

## Energy Based Greenhouse Gas Inventory of Port Operations: A Case Study from Lampung, Indonesia

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### Abstract

This study aims to conduct an energy-based greenhouse gas (GHG) inventory of port operations at PT X, Lampung Province, Indonesia. The research evaluates direct (Scope 1) and indirect (Scope 2) emission sources to provide a quantitative overview of the port's carbon footprint and support the development of strategic decarbonization measures. The study employed the GHG Protocol using an energy consumption based approach covering the period from January to December 2023. Secondary data were obtained from company reports, including diesel fuel and electricity consumption. Emission calculations were performed using activity data and standardized emission factors from the Intergovernmental Panel on Climate Change (IPCC) and the Indonesian Ministry of Environment and Forestry (KLHK). The results show that the total annual GHG emissions from PT X amount to 6,287.74 tons of CO<sub>2</sub>, consisting of 2,850.96 tons from direct emissions and 3,436.78 tons from indirect emissions. The higher proportion of indirect emissions (54.66%) indicates a strong dependence on electricity supplied by PLN, which still relies heavily on fossil fuels. Electrification of heavy equipment and the adoption of energy-efficient LED lighting have effectively reduced direct emissions. The findings emphasize the importance of clean energy transition and integration of GHG inventories into environmental management documents. This study provides essential insights for achieving national decarbonization goals and developing sustainable low-carbon ports in Indonesia.

**Keywords:** *Electrification; Energy Consumption; Decarbonization; Greenhouse Gas Inventory*

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## INTRODUCTION

Global climate change, primarily caused by excessive greenhouse gas (GHG) emissions, represents one of the most urgent environmental challenges confronting the modern world (Filonchuk et al., 2024; Singh, 2021). In response, numerous industrial sectors have begun to evaluate their carbon footprints as part of international commitments to climate mitigation and sustainable development (Anzolin & Lebdioui, 2021; Karwacka et al., 2020; Labaran et al., 2022). Recent applied studies in Indonesia have also highlighted the relevance of sustainable infrastructure planning and emission-conscious development policies, particularly in transport and urban systems (Mawardi & Ardianti, 2025). Within this context, seaports function as vital logistical nodes that facilitate global trade while simultaneously contributing substantially to GHG emissions (Tae-Woo Lee et al., 2024; Verschuur et al., 2022; Zeng et al., 2023). These emissions originate not only from maritime vessel operations—such as propulsion during approach, mooring, and cargo handling but also from energy-intensive onshore activities involving heavy machinery, transportation fleets, and port facilities (Sarbanha et al., 2023; Xu & Chen, 2025). The combination of maritime and terrestrial energy consumption positions ports as critical focal points for emission reduction and low carbon transition initiatives (Wan et al., 2025; Zhang et al., 2024).

The inherently energy intensive nature of port operations underscores the necessity of integrated energy management and accurate emissions accounting (Yildiz et al., 2024). As demonstrated by (Huang et al., 2023), implementing integrated port energy systems and advancing port electrification can substantially reduce dependence on fossil fuels, thereby lowering total GHG emissions. In parallel, (Yona et al., 2020) emphasize that reliable and transparent GHG inventories are fundamental for both national and international climate governance, serving as baselines for evaluating emission trends and measuring policy effectiveness. Consequently, energy-based GHG inventorying emerges as a vital analytical tool that links operational energy consumption with emission sources, enabling more precise energy efficiency planning and evidence-based decarbonization strategies within the maritime logistics sector (Cholidis et al., 2025).

In Indonesia, ports play a strategic role in supporting national economic growth and inter-island connectivity (Curtis & Manuela Jr., 2025; Taharuddin et al., 2025). Lampung Province, which serves as a maritime gateway linking Sumatra and Java, has experienced rapid expansion in port activities to accommodate increasing cargo volumes. This expansion, however, has been accompanied by rising energy consumption. Previous studies in Lampung Province have also examined environmental quality indicators and thermal comfort analysis within university and urban facilities, providing methodological parallels for local-scale energy and emission but also to align port activities with national commitments to the energy transition and climate neutrality agenda (Alavi-Borazjani et al., 2025; Panggabean et al., 2024; Song, 2024).

