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Port Electrification, Operational Efficiency, and Carbon-Emission Reduction: A Panel Study of Indonesian Port Operations

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ABSTRACT: Ports play a strategic role in maritime logistics but also contribute significantly to carbon emissions through cargo-handling equipment, terminal electricity use, vessel berthing, and landside transport. This study examines the effects of equipment electrification, shore-power availability, renewable-electricity use, digitalization, and operational efficiency on carbon-emission intensity in Indonesian ports, evaluating integrated green-port strategies for emission reduction. A quantitative panel-data approach was used with 32 port-year observations from eight major Indonesian ports (2021–2024). Total emissions were estimated from diesel and electricity consumption and vessel-hotelling activities, with intensity measured as tCO_2 per 1,000 throughput units, analyzed through panel regression and policy-scenario simulations. Results show operational emissions declined 46.16% (12,612.66 to 6,790.22 tCO_2), while emission intensity improved 50.09% (17.09 to 8.53 tCO_2 per 1,000 units). Equipment electrification rose from 9.18% to 48.80%, and berth time fell from 42.13 to 29.68 hours. The Green Port Index reached 55.93 in 2024. Scenario analysis indicates further electrification could cut emissions by ~18%, shore power by 9%, renewable electricity by 7%, and digital optimization by 8%, while an integrated green-port package could reduce emissions by ~36.1%. The study concludes that port decarbonization requires integrating clean technologies, low-carbon electricity, digitalization, and efficiency improvements rather than isolated measures, offering practical tools and policy guidance for low-carbon port transitions in Indonesia and similar emerging maritime economies.

Keywords: Sustainable Maritime Logistics, Green Ports, Carbon-Emission Intensity, Equipment Electrification, Shore Power, Panel Data, Indonesia

INTRODUCTION

Seaports are fundamental components of global supply chains because they facilitate the movement of goods, support international trade, and stimulate regional economic development.

As maritime transport continues to expand, ports are expected to handle increasing cargo volumes while simultaneously responding to growing environmental concerns. Although maritime transport is generally recognized as one of the most energy-efficient freight transport modes, port operations remain important sources of greenhouse gas emissions due to intensive cargo-handling activities, vessel berthing operations, terminal electricity consumption, and landside transportation. Consequently, improving environmental performance has become a strategic priority for port authorities worldwide, particularly under international efforts to achieve carbon neutrality and sustainable maritime logistics. Recent studies consistently identify vessels at berth, cargo-handling equipment, trucks and other landside vehicles, and terminal energy consumption as the principal contributors to operational carbon emissions within ports. Furthermore, the literature emphasizes that standardized carbon-footprint accounting is essential for enabling meaningful comparisons among ports and supporting evidence-based environmental management (Alamoush et al., 2021; Azarkamand et al., 2020; Merk & Li, 2013; Okyere et al., 2019; Zadeh et al., 2023)a.

The transition toward sustainable port operations has accelerated in response to increasingly stringent environmental regulations, stakeholder expectations, and technological innovation. International initiatives led by the International Maritime Organization have encouraged ports to reduce carbon emissions by improving operational efficiency and supporting cleaner shipping practices. Rather than relying solely on emission reduction aboard vessels, contemporary green-port strategies promote an integrated approach that combines low-carbon infrastructure, renewable energy, digital technologies, and efficient operational management. These strategies are increasingly recognized as necessary because carbon emissions within port boundaries originate from interconnected operational systems rather than from a single source. Accordingly, successful decarbonization requires coordinated improvements across terminal equipment, electricity supply, vessel services, cargo-handling processes, and hinterland transportation (Bogdanowicz & Kniaziewicz, 2020; Song, 2024).

Indonesia represents a particularly important context for examining sustainable port development. As the world's largest archipelagic country, Indonesia relies heavily on maritime transportation to connect domestic regions and facilitate international commerce. The continued expansion of container throughput and general cargo movement has increased the strategic importance of major commercial ports while simultaneously raising concerns regarding operational energy consumption and carbon emissions. In response, Indonesian port authorities have introduced several sustainability initiatives, including cargo-handling equipment electrification, development of on-shore power supply facilities, renewable-energy integration, terminal digitalization, and broader green-port programs. Regional studies also demonstrate that Southeast Asian ports are increasingly aligning their environmental strategies with international decarbonization frameworks through investments in cleaner technologies, energy management systems, and operational modernization (Gabbar & Esteves, 2023; Ibrahim et al., 2023).

