage least squares (2SLS) regression (Hering & Poncet, 2014). This instrument captures historical communication infrastructure development that influenced regional ICT investment patterns. The 1984 post office distribution reflects early regional development differences that preceded both current ICT investment decisions and modern port operations, satisfying the exogeneity requirement.

Since the 1984 post office variable is time-invariant and would be absorbed by individual fixed effects, following established methodology, we construct interaction terms between this historical instrument and time-varying ICT investment components (Nunn & Qian, 2014). This approach generates time-varying instruments that preserve the exogenous historical variation while providing identification in the fixed effects framework. Therefore, IV in Table 12 represents the interaction between 1984 post office numbers and respective ICT components.

Table 12. Instrumental Variable Estimation Results

Variable	(1) first LnICT	(2) second CEE	(3) first LnHW	(4) second CEE	(5) first LnCW	(6) second CEE	(7) first LnSW	(8) second CEE
IV	0.199***		0.182***		0.210***		0.232***	
	(0.0197)		(0.0186)		(0.0175)		(0.0289)	
LnICT		0.205***						
		(0.0524)						
LnHW				0.226***				
				(0.0698)				
LnCW						0.199***		
						(0.0469)		
LnSW								0.075**
								(0.0315)
Controls	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Individual FE	YES	YES	YES	YES	YES	YES	YES	YES
Kleibergen-Paaprk LM statistic		25.67***		25.60***		29.60***		13.22***
Kleibergen-Paaprk Wald F statistic		102.59***		96.02***		144.40***		64.44***
Cragg-Donald Wald F statistic		110.68***		104.76***		154.77***		187.88***
Observations	108	108	108	108	108	108	108	108
R-squared		0.243		0.256		0.262		0.191

Note: robust standard errors in parentheses, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The regression results demonstrate that after accounting for endogeneity, the effects of ICT investment and its hardware, communications, and software components on carbon emission efficiency remain consistent with baseline regressions. IV's estimated coefficients are significantly positive at the 1% level, satisfying the positive correlation assumption. The Kleibergen-Paap LM statistic rejects the null hypothesis of underidentification, while the Kleibergen-Paap Wald F statistic passes the weak instrument test.

Second-stage regression results show ICT's estimated coefficient remains significantly positive at the 1% level, consistent with baseline regression results. These findings confirm our main research conclusions remain valid after addressing endogeneity concerns.

6. Conclusions and Policy Implications

6.1. Main Findings

This research demonstrates that ICT investment significantly enhances carbon emission efficiency in regional port groups, though the relationship operates through multiple distinct pathways rather than a simple direct effect. Our analysis reveals important differences across types of digital investment. Hardware investment exerts the strongest impact, directly reducing energy consumption and emissions through automated loading systems, intelligent warehousing, and smart energy management equipment. Communication infrastructure ranks second in importance, enabling better coordination across port facilities by reducing vessel waiting times and facilitating real-time information exchange among stakeholders. Software investment shows a different pattern, with its influence on carbon efficiency operating primarily through organisational changes rather than direct technical improvements. These differential effects suggest that the composition of digital investment portfolios matters considerably. Ports cannot simply invest in any digital technology and expect similar environmental returns; rather, strategic choices about which technologies to prioritise and how to deploy them determine the magnitude of environmental benefits. The finding that different ICT components work through different channels also implies that effective digital transformation requires integrated approaches that combine physical infrastructure, communication networks, and software applications in ways that reinforce each other.

The mechanisms underlying these effects reveal how technology and organisation interact to produce environmental outcomes. Port specialisation emerges as a significant pathway, with digital infrastructure enabling individual ports within regional clusters to develop clearer functional differentiation. When ports specialise in particular cargo types or operational functions, they achieve economies of scale and develop technical expertise that reduces emissions per unit of throughput. However, this specialisation effect varies across technologies. Hardware and communication investments demonstrate both direct operational impacts and indirect effects through specialisation, while software relies more heavily on enabling organisational restructuring as its primary channel of influence. The moderating role of port integration adds another layer of complexity through an inverted U-shaped pattern. At low integration levels, fragmented governance and poor coordination constrain the potential benefits of digital technologies. As integration increases to moderate levels, enhanced coordination enables more effective utilisation of digital infrastructure for network-wide optimisation. Beyond certain thresholds, however, excessive consolidation generates bureaucratic complexity and reduces local flexibility, diminishing the positive effects of ICT investment. These optimal integration points differ across hardware, communication, and software contexts, suggesting that governance structures should be tailored to specific technological investments rather than pursuing uniform consolidation approaches.