Although recent studies have advanced GHG inventory methodologies and decarbonization frameworks across multiple sectors, research specific to port operations remains limited (Alamouh et al., 2022; Anantharaman et al., 2025). (Yona et al., 2020) stress the importance of refining national GHG inventory methodologies, while (Woolf et al., 2021) propose a biochar-based model for terrestrial carbon mitigation. (*Greenhouse gas emissions inventory data acquisition and analytics for low carbon cities*, 2022) and (*Adoption of quality standards for corporate greenhouse gas inventories: The importance of other stakeholders*, 2023) highlight the necessity of standardized reporting and data accuracy to ensure transparency, whereas

*(Uncertainties in the Emissions Database for Global Atmospheric Research (EDGAR) emission inventory of greenhouse gases, 2021)* reveal significant uncertainties in the global EDGAR database, indicating the need for more sector-specific emission accounting. Within maritime research, explore decarbonization pathways through alternative fuels, nuclear propulsion, and dual-fuel engine optimization, while investigate emissions arising from port operations, particularly during cargo handling and heavy equipment use. Nevertheless, most of these studies remain technologically oriented and lack comprehensive, energy-based GHG inventory frameworks that quantify both direct (Scope 1) and indirect (Scope 2) emissions at the operational level of ports in developing economies. This gap highlights the absence of empirical, energy-driven assessments in Indonesian ports that could inform the national Net Zero Emission 2060 roadmap.

This research aims to develop an energy-based greenhouse gas inventory for port operations at PT X in Lampung Province, Indonesia, following the methodological framework of the GHG Protocol. The study quantifies direct (Scope 1) and indirect (Scope 2) emissions associated with fossil fuel combustion and electricity consumption, identifies key emission sources, and proposes strategic recommendations for emission reduction. The outcomes are expected to serve as a scientific foundation for integrating GHG inventories into environmental management systems and supporting Indonesia's transition toward sustainable and low-carbon port operations.

## METHODS

### Study Area

This research was conducted at PT X, a port operator located in Lampung Province, Indonesia. The port serves as a major logistics hub connecting Sumatra and Java and operates as a center of energy consumption for various maritime and land-based activities. The study focused on energy related activities directly managed by the company, excluding activities from third-party tenants, visitors, and subsidiaries to ensure data consistency and operational accountability.

### Data Collection

The GHG inventory was developed using an energy consumption-based approach referring to the Intergovernmental Panel on Climate Change (IPCC). The analysis covered the period from January to December 2023. Secondary data were obtained from the company's internal energy records, which included:

1. Electricity consumption (kWh) for port facilities and equipment operations.
2. Fuel consumption (liters of diesel) for operational vessels, vehicles, and backup generators.

These datasets were verified through cross referencing with financial energy reports and monthly operational summaries to ensure accuracy and completeness.

## Emission Calculation

GHG emissions were calculated using the standard formula:

$$E = AD \times EF \dots\dots\dots (1)$$

where E denotes total GHG emissions (in tons of CO<sub>2</sub>), AD represents activity data (energy consumed), and EF refers to the emission factor (kg CO<sub>2</sub> per unit energy). Emission factors were derived from the Intergovernmental Panel on Climate Change and the Ministry of Environment and Forestry of Indonesia.

Two emission scopes were analyzed:

- Scope 1 (Direct emissions): Fossil fuel combustion under direct company control, including diesel used for generators and operational vessels.
- Scope 2 (Indirect emissions): Emissions from purchased electricity supplied by the national grid (PT PLN).

The calorific value of diesel fuel was assumed to be  $36 \times 10^{-6}$  TJ per liter, and the emission factor used for electricity was 0.74 kg CO<sub>2</sub>/kWh, in accordance with Indonesia's national grid average.

## Data Analysis

The emission data were processed using Microsoft Excel to perform quantitative estimations and comparative analyses between emission sources. Results were expressed in tons of CO<sub>2</sub> per year and categorized by energy type to determine dominant sources. The distribution of Scope 1 and Scope 2 emissions was then visualized using charts to illustrate the proportional contributions of direct and indirect emissions. Finally, emission intensity per operational activity was evaluated to support the identification of key areas for emission reduction and energy efficiency improvements.