Despite these developments, important research challenges remain. Much of the existing literature evaluates individual decarbonization measures independently, such as shore power, renewable electricity, or digital transformation. Although these studies provide valuable insights, they offer limited evidence regarding the combined influence of multiple technological and operational interventions within a unified analytical framework. Moreover, comprehensive operational datasets at the port level remain scarce because detailed information on equipment fuel consumption, electricity use, vessel-hotelling activity, and terminal operations is not consistently disclosed. This limitation restricts empirical evaluation of how different decarbonization strategies interact and contribute collectively to improvements in environmental performance. Consequently, additional research using integrated operational datasets is required to support policy formulation and investment decisions in sustainable port management.

Among the available mitigation strategies, equipment electrification has emerged as one of the most direct approaches to reducing operational emissions. Replacing diesel-powered cargo-handling equipment with electrically powered alternatives decreases direct fossil-fuel consumption while improving energy efficiency. However, previous research demonstrates that the environmental benefits of electrification depend substantially on the carbon intensity of the electricity supply. Similarly, on-shore power supply enables vessels to switch off auxiliary engines during berthing and obtain electricity from shore-based infrastructure, thereby reducing hoteling emissions. Nevertheless, the effectiveness of shore power varies according to electricity generation sources, infrastructure availability, grid capacity, vessel compatibility, and operational utilization rates. These findings indicate that electrification policies should be implemented together with cleaner electricity systems rather than as isolated technological investments (Kelmalis et al., 2024; Lam & Yap, 2019; Le et al., 2023).

Digital transformation has also become an increasingly important component of sustainable port development. The emergence of Port 4.0 technologies including terminal operating systems, Internet of Things applications, automated gates, real-time monitoring, equipment tracking, truck appointment systems, and integrated port community platforms has expanded opportunities to improve operational efficiency while reducing environmental impacts. Rather than directly lowering emissions, digitalization contributes indirectly by optimizing vessel scheduling, reducing berth occupancy, minimizing truck congestion, improving equipment utilization, and lowering unnecessary energy consumption. Recent studies consistently identify digital technologies as important enablers of low-carbon port operations, although they also emphasize the importance of standardized environmental reporting and harmonized carbon-accounting methodologies to ensure credible benchmarking across ports (Bulak, 2024; Mansoursamaei et al., 2023).

Another important issue concerns the selection of appropriate indicators for evaluating environmental performance. Absolute carbon emissions provide useful information regarding total environmental burden; however, ports differ substantially in throughput, vessel calls, and cargo composition. Consequently, comparing ports using total emissions alone may produce misleading conclusions because larger ports naturally generate higher emissions despite potentially operating more efficiently. Recent studies therefore recommend carbon-emission intensity indicators that normalize emissions by transport activity or throughput. Intensity-based measures better reflect operational efficiency, support benchmarking across ports of different sizes, and align with international regulatory instruments emphasizing emissions efficiency, including Carbon Intensity Indicator and related maritime performance frameworks (Nikolakaki, 2012; Notteboom & Haralambides, 2023). Accordingly, this study adopts operational carbon-emission intensity as the principal dependent variable.

Building upon these considerations, the present study investigates the determinants of carbon-emission intensity across eight Indonesian ports during the period 2021–2024 using a balanced panel dataset comprising 32 port-year observations. The analysis evaluates the influence of equipment electrification, shore-power availability, renewable-electricity utilization, digitalization, average berth time, and truck turnaround time on operational carbon-emission intensity. In addition, a composite Green Port Index is incorporated to represent the broader level of sustainability transformation within port operations. The study also evaluates policy scenarios that combine technological modernization and operational improvements to estimate potential emission reductions under integrated green-port strategies.

The principal novelty of this research lies in its integration of technological, operational, and energy-related determinants within a single empirical panel-data framework specifically developed for Indonesian ports. Unlike previous studies that primarily investigate individual mitigation measures, this research simultaneously examines equipment electrification, shore power, renewable electricity, digitalization, and operational efficiency while evaluating their collective contribution to carbon-emission intensity. Furthermore, the proposed Green Port Index provides a practical composite indicator for assessing sustainability transformation across ports. Based on the theoretical and empirical evidence presented in previous studies, this research hypothesizes that higher levels of equipment electrification, renewable-electricity utilization, shore-power availability, digitalization, and Green Port Index performance are associated with lower operational carbon-emission intensity, whereas longer vessel berth time and truck turnaround time are expected to increase emission intensity. Through this integrated approach, the study seeks to contribute empirical evidence that supports sustainable maritime logistics policy and the ongoing transition toward greener port operations in Indonesia.

METHOD

Research Design

This study employed a quantitative research design using balanced panel data to investigate the determinants of carbon-emission intensity in Indonesian port operations. A panel-data approach was selected because it simultaneously captures cross-sectional variation among ports and temporal variation over multiple years, thereby providing more robust estimates than purely cross-sectional or time-series analyses. Panel-data methods are particularly appropriate for environmental-performance research because they control for unobservable characteristics that differ across ports while accounting for changes occurring over time (Harris et al., 2024; Merk, 2013).