These findings also illuminate important societal and governance implications. The transition towards automated and intelligent operations profoundly reshapes labour dynamics in port communities, as traditional manual processes give way to technology-intensive operations requiring different skill sets. While automation enhances environmental performance, it raises questions about workforce displacement and the need for retraining programmes that enable port workers to transition into new roles managing digital systems rather than performing physical tasks. The environmental benefits of digitalisation are also unevenly distributed across space and social groups. Ports located in densely populated urban areas stand to deliver greater health benefits from emission reductions, yet these same communities may face disruptions during the infrastructure upgrades necessary for digital transformation. The governance challenges revealed by the inverted U-shaped integration effect extend beyond efficiency considerations to encompass questions of political economy and stakeholder representation. Excessive consolidation not only reduces operational flexibility but may also concentrate decision-making authority in ways that limit local community input into port development priorities. The finding that specialisation serves as a mediating mechanism suggests that regional port systems function as complex socio-technical networks where individual facility decisions generate system-wide effects. This requires governance frameworks that balance local autonomy with regional coordination. These dynamics are particularly salient in emerging economies where ports simultaneously pursue digitalisation, economic development, and environmental sustainability while navigating diverse stakeholder interests and institutional capacities. The research thus underscores that successful port digital transformation depends not only on technology adoption but on managing the social transitions, governance adaptations, and stakeholder negotiations that accompany technological change.

6.2. Policy Recommendations

(1) Prioritise hardware and communication infrastructure investments. Given their strong direct effects on carbon efficiency, port authorities should allocate substantial resources to physical digital infrastructure and communication networks. Investment priorities should include automated loading and unloading systems, intelligent warehousing facilities, shore power infrastructure, and clean energy equipment that directly reduce operational emissions. Communication infrastructure development should focus on establishing robust networks enabling real-time coordination across spatially distributed facilities. To maximise returns, these investments should follow standardisation principles, establishing unified technical standards for digital devices and communication protocols across port clusters. Dedicated funding mechanisms can support equipment upgrades, while compatibility certification systems ensure new technologies integrate effectively with existing infrastructure. This approach avoids creating isolated technological islands that limit network-wide optimisation opportunities.

(2) Emphasise quality over quantity in software investments. Unlike hardware and communication infrastructure, software primarily influences environmental performance by enabling organisational specialisation rather than through direct operational improvements. Investment strategies should therefore shift from broad coverage of digital applications to targeted deployment aligned with functional differentiation objectives. Performance evaluation should move beyond simple adoption metrics to assess whether software genuinely enables better specialisation and coordination within regional port systems. Collaborative partnerships with research institutions can facilitate development of sophisticated scheduling algorithms and data integration solutions that support specialised operations. Training programmes should accompany software deployment to ensure personnel can effectively utilise digital tools and organisational structures evolve to capitalise on new capabilities. Software platforms should prioritise applications that clarify and reinforce functional divisions within port clusters while maintaining system-wide coordination.

(3) Adopt phased approaches to port integration. The inverted U-shaped moderating effect indicates that consolidation policies should recognise varying optimal levels and avoid excessive centralisation. Initial integration stages should prioritise connecting ports with similar technical standards while maintaining operational autonomy. This means establishing common data standards and shared information platforms

without requiring full administrative merger. Provincial or regional authorities should facilitate coordinated planning mechanisms that allow individual ports to participate in network-wide optimisation while preserving local decision-making capacity. As integration progresses, regular monitoring becomes essential to detect when consolidation approaches thresholds beyond which additional centralisation yields diminishing returns. Third-party evaluation institutions should conduct periodic assessments examining multiple performance dimensions including innovation capacity and environmental outcomes, not merely short-term efficiency gains. These evaluation systems provide evidence-based guidance on whether further consolidation serves regional objectives or whether preserving greater autonomy would better support long-term sustainability and adaptability.