# RESULT AND DISCUSSIONS

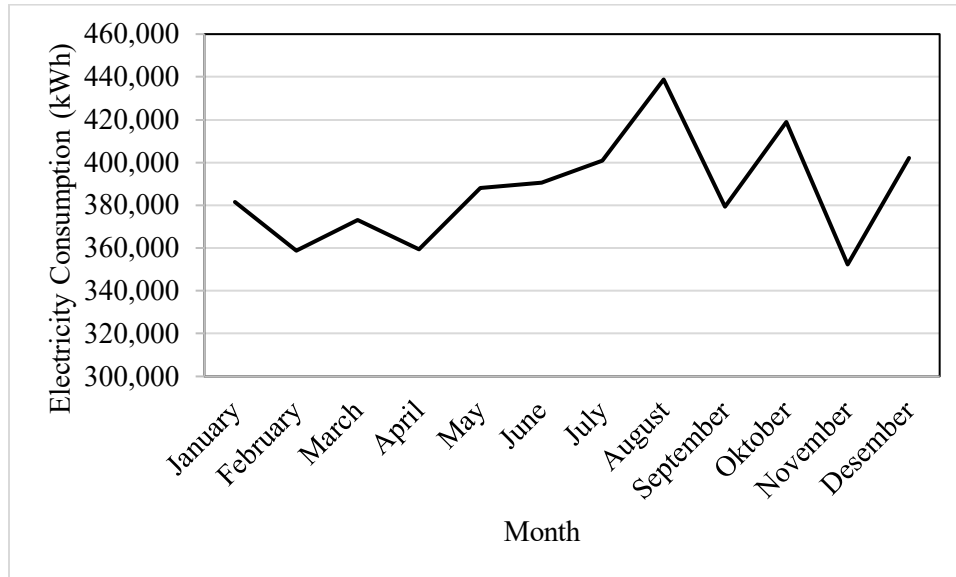
## Emission Source Identification

### Scope 1 (Direct Emissions)

Direct emissions refer to all greenhouse gas emissions that are generated from sources under the direct control of an organization or company (Teske et al., 2022). At PT X, direct emissions consist of those produced by generator units (as stationary sources) and operational vessels (as mobile sources), both of which fall under the company's direct operational control. PT X utilizes two generator units as stationary sources, which are activated during emergency situations when power outages occur from PT PLN, the electricity provider. These generators run on diesel fuel, resulting in greenhouse gas emissions from the combustion process. The recorded diesel fuel consumption for the generator units is 4,150 liters per year. PT X also operates marine vessels as part of its daily activities, including towing barges and cleaning the port basin. The use of these operational vessels contributes to greenhouse gas emissions through fuel consumption. Based on the identification, PT X owns 8 vessels categorized as mobile sources. The total diesel fuel consumption for these vessels is recorded at 1,064,588 liters per year.

## Scope 2 (Indirect Emissions)

Indirect emissions refer to greenhouse gas emissions resulting from the consumption of electricity, steam, and/or heat that is purchased from external providers (Teske et al., 2022). At PT X, indirect emissions are generated from the purchase of electricity supplied by PT PLN. In this case, the emission factor applied does not account for distribution losses. The total electricity consumption recorded by PT X amounts to 4,644,305 kWh per year.



**Figure 1.** Electricity Consumption per Month

Figure 1 illustrates the monthly electricity consumption at PT X's port throughout the year, showing a fluctuating pattern that reflects operational dynamics. The highest consumption was recorded in August at 438.80 kWh, likely driven by increased cargo handling activities or intensive use of heavy equipment such as cranes and RTGs. In contrast, the lowest consumption occurred in November at 352.33 kWh, possibly due to reduced operational volume or the implementation of energy efficiency measures. The average monthly electricity consumption was 387.03 kWh. This trend highlights the port as a significant energy consumer, and the fluctuations in electricity use can serve as key indicators for energy efficiency planning and GHG emission management in the maritime sector.