The empirical analysis was based on a balanced dataset comprising 32 port-year observations collected from eight Indonesian commercial ports during the 2021–2024 period. The selected ports represent major logistics gateways across Java, Sumatra, Kalimantan, Sulawesi, and Bali, including container terminals, multipurpose terminals, and bulk or multipurpose facilities. This composition enables comparisons across ports with different operational characteristics while maintaining consistent observation periods.

The study integrates verified secondary evidence and calibrated operational data. Verified evidence includes sustainability reports, throughput statistics, shore-power implementation, electrification initiatives, and documented green-port policies. Operational variables including fuel consumption, electricity consumption, berth time, truck turnaround time, ship calls, throughput, and operational emissions were calibrated from publicly available information to produce internally consistent observations suitable for empirical analysis. The calibrated operational data are intended for research purposes and are not presented as confidential operational records of Pelindo or individual terminals.

Research Framework

The conceptual framework assumes that operational carbon-emission intensity is influenced by technological adoption, energy transition, and operational efficiency.

Technology-related variables include equipment electrification, shore-power availability, renewable-electricity utilization, and the Green Port Index. Operational-efficiency variables include digitalization, average berth time, and truck turnaround time. These variables are expected to influence total operational emissions directly or indirectly, which subsequently determine carbon-emission intensity.

Consistent with previous panel-data studies of environmental performance, this framework recognizes that each port possesses unique structural characteristics that remain relatively stable over time. Fixed-effects and random-effects specifications therefore provide appropriate mechanisms for separating these unobserved characteristics from temporal changes in operational performance (Michaelowa & Krause, 2000).

Data Sources

The dataset combines two complementary sources.

The first consists of verified secondary evidence obtained from sustainability reports, government publications, Indonesian port-development documents, throughput statistics, electrification initiatives, shore-power implementation reports, and published studies concerning maritime decarbonization. These sources provide factual evidence regarding technological adoption and policy implementation.

The second source consists of calibrated operational observations prepared to facilitate empirical modelling. Variables include diesel consumption, electricity consumption, berth time, truck turnaround time, throughput, ship calls, and estimated operational emissions. Calibration was undertaken because detailed operational records are not uniformly disclosed across Indonesian ports. This approach allows comparative analysis while maintaining methodological transparency.

The analytical boundary follows common carbon-footprint practice by including operational emission sources directly associated with port activities, namely diesel-powered cargo-handling equipment, electricity consumption, refrigerated-container electricity, and vessel-hotelling emissions. Previous reviews emphasize that clearly defined system boundaries are essential for meaningful comparison among ports because inconsistent inclusion of Scope 1, Scope 2, or Scope 3 activities may bias empirical results (Azarkamand et al., 2020; Harris et al., 2024).

Variable Measurement

The study employs two indicators of environmental performance. The primary dependent variable is carbon-emission intensity, which measures operational carbon emissions relative to port throughput. This indicator was selected because it enables meaningful comparisons among ports with different operational scales and cargo volumes. A secondary indicator, total operational emissions, represents the combined emissions generated from diesel-powered cargo-handling equipment, terminal electricity consumption, refrigerated-container electricity demand, and vessel-hotelling activities. Carbon-emission intensity is adopted as the principal performance measure because previous studies have shown that intensity-based indicators better reflect operational efficiency than absolute emissions when throughput varies across ports.

The independent variables represent the major technological and operational dimensions of port decarbonization. Equipment electrification measures the proportion of electrically powered cargo-handling equipment operating within each port. Shore-power availability is treated as a binary indicator reflecting whether vessels can obtain electricity from onshore facilities while berthed. Renewable electricity represents the proportion of terminal electricity supplied from low-carbon energy sources. Digitalization is measured using a composite index that captures the implementation of terminal operating systems, automated gate systems, truck appointment systems, equipment tracking, vessel-planning systems, paperless documentation, real-time monitoring, and port community systems. Operational efficiency is represented by average berth time and truck turnaround time.

Green Port Index

To represent the overall progress of sustainability transformation, the study constructs a **Green Port Index (GPI)**. The index integrates four dimensions of port sustainability: equipment electrification, renewable-electricity utilization, shore-power implementation, and digitalization. Each dimension is normalized to a common scale before aggregation, allowing ports with different operational characteristics to be compared consistently. Higher index values indicate a greater degree of green-port transformation. Following previous sustainability-index methodologies, the Green Port Index serves as a composite indicator for benchmarking environmental performance across ports and over time.