(4) Guide functional specialisation aligned with environmental objectives. Since specialisation serves as an important mediating mechanism, policies should actively support functional differentiation within regional port systems. Port planning authorities should clarify divisions among facilities, designating hub ports for transhipment operations, logistics ports for value-added services, and specialised facilities for particular cargo types, with ICT deployment customised to support these distinctive functions. Carbon performance metrics should be integrated into berth allocation and scheduling mechanisms, creating incentives for specialised facilities to adopt low-carbon operational practices. Specialisation strategies should coordinate with regional industrial development plans to ensure port functional positioning aligns with hinterland economic structures. However, these policies must maintain sufficient flexibility for ports to adapt their functional positioning as market conditions and technological capabilities evolve, avoiding rigid assignments that constrain long-term development.

(5) Strengthen international cooperation on port digitalisation. Our findings provide empirical support for international frameworks promoting port digitalisation, including IMO initiatives and Paris Agreement provisions related to maritime emissions. International development institutions should consider prioritising digital infrastructure investments in developing country ports as cost-effective emission reduction pathways that simultaneously enhance operational capacity. Development assistance programmes should facilitate not only technology adoption but also capacity building that enables countries to adapt digital solutions to local contexts. Technology transfer initiatives should emphasise organisational knowledge and governance capabilities necessary for effective deployment, not merely hardware and software provision. International cooperation frameworks should promote sharing of best practices regarding investment composition strategies, governance models, and specialisation approaches that maximise environmental returns while maintaining operational flexibility. However, our finding regarding the inverted U-shaped integration effect offers an important caution. Rather than uniformly promoting port consolidation, international guidance should emphasise coordination mechanisms that preserve healthy competition and local autonomy while enabling network-wide optimisation. Port digitalisation initiatives should be coordinated with broader regional smart city development programmes, recognising that ports function as critical nodes within urban digital ecosystems whose environmental performance interconnects with surrounding communities and transportation networks. This coordination is particularly important for managing the workforce transitions and community impacts associated with automation and intelligent operations. Such integrated approaches can help ensure that environmental benefits are achieved in ways that support rather than undermine social equity and local economic development.

6.3. Limitations and Future Research

While this research provides valuable insights, several limitations warrant acknowledgement. First, our carbon emission measurement uses provincial-level data encompassing but not limited to port operations.

Though justified by systemic port-regional integration and data constraints, and controlled through fixed effects, future research should employ emerging port-specific emission inventories for more precise attribution. Second, provincial-level ICT investment measures capture regional digital infrastructure supporting ports but limit assessment of port-targeted investments. Future studies should exploit port-specific digitalisation programmes or enterprise-level data. Third, our sample of nine coastal provinces limits generalisability. Future research should extend to inland ports and international comparisons. Fourth, the 2008–2019 period predates major developments like 5G, AI, and blockchain; longer time series are needed. Fifth, we focus on specialisation as mediator while other channels (labour productivity, supply chain integration, modal shift) remain unexplored. Sixth, integration measurement through establishment years does not capture multidimensional consolidation aspects. Seventh, we do not examine heterogeneity across port types within systems. Eighth, potential nonlinear ICT investment effects require threshold models. Ninth, focusing solely on carbon emissions excludes other environmental dimensions. Finally, policy and institutional mediation factors warrant qualitative integration. Despite limitations, our findings provide robust evidence for environmental benefits of digital transformation in regional port systems.

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Data Availability

The datasets generated and analysed during the current study are available as supplementary files accompanying this article. Supplementary materials include the complete panel dataset (Data.xlsx) and Stata code for all statistical analyses (Analysis_Code.do). The primary data sources include publicly available statistical yearbooks and databases: China Port Yearbook, China Marine Statistical Yearbook, China Statistical Yearbook, China Electronic Information Industry Statistical Yearbook, China Energy Statistical Yearbook, China Regional Economic Statistical Yearbook, the National Bureau of Statistics website, and the EPS Global Statistical Data Analysis Platform.

Competing Interests

The authors declare no competing interests.