## Greenhouse Gas Calculations

Greenhouse gas emission calculations can be classified based on levels of methodological detail known as "tiers," which consist of three levels: Tier 1 uses standard activity data and default emission factors provided by the IPCC; Tier 2 applies more detailed activity data along with country or facility specific emission factors; and Tier 3 relies on national methods using directly measured data and highly specific emission factors. In this study, GHG emissions were calculated using the Tier 1 approach, as outlined in the National Greenhouse Gas Inventory Guidelines, Book II Volume I, published in 2012.

### Scope 1 Emission Calculation

Emission calculation for direct emissions uses activity data in the form of the amount of fuel used and default emission factors according to IPCC 2006, adjusted to the type of emission source produced. For stationary emission sources, the emission factor for diesel fuel in the manufacturing industry is 74,100 kg CO<sub>2</sub>/TJ. The default emission factor from IPCC is expressed in units of emissions per unit of energy consumed (kg GHG/TJ). However, the available energy consumption data is in physical units, namely liters of diesel fuel. Therefore, before being used in Equation 1, the energy consumption data as activity data needs to be converted into energy units (TJ - Terajoules) using the following equation:

$$AD = EC \times CV \dots\dots\dots (2)$$

EC = Energy Consumption, which refers to the amount of energy used (in liters of diesel fuel).

CV = Calorific value refers to the amount of energy released when a fuel is consumed or completely combusted ( $36 \times 10^{-6}$  TJ per liter of diesel fuel).

Based on the above formula, the following is the result of the emission calculation from the direct emission category:

**Table 1.** Direct Greenhouse Gas (GHG) Emissions from Fuel Combustion in Port Operations (Scope 1)

| No           | Emission Source               | Fuel Type | Energy Consumption (L) | Activity Data (TJ) | Emission Factor (kg CO <sub>2</sub> /TJ) | Total CO <sub>2</sub> Emissions (tons) |
|--------------|-------------------------------|-----------|------------------------|--------------------|--|--|
| 1            | Generator Operation           | Diesel    | 4,150                  | 0.15               | 74,100                                   | 11.07                                  |
| 2            | Operational Vessel Activities | Diesel    | 1,064,588              | 38.33              | 74,100                                   | 2,839.89                               |
| <b>TOTAL</b> |                               |           |                        |                    |  | <b>2,850.96</b>                        |

### Scope 2 Emission Calculation

Indirect emissions are generated from the use of electricity supplied by the national grid (PLN) over the course of one year. These emissions are calculated by multiplying the total electricity consumption of 4,644,305 kWh by an emission factor of 0.74 kg CO<sub>2</sub>/kWh. The result is a greenhouse gas (GHG) emission of 3,436.78 tons of CO<sub>2</sub>. This category of emissions falls under Scope 2, which includes indirect GHG emissions from the generation of purchased electricity consumed by the organization. The emission factor used (0.74 kg CO<sub>2</sub>/kWh) reflects the average carbon intensity of the national electricity grid. By applying this factor to the annual electricity consumption, the total indirect emissions can be quantified, providing a basis for evaluating energy-related environmental impacts and identifying opportunities for emission reduction through energy efficiency or renewable energy sourcing.

## Results of GHG Emissions Inventory

The total greenhouse gas emissions generated by PT X during the reporting period are derived from two main categories: direct emissions (Scope 1), which originate from fuel combustion in operational activities, and indirect emissions (Scope 2), which result from electricity consumption. The summary of these emissions is presented in the table below, providing a comprehensive overview of the company's carbon footprint and serving as a baseline for future mitigation strategies. Based on the calculation results of both direct and indirect emissions, the total emissions produced by PT X can be seen in the following table:

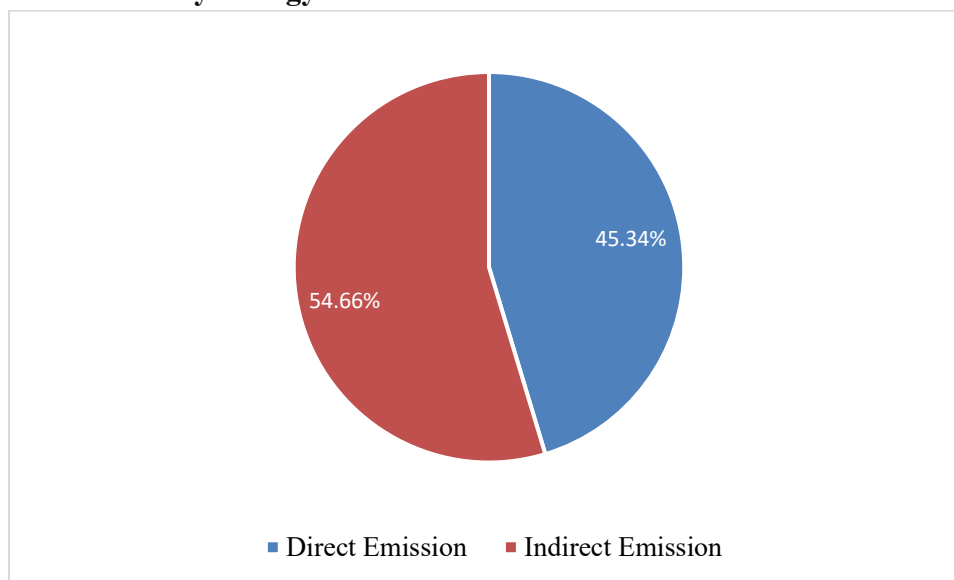
**Table 2.** Summary of Total Greenhouse Gas (GHG) Emissions from Port Operations (Scope 1 and Scope 2)

| No | Emission Source   | Total Emissions (tons CO <sub>2</sub> ) |
|----|-------------------|---|
| 1  | Direct Emission   | 2,850.96                                |
| 2  | Indirect Emission | 3,436.78                                |
|    | TOTAL             | 6,287.74                                |

Based on the emissions inventory data, the total greenhouse gas (GHG) emissions produced by PT X amount to 6,287.74 tons of CO<sub>2</sub>. This figure comprises 2,850.96 tons of CO<sub>2</sub> from direct sources (Scope 1) and 3,436.78 tons of CO<sub>2</sub> from indirect sources (Scope 2).

Direct emissions primarily result from the combustion of fossil fuels in port operations, such as the use of heavy machinery and vehicles. Indirect emissions, on the other hand, stem from the consumption of purchased electricity used to support port activities. The higher proportion of indirect emissions highlights the critical importance of improving energy efficiency and transitioning to low-carbon energy sources as part of the overall strategy to reduce emissions.

## Emission Distribution By Energy Source



**Figure 2.** Emission Distribution By Energy Source

Figure 2 illustrates the distribution of PT X's greenhouse gas (GHG) emissions, with direct emissions accounting for 45.34% and indirect emissions for 54.66%. Direct emissions originate from on-site fossil fuel combustion activities, such as diesel-powered generators and operational vehicles. Meanwhile, indirect emissions are entirely attributed to electricity purchased from the national grid (PLN), which powers heavy equipment that has been transitioned to electrified systems. This electrification initiative is part of PT X's decarbonization strategy for port operations, aligning with the global trend of electrifying heavy industrial sectors.

Electrification of heavy equipment such as cranes, RTGs, reach stackers, and forklifts at PT X's port has significantly reduced fossil fuel consumption. However, since Indonesia's electricity supply is still predominantly generated from fossil fuel-based power plants, especially coal, indirect emissions remain the largest contributor to the company's overall carbon footprint. A study by Adicita et al. (2021) [8] indicates that electricity consumption in the industrial sector can result in emissions of up to 0.975 tons of CO<sub>2</sub> per MWh, depending on the national energy mix. Therefore, while electrification helps reduce direct emissions, transitioning to cleaner electricity sources is essential to lowering indirect emissions. PT X's electrification strategy represents a progressive step toward a low-emission port. Nevertheless, to meet national GHG reduction targets, the company should consider sourcing electricity from renewable energy or adopting green electricity procurement schemes to further reduce its indirect emissions.