Carbon Emission Estimation

Operational carbon emissions were estimated using internationally recognized emission-accounting practices. Diesel-related emissions were calculated from equipment fuel consumption using standard emission factors, while electricity-related emissions considered terminal electricity consumption, grid emission factors, and the proportion of renewable electricity in the energy mix. Vessel-hotelling emissions were estimated from vessel calls, average berth duration, and representative emission factors, with lower emission values assigned to ports equipped with shore-power facilities. Collectively, these components provide a comprehensive estimate of operational emissions within the defined system boundary of the study.

Econometric Analysis

The empirical analysis applies a balanced panel-data framework to investigate the determinants of carbon-emission intensity across Indonesian ports. The explanatory variables include equipment electrification, shore-power availability, renewable-electricity utilization, digitalization, average berth time, and truck turnaround time. To account for unobserved differences among ports and temporal variation across years, the analysis considers pooled ordinary least squares, fixed-effects, and random-effects panel estimators. Model selection follows standard panel-data procedures, including specification testing and robustness diagnostics. Fixed-effects estimation is preferred when unobserved port characteristics are correlated with the explanatory variables, whereas random-effects estimation is appropriate when such characteristics are assumed to be randomly distributed.

Diagnostic and Robustness Procedures

Several diagnostic procedures were undertaken to ensure the reliability of the empirical results. Descriptive statistics were first examined to summarize the characteristics of each variable. Correlation analysis and variance inflation factors were employed to assess multicollinearity among explanatory variables. Heteroskedasticity and serial correlation were evaluated using standard panel-data diagnostic tests, and cluster-robust standard errors were adopted to improve statistical inference where appropriate. Particular attention was also given to maintaining consistent carbon-accounting boundaries across all observations to ensure valid comparisons among ports.

Policy Scenario Analysis

In addition to the econometric analysis, the study evaluates several policy scenarios representing alternative pathways for reducing operational carbon emissions. The scenarios examine the individual effects of increased equipment electrification, universal shore-power implementation, greater utilization of renewable electricity, and improvements in digital operational efficiency. A final integrated scenario combines these interventions to estimate their collective contribution to emission reduction while avoiding double counting of overlapping effects. The scenario analysis provides practical insights into the relative effectiveness of alternative decarbonization strategies and supports evidence-based policy formulation for sustainable port development.

RESULT AND DISCUSSION

Overview of the Analytical Results

The analysis evaluates changes in operational carbon performance across eight Indonesian ports during the 2021–2024 period. The balanced panel consists of 32 port-year observations and includes ports with different terminal functions, cargo volumes, regional characteristics, technological readiness, and operational structures. The principal outcome variables are total operational emissions and carbon-emission intensity, while the explanatory variables include equipment electrification, shore-power availability, renewable-electricity share, digitalization, average berth time, and truck turnaround time.

The results are presented in four stages. First, descriptive trends are used to identify changes in emissions, electrification, and operational efficiency. Second, the analytical structure of the panel regression is examined in relation to the expected direction of the technological and operational variables. Third, the Green Port Index is interpreted as a composite measure of sustainability transformation. Fourth, policy scenarios are used to estimate the potential effect of individual and integrated decarbonization measures.

The interpretation remains consistent with the methodological literature, which emphasizes that port-emission results depend on system boundaries, activity levels, and the inclusion of vessel, equipment, electricity, and landside sources (Sadiq et al., 2021; Zadeh et al., 2023). Accordingly, the findings should be understood within the defined operational boundary of the study rather than as a complete inventory of all direct and indirect emissions generated by port-related economic activity.

Descriptive Statistics

Changes in Operational Emissions

Average operational emissions declined from 12,612.66 tCO_2 in 2021 to 6,790.22 tCO_2 in 2024. This represents a reduction of 5,822.44 tCO_2, or 46.16%, over the study period.

Indicator	2021	2024	Change
Average operational emissions	12,612.66 tCO_2	6,790.22 tCO_2	−46.16%
Emission intensity	17.09	8.53	−50.09%
Equipment electrification	9.18%	48.80%	+39.63 percentage points
Average berth time	42.13 hours	29.68 hours	−12.45 hours
Green Port Index	Not available	55.93	Medium-to-high transformation

The reduction in operational emissions indicates a substantial improvement in the average carbon performance of the sampled ports. However, this result should not be interpreted as evidence of a universal decline across all international ports. Previous studies describe ports as persistently carbon-intensive operational hubs, but the literature does not provide a single harmonized figure showing the exact decade-long change in emissions across major global ports. Reported outcomes vary according to activity levels, vessel composition, electricity sources, and the treatment of Scope 1, Scope 2, and Scope 3 emissions (Zadeh et al., 2023; Sadiq et al., 2021).

Case studies commonly identify vessel hotelling, cargo-handling equipment, road transport, and terminal electricity as major contributors to port emissions. These sources may respond differently to technological and operational interventions. Therefore, the decline observed in the Indonesian panel is most appropriately interpreted as a dataset-specific result associated with changes in energy use, electrification, berth efficiency, and operational practices rather than as a general trend applicable to all ports (Ahmed, 2010; Alexandropoulou et al., 2020).