Artificial Intelligence (AI) Disclosure

No artificial intelligence tools were used in any aspect of the research process or manuscript preparation.

Ethical Approval

This article does not contain any studies with human participants performed by any of the authors.

Informed Consent

This article does not contain any studies with human participants performed by any of the authors.

Author Contributions

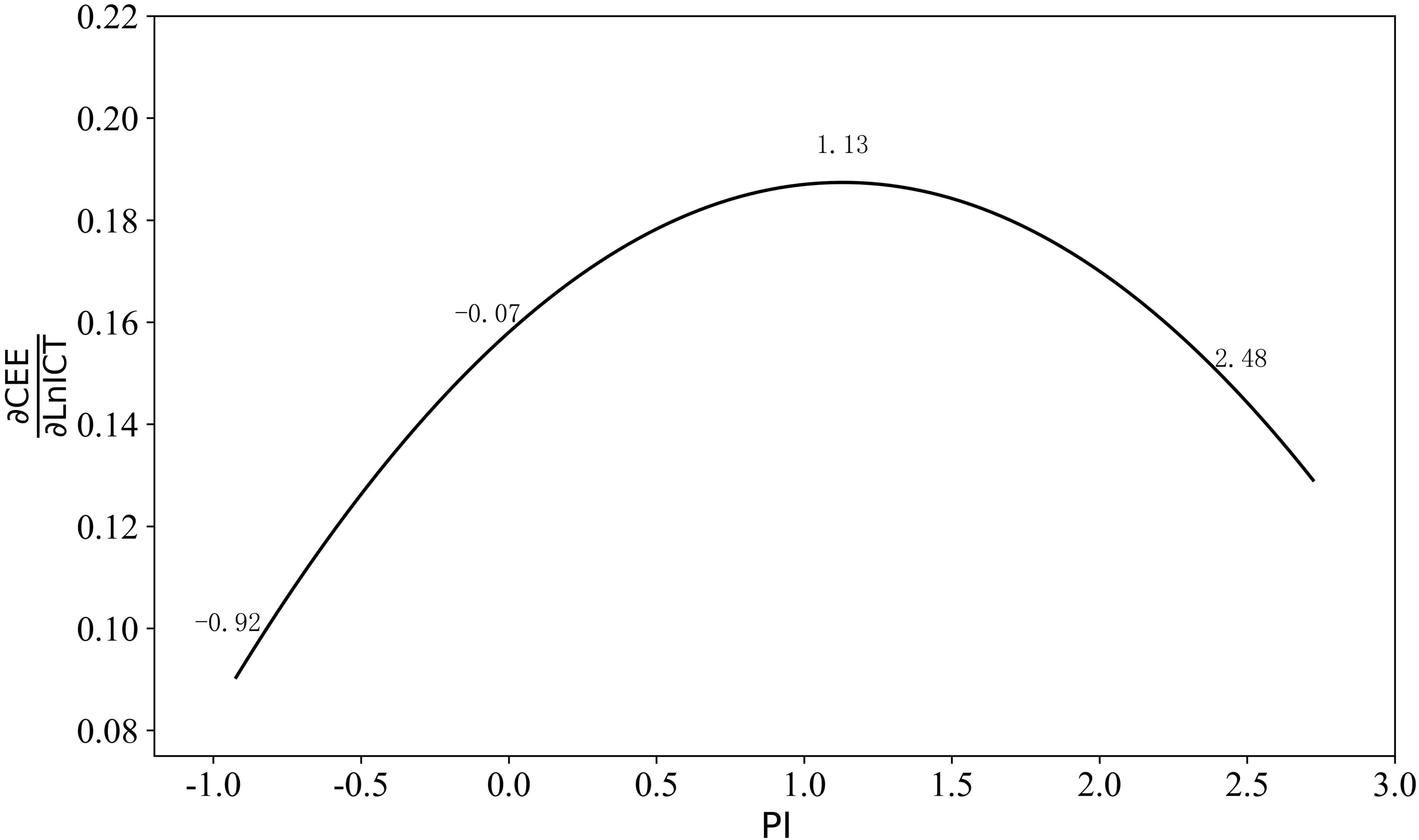
The first author conceptualized the study and contributed to methodology development; the second author participated in initial dr aft preparation and manuscript revision; the third author conducted formal analysis, data validation, wrote the main manuscript te xt, and led the writing and editing process. All authors have read and agreed to the published version of the manuscript.