### **Emission Reduction Programs**

Maritime transportation is globally recognized as one of the most efficient modes of transport, capable of moving large volumes of cargo with relatively low fuel consumption per unit mass of product. According to Zulfikar et al. (2023) [1], maritime transport contributes approximately 3.3% to total global greenhouse gas (GHG) emissions. The emissions inventory results indicate that PT X's indirect emissions are higher than its direct emissions, amounting to 3,436.78 tons of CO<sub>2</sub>, or 54.66% of the total emissions. This is primarily due to the electrification of heavy equipment that previously operated on diesel fuel and now runs on electricity supplied by PLN. Electrification is a strategic step in the port's operational decarbonization efforts, aligned with the national program for green port transformation. Electrification is often integrated with automation systems that utilize modern technologies such as sensors and automatic controls. This integration aims to streamline operational processes, reduce energy consumption, and enhance both efficiency and productivity.

The heavy equipment electrification program has proven to significantly reduce direct emissions. For instance, a single diesel-powered Rubber Tyred Gantry (RTG) can generate up to 1,072 kg of CO<sub>2</sub> per day, whereas its electric counterpart produces zero direct emissions. However, since electricity supplied by PLN is still predominantly generated from fossil fuel-based power plants, indirect emissions remain a challenge. A study conducted by Pustral UGM (2025) [10] found that electrifying operational vehicles at ports can reduce emissions by up to 78.5%, although the effectiveness of this reduction is highly dependent on the national electricity generation mix.

In addition, as part of its efforts to reduce emissions from electricity consumption in the lighting sector, PT X has implemented a lighting system transition strategy by replacing incandescent and fluorescent lamps with energy-efficient LED lighting. The use of LED lamps results in emissions of approximately 70 tons of CO<sub>2e</sub> per hectare, compared to 92 tons from fluorescent lamps and 422 tons from incandescent lamps. This clearly demonstrates that LED technology is significantly more efficient in terms of carbon emissions than other lighting types

In the context of national policy, electrification and the adoption of clean energy have become key components of the government's strategy to achieve Net Zero Emissions (NZE) by 2060. Aligned with this national goal, Pelindo, as the national port operator, has set a target to reduce greenhouse gas (GHG) emissions by 31.89% by 2030 through electrification, energy efficiency, and digitalization of services. Accordingly, PT X's initiative to electrify heavy equipment represents a concrete contribution to national climate targets and the broader decarbonization agenda. Although decarbonization technologies such as electrification, energy efficiency, and renewable energy utilization are already available and proven to significantly reduce emissions, high initial investment costs often pose a major barrier for industries, particularly in the manufacturing and logistics sectors. As a result, many companies delay implementation, despite the substantial potential for long-term cost savings and improved competitiveness. With such an approach, the transition toward a low-carbon industry becomes not only an environmental responsibility but also a sustainable economic opportunity. A study conducted by Climateworks (2025) highlights that energy-intensive sectors such as chemical, textile, and food & beverage industries have significant potential for energy savings through technological and process upgrades. However, high initial investment costs remain a major obstacle, even though the long-term benefits in terms of efficiency and reduced dependence on fossil fuels are highly promising.

### **Policy Recommendations**

- **Clean Energy Procurement**  
PT X is advised to begin transitioning its electricity source from conventional PLN supply to renewable energy options, such as rooftop solar PV systems, purchasing electricity from green energy providers, or entering Power Purchase Agreements (PPAs) with renewable energy producers. This shift would significantly reduce indirect emissions and support the national energy transition agenda.
- **Integration of Emissions Inventory into Environmental Documents**  
The results of the GHG emissions inventory should be incorporated into environmental documents such as AMDAL, RKL-RPL, and the company's sustainability reports. This integration will enhance transparency and accountability in environmental management and serve as a foundation for setting emission reduction targets aligned with Science-Based Targets (SBTi).
- **Incentives and Regulations for Electrification**  
The government should expand fiscal incentives for the electrification of heavy equipment in the port sector, including tax reductions, investment subsidies, and streamlined permitting

processes. This aligns with existing policies such as PMK No. 38 of 2023 and ESDM Regulation No. 3 of 2023, which support electric vehicle incentives.

- **Digitalization and Emissions Monitoring**  
PT X can adopt digital systems such as PLN Climate Click to monitor GHG emissions in real-time, facilitate reporting, and access carbon trading schemes. Collaboration with the Directorate General of Electricity (Ditjen Gatrik) and PLN will improve data accuracy and enhance the effectiveness of emission mitigation efforts.
- **Multi-Stakeholder Collaboration and Education**  
Collaboration among companies, government, academia, and communities is essential for developing low-carbon technologies, promoting environmental education, and training human resources. This approach will strengthen institutional capacity to address climate change challenges.