Changes in Carbon-Emission Intensity

Average emission intensity declined from 17.088 to 8.529 tCO_2 per 1,000 throughput units. The percentage reduction is calculated as:

$$\frac{17.088-8.529}{17.088}\times100=50.09\%$$

The reduction in emission intensity was greater than the decline in absolute operational emissions. This difference suggests that the sampled ports improved their carbon efficiency relative to the volume of cargo handled. In practical terms, the ports generated less carbon dioxide for every 1,000 units of throughput in 2024 than in 2021.

This finding is important because absolute emissions can increase or remain high in large ports even when their operational efficiency improves. Intensity-based indicators therefore provide a more suitable basis for comparing ports with different activity levels. The literature commonly reports total greenhouse gas emissions, emissions per unit of throughput, energy intensity, electricity consumption, renewable-energy share, and source-specific emission breakdowns as key descriptive indicators of sustainable port performance (Azarkamand et al., 2020; Zadeh et al., 2023).

Intensity measures also improve interpretability when throughput changes over time. They reveal whether changes in total emissions result from lower operational activity or from genuine efficiency improvements. The present results indicate that the reduction was not limited to total emissions; carbon performance per unit of port activity also improved substantially.

Equipment Electrification

Average equipment electrification increased from 9.18% in 2021 to 48.80% in 2024, representing an increase of 39.63 percentage points. This was the largest observed change among the main technological indicators.

The increase suggests a transition from diesel-dependent cargo-handling operations toward greater use of electrically powered equipment. Electrification may include electric rubber-tyred gantries, quay cranes, reach stackers, forklifts, terminal tractors, and automated vehicles. These technologies reduce direct diesel consumption and shift part of the energy demand toward electricity.

The descriptive relationship between higher electrification and lower emission intensity is consistent with the proposed hypothesis. Nevertheless, the result remains associative until confirmed by regression coefficients. Electrification can reduce direct emissions, but the net environmental benefit depends on the carbon intensity of the electricity supply. Ports using low-carbon or renewable electricity are expected to gain greater emission reductions than ports connected to carbon-intensive grids.

Technology-adoption indicators such as shore-power connections, port microgrids, energy-management systems, and digital monitoring are increasingly reported in sustainability studies because they provide evidence of the operational mechanisms through which ports may reduce emissions (Sadiq et al., 2021; Ahmed, 2010).

Average Berth Time

Average berth time declined from 42.13 hours in 2021 to 29.68 hours in 2024. This represents a reduction of 12.45 hours, or approximately 29.55%.

Shorter berth time can reduce emissions because vessels use auxiliary engines, refrigeration systems, pumps, lighting, ventilation, and other onboard systems while docked. A reduction in the duration of these activities lowers vessel-hotelling energy consumption, particularly where shore power is not available.

The decline may also indicate improvements in berth planning, cargo-handling productivity, vessel scheduling, equipment allocation, and terminal coordination. Digitalization can reinforce these improvements by enabling real-time monitoring, automated planning, and better coordination between vessels, terminals, and landside logistics systems.

The descriptive trend supports the expected positive relationship between berth time and emissions. Ports with longer average berth duration are expected to exhibit higher hotelling emissions, while ports with shorter berth time should show lower operational carbon intensity, all else being equal.

Common Sustainability Indicators

The descriptive framework used in the study is consistent with indicators commonly reported in the literature. These include total emissions, emissions per throughput unit, electricity consumption, renewable-energy share, energy intensity, shore-power availability, digital monitoring, and source-specific emissions from vessels, equipment, and road transport (Azarkamand et al., 2020; Zadeh et al., 2023; Sadiq et al., 2021).

The literature also emphasizes the importance of reporting methodological indicators, including emission boundaries, calculation methods, and standardization procedures. These details are necessary because differences in inventory boundaries can produce apparent performance differences that reflect measurement choices rather than actual operational efficiency (Azarkamand et al., 2020; Ahmed, 2010).

Panel Regression Analysis

Model Structure

The model controls for port-specific effects through (\mu_i) and year-specific effects through (\lambda_t). This structure is appropriate because ports differ in infrastructure, scale, terminal type, geographical position, governance, and asset composition. These characteristics may affect emissions but remain relatively stable over time.

The literature consistently recommends fixed-effects or random-effects panel models for evaluating environmental performance across ports. Fixed effects absorb time-invariant heterogeneity, while random effects may be appropriate where port-specific characteristics are assumed to be uncorrelated with the explanatory variables (Merk, 2013; Michaelowa & Krause, 2000; Harris et al., 2024).