Figure Legends

Figure 1. U-shaped Moderation of Port Integration on Digital Investment-Carbon Efficiency

Figure 2. U-shaped Moderation of Port Integration on Hardware Investment-Carbon Efficiency

Figure 3. U-shaped Moderation of Port Integration on Communication Investment-Carbon Efficiency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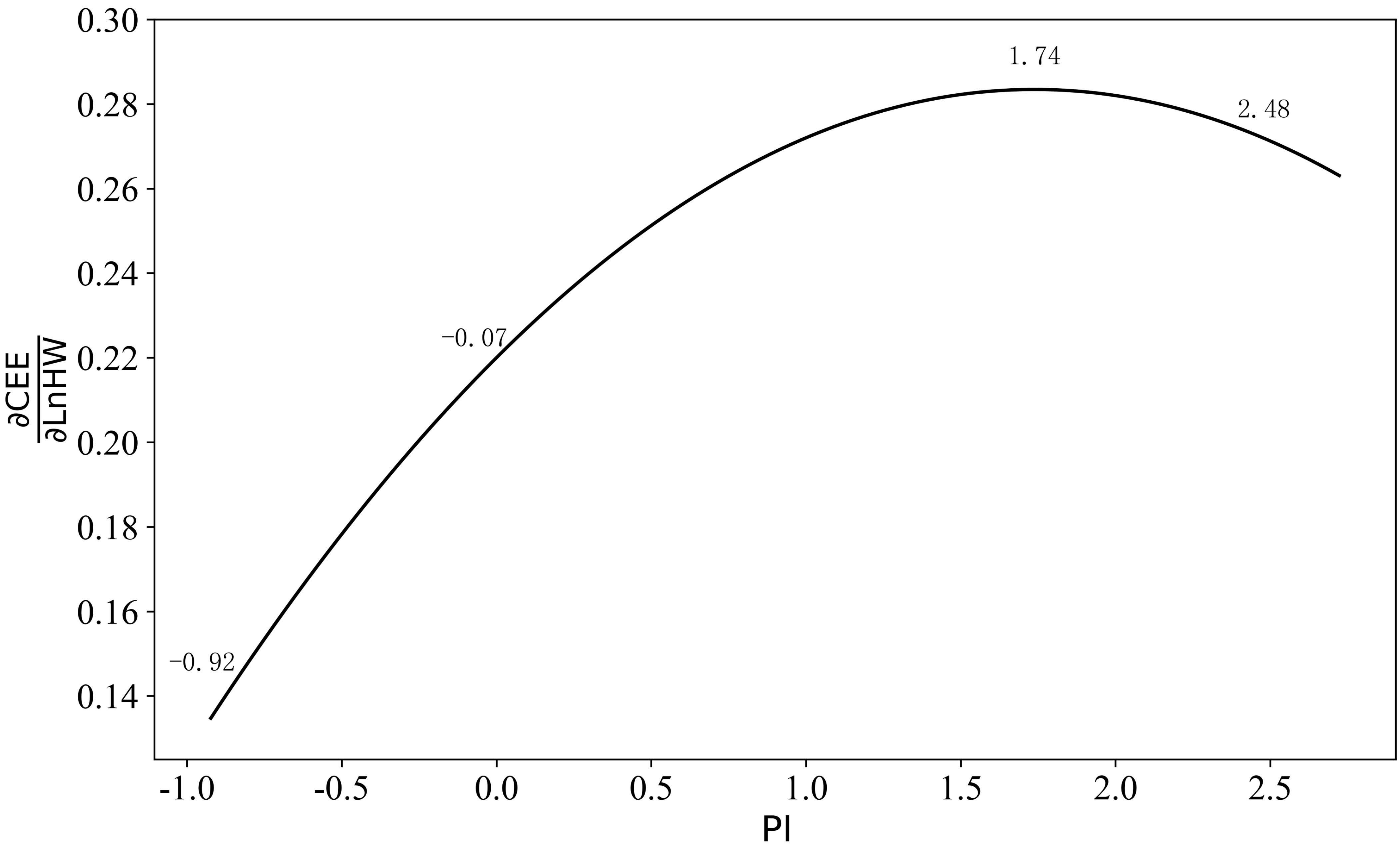
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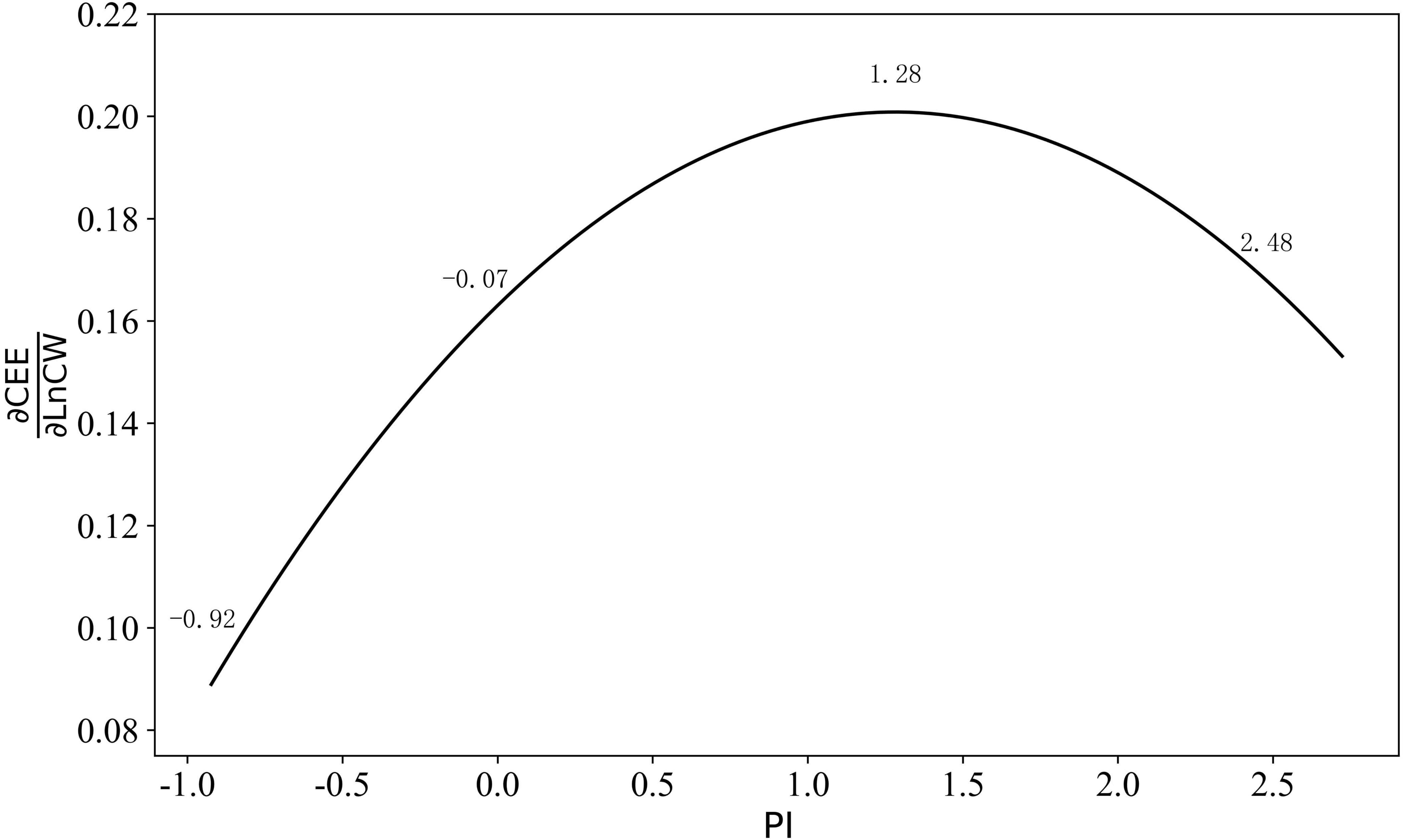
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