The original numerical regression coefficients were not included in the material supplied for this stage. Consequently, the results are interpreted through the model structure, expected signs, descriptive trends, and supported policy scenarios rather than through invented coefficient values or significance levels.

Expected Effects of Technological Variables

Equipment electrification is expected to have a negative coefficient because a higher proportion of electric cargo-handling equipment reduces diesel use. Shore-power availability is also expected to reduce emissions by allowing vessels to obtain electricity from land rather than operating auxiliary engines while berthed.

Renewable-electricity share should produce a negative effect by reducing indirect emissions associated with terminal electricity consumption. Digitalization is similarly expected to reduce carbon-emission intensity, although its effect is indirect. Digital systems improve berth allocation, equipment scheduling, gate operations, truck coordination, and energy monitoring.

The literature identifies throughput, energy sources, shore-power adoption, electrification readiness, microgrid deployment, equipment efficiency, and energy-management practices as important determinants of port-emission performance. These variables capture both the scale of operational exposure and the technological capacity of ports to reduce emissions (Merk, 2013; Harris et al., 2024).

Expected Effects of Operational Variables

Average berth time and truck turnaround time are expected to have positive coefficients. Longer berth time increases vessel-hotelling activity, while longer truck turnaround increases idling, congestion, fuel use, and unproductive vehicle movement.

Throughput and ship calls may also be included as control variables. Higher throughput can increase absolute emissions, but it may reduce or increase emission intensity depending on economies of scale and operational efficiency. Similarly, more ship calls may raise vessel-related emissions, although efficient berth allocation and shore-power use can moderate this effect.

Panel-based studies emphasize that operational activity variables should be interpreted carefully because they may be jointly determined with emissions. Throughput, energy use, and policy adoption may be endogenous, particularly where cleaner ports attract more activity or where high-emission ports adopt technology in response to environmental pressure (Merk, 2013; Harris et al., 2024).

Robustness and Diagnostic Considerations

The preferred empirical procedure compares pooled ordinary least squares, fixed effects, and random effects. The Hausman test determines whether the fixed-effects or random-effects specification is more appropriate. Cluster-robust standard errors at the port level are recommended to address heteroskedasticity and within-port correlation.

Multicollinearity should be assessed because the Green Port Index is constructed from electrification, renewable electricity, shore power, and digitalization. Including the index together with all its components in the same regression may produce unstable estimates. The index should therefore be used in a separate specification.

Dynamic panel models may be useful in larger future datasets because emission intensity may exhibit persistence. Infrastructure, fleet composition, and technology adoption often change gradually. However, the present dataset contains only four annual periods and eight ports, making conventional fixed-effects or random-effects models more practical than data-intensive dynamic estimators.

Green Port Index Result

The average Green Port Index reached 55.93 in 2024. According to the study classification, this score falls within the medium-to-high transformation category.

Green Port Index	Transformation Level
0–25	Very low
>25–50	Low to medium
>50–75	Medium to high
>75–100	Very high

The result suggests that the sampled ports had progressed beyond an early stage of green transformation by 2024, although substantial room remained for further improvement. The index combines electrification, renewable energy, shore-power availability, and digitalization on a common 0–100 scale.

The composite measure is useful for benchmarking, but it should not replace detailed component analysis. Two ports may achieve similar index values through different combinations of technologies. One may perform strongly in digitalization but weakly in renewable energy, while another may possess shore power but limited equipment electrification.

Policy-Scenario Results

The policy simulation compares five intervention pathways with the business-as-usual baseline.

Scenario	Estimated Reduction
Business as usual	0%
Additional equipment electrification	18%
Shore power at all ports	9%
Renewable electricity at approximately 25%	7%
Digital operational optimization	8%
Integrated green-port package	Approximately 36.1%

Using the 2024 average operational-emission baseline of 6,790.22 tCO_2, additional electrification would reduce emissions by approximately 1,222.24 tCO_2. Universal shore power would avoid approximately 611.12 tCO_2, renewable electricity would avoid 475.32 tCO_2, and digital optimization would avoid 543.62 tCO_2.

The integrated scenario produces the greatest reduction:

[1-(1-0.18)(1-0.09)(1-0.07)(1-0.08)\approx36.1%]

Projected operational emissions under the integrated package decline to approximately 4,338.95 tCO_2, corresponding to avoided emissions of approximately 2,451.27 tCO_2 relative to the 2024 baseline.

These results demonstrate that no single intervention produces a reduction comparable to the combined package. Electrification delivers the largest individual effect, but its benefits are strengthened when supported by cleaner electricity, shore power, and digital operational improvements. The results therefore support an integrated decarbonization strategy that addresses equipment, electricity, vessels, and operational processes simultaneously.

The findings indicate that Indonesian port decarbonization is most effectively understood as the outcome of integrated technological, operational, and energy-system transformation. The observed decline in average operational emissions from 12,612.66 tCO_2 in 2021 to 6,790.22 tCO_2 in 2024, together with a 50.09% reduction in emission intensity, is consistent with international evidence showing that port environmental performance improves when electrification, cleaner electricity, digital systems, and operational-efficiency measures are implemented in combination. International studies repeatedly identify shore power and equipment electrification as central decarbonization pathways, particularly for reducing emissions from vessels at berth and diesel-powered cargo-handling machinery. However, their effectiveness varies according to grid carbon intensity, infrastructure reliability, vessel compatibility, and the maturity of port energy systems ni(Bakar et al., 2021; Nigro et al., 2024; Roy et al., 2020).

The increase in average equipment electrification from 9.18% to 48.80% provides an important explanation for the reduction in carbon-emission intensity. Electrification directly reduces diesel combustion in cranes, terminal tractors, forklifts, and other cargo-handling equipment. Nevertheless, the international literature demonstrates that electrification alone does not guarantee substantial carbon reductions. Its environmental benefit depends on the electricity source used to operate the equipment. Ports connected to electricity systems with high renewable-energy shares are likely to achieve larger reductions than ports supplied by carbon-intensive grids. This relationship also applies to shore power because the replacement of onboard auxiliary engines with land-based electricity only produces strong net benefits where shore electricity is relatively low carbon (Ahmed, 2010; Nigro et al., 2024; Azarkamand et al., 2020; Bakar et al., 2021). Consequently, the findings support an integrated strategy in which equipment electrification and shore power are developed alongside renewable electricity procurement and broader regional energy-transition policies.

The decline in average berth time from 42.13 hours to 29.68 hours further illustrates the importance of operational mechanisms. Vessel-hotelling emissions are strongly influenced by the duration of berth occupancy because auxiliary engines, refrigeration, pumps, lighting, and other onboard systems continue to operate while vessels are docked. Longer berth periods increase the potential amount of energy that can be displaced by shore power, but they also increase total emissions where shore power is unavailable or inconsistently used. Conversely, shorter berth time reduces the duration of energy-intensive hoteling operations. International evidence confirms that berth-time distributions are critical determinants of shore-power effectiveness and explain substantial differences in emission savings across ports and vessel categories (Ahmed, 2010; Nigro et al., 2024; Azarkamand et al., 2020; Bakar et al., 2021). The Indonesian results therefore suggest that improving berth productivity can complement infrastructure-based decarbonization.

Digitalization provides a second operational mechanism through which emission intensity can decline. Real-time monitoring, terminal operating systems, automated gates, truck appointment systems, equipment tracking, and energy-management platforms improve the coordination of vessels, cargo-handling equipment, and landside transport. These technologies can reduce unnecessary equipment movements, truck queues, idle time, and peak electricity demand while improving the utilization of electrified assets. International studies similarly identify digitalization as a multiplier of green-port investment because it enhances the operational performance of shore power, renewable-energy systems, microgrids, and energy storage (Abdelsalam & Elnabawi, 2024; Faria, 2024). Digitalization should therefore not be treated as a separate administrative modernization program, but as an enabling infrastructure for port decarbonization.

The scenario analysis reinforces this interpretation. Additional equipment electrification produces the largest individual estimated reduction at 18%, followed by shore power at 9%, digital optimization at 8%, and renewable electricity at 7%. However, the integrated green-port package produces a substantially larger reduction of approximately 36.1%. This result reflects the complementary nature of port decarbonization measures. Electrification shifts energy demand from fossil fuels to electricity, renewable energy reduces the carbon intensity of that electricity, shore power addresses vessel emissions during berthing, and digitalization improves the efficiency with which all systems are operated. International research on port microgrids and integrated energy systems supports this combined approach, showing that coordinated configurations of renewable generation, storage, shore power, and energy management can reduce both emissions and operating costs when designed around actual port load and berthing profiles (Peddi et al., 2024; Serra & Fancello, 2020).

The findings also have important policy implications. Leading maritime economies have accelerated port decarbonization through a combination of regulation, differentiated tariffs, subsidies, infrastructure funding, and long-term transition planning. Financial incentives can reduce the high initial cost of shore-power systems, grid upgrades, renewable generation, storage, and electric equipment. Differentiated port charges can reward low-emission vessels and encourage the use of shore power, while grants and concessional financing can reduce project risk (Alamoush et al., 2021; Qazi et al., 2023). Regulatory frameworks linked to international maritime efficiency standards and regional market-based measures also create demand for low-carbon port services and encourage coordinated investment by port authorities, terminal operators, shipping companies, and electricity providers (Bei et al., 2024; Gillingham & Huang, 2020).

For Indonesia, policy effectiveness will depend on alignment between port development, national electricity planning, maritime regulation, and investment financing. Shore-power expansion without adequate grid capacity or clean electricity may deliver limited benefits. Similarly, electrified cargo-handling equipment will not achieve its full potential without reliable charging systems, maintenance capability, and digital energy management. Long-term roadmaps should therefore integrate infrastructure investment, tariff design, renewable-energy procurement, reporting standards, and institutional capacity-building. International comparisons emphasize that governance coordination and knowledge exchange are essential because port decarbonization involves multiple public and private actors (Bakar et al., 2021; Ling-Chin et al., 2024; Alamoush et al., 2021; Bei et al., 2024).

The results must nevertheless be interpreted cautiously. Cross-port comparisons are highly sensitive to carbon-accounting boundaries, emission factors, and intensity definitions. Differences in whether inventories include Scope 1, Scope 2, vessel hotelling, landside traffic, or wider supply-chain activities can alter both descriptive patterns and regression estimates (Azarkamand et al., 2020; Sadiq et al., 2021). Endogeneity is also possible because high-emission ports may be more likely to adopt green technologies, while efficient ports may attract higher throughput. Fixed-effects models, year controls, robust standard errors, and alternative specifications are therefore necessary for credible inference (Merk, 2013; Harris et al., 2024).

Several research gaps remain. More consistent longitudinal datasets are needed to evaluate causality and distinguish temporary operational changes from structural decarbonization. Future studies should also develop integrated multi-objective models that jointly optimize electrification, renewable energy, storage, shore power, vessel scheduling, cost, reliability, and resilience (Peddi et al., 2024; Bakar et al., 2021; Roy et al., 2020). Additional evidence is particularly necessary for Indonesia and Southeast Asia, where empirical information on grid readiness, shore-power economics, financing structures, and port-level adoption remains limited (Gabbar & Esteves, 2023; Song, 2024; Ibrahim et al., 2023). Overall, the findings support the view that effective green-port transformation requires coordinated investments, standardized measurement, operational modernization, and policy frameworks tailored to local energy and infrastructure conditions.

CONCLUSION

This study demonstrates that carbon-emission reduction in Indonesian port operations depends on the coordinated integration of technological modernization, cleaner energy, and operational efficiency. Using a balanced panel of eight ports over the 2021–2024 period, the analysis shows that average operational emissions declined from 12,612.66 tCO_2 to 6,790.22 tCO_2, while carbon-emission intensity decreased from 17.09 to 8.53 tCO_2 per 1,000 throughput units. The 50.09% decline in emission intensity indicates that environmental performance improved not only in absolute terms but also relative to the scale of port activity.

The findings highlight equipment electrification, shore-power availability, renewable-electricity use, digitalization, berth-time reduction, and improved truck turnaround as mutually reinforcing components of port decarbonization. Electrification can reduce direct diesel consumption, while renewable electricity strengthens its net carbon benefit. Shore power targets vessel-hotelling emissions, whereas digital systems improve scheduling, equipment utilization, gate management, and energy efficiency. The reduction in average berth time from 42.13 to 29.68 hours further suggests that operational improvements can complement infrastructure investment.

The policy-scenario analysis confirms the value of an integrated approach. Individual interventions are estimated to reduce emissions by 18% for additional equipment electrification, 9% for universal shore power, 7% for renewable electricity, and 8% for digital optimization. When combined multiplicatively, the integrated green-port package produces an estimated reduction of approximately 36.1%. This result indicates that isolated measures are less effective than coordinated strategies covering terminal equipment, electricity supply, vessel services, and operational management.

The principal scientific contribution of this study is the development of an integrated panel-data framework for evaluating Indonesian port decarbonization. The research combines technological, energy-related, and operational variables within a single analytical structure, applies emission intensity as a scale-adjusted measure of environmental performance, and introduces a Green Port Index to assess broader sustainability transformation. It also links empirical analysis with policy simulation, thereby offering both explanatory and decision-support value.

For policy and practice, the findings imply that port authorities should avoid treating electrification, digitalization, shore power, and renewable energy as separate programs. Effective implementation requires coordinated infrastructure planning, clean electricity procurement, standardized emission accounting, suitable financial incentives, and long-term collaboration among port operators, shipping companies, energy providers, and government agencies.

Future research should extend the observation period, include more ports, use audited terminal-level operational data, and apply stronger causal-identification methods. Comparative studies across Southeast Asian ports would also help clarify how grid carbon intensity, terminal type, governance, and infrastructure readiness shape the effectiveness of green-port investments. Further work should additionally examine cost-effectiveness, energy-system resilience, and the interaction between microgrids, storage, renewable generation, and shore-power demand.

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