## **Discussion**

The findings of this study indicate that the total greenhouse gas (GHG) emissions generated from port operations at PT X reached 6,287.74 tons of CO<sub>2</sub> per year, with indirect emissions (Scope 2) accounting for 54.66% a reflection of the port's heavy dependence on fossil based electricity supplied by the national grid. Although the electrification of heavy equipment such as cranes, rubber tyred gantries, and forklifts has significantly reduced direct emissions and improved operational efficiency, the carbon intensity of grid electricity remains a substantial barrier to achieving full decarbonization. This condition highlights that electrification alone is insufficient unless accompanied by a transition toward renewable energy sources such as rooftop solar PV systems or green electricity procurement schemes. Moreover, the implementation of energy efficient technologies, particularly the replacement of conventional lighting with LEDs, has further contributed to emission reductions while enhancing energy performance and maintenance efficiency. Integrating GHG inventory data into environmental management systems, including AMDAL and RKL RPL, is essential for institutionalizing emission accountability and aligning corporate practices with the Science-Based Targets initiative (SBTi). From a policy standpoint, this study underscores the importance of government incentives and cross-sectoral collaboration to accelerate low-carbon transitions within the maritime sector. Overall, the case of PT X demonstrates that energy based GHG inventorying provides not only a quantitative understanding of emission profiles but also a practical foundation for designing comprehensive mitigation strategies that advance Indonesia's pathway toward sustainable and climate-resilient port operations.

## **Implication**

The implications of this study extend beyond the operational boundaries of PT X, offering valuable insights for the advancement of sustainable port management and national decarbonization policy. The results demonstrate that integrating energy-based GHG inventories into port operations provides a robust foundation for decision-making related to emission mitigation, energy transition, and environmental accountability. By identifying electricity consumption as the dominant

emission source, this research emphasizes the urgent need to accelerate renewable energy adoption within the port sector and strengthen collaboration between port authorities, energy providers, and policymakers to ensure a cleaner electricity mix. Furthermore, the successful implementation of electrification and energy efficient technologies, such as LED systems, underscores the potential of technology driven interventions to enhance both environmental and economic performance. These findings also suggest that embedding GHG accounting within regulatory and corporate frameworks such as AMDAL, RKL RPL, and sustainability reporting can institutionalize low carbon practices and improve transparency across the maritime industry. Ultimately, this study contributes to the broader discourse on sustainable transportation and climate mitigation by demonstrating how evidence-based emission inventories can guide the design of resilient, low-emission ports that support Indonesia's Net Zero Emission 2060 agenda.

### **Limitation and Suggestion for Further Research**

This study is limited by the availability and scope of secondary data, which primarily rely on annual records of fuel and electricity consumption obtained from company reports without incorporating temporal variability or operational fluctuations. The analysis also applies the Tier 1 approach using default emission factors from the IPCC and national guidelines, which, although reliable for baseline estimation, may not fully capture site-specific emission dynamics influenced by fuel quality, equipment efficiency, and local grid composition. Additionally, the study focuses solely on Scopes 1 and 2 emissions, excluding Scope 3 activities such as logistics, third-party operations, and waste management, which could represent significant sources of indirect emissions. Future research should adopt higher-tier methodologies (Tier 2 or Tier 3) incorporating direct measurements, continuous monitoring systems, and life-cycle assessment (LCA) approaches to enhance emission accuracy and comprehensiveness. Further studies could also explore scenario modeling for renewable energy integration, techno-economic assessments of port decarbonization strategies, and comparative analyses among different ports to formulate scalable frameworks for achieving sustainable and low-carbon maritime logistics.

## **CONCLUSION**

In conclusion, this study establishes that energy-based greenhouse gas (GHG) inventorying serves as an effective and quantifiable framework for assessing emission sources in port operations, thereby facilitating evidence-based decarbonization planning. The total emissions of 6,287.74 tons of CO<sub>2</sub> identified at PT X highlight the dominance of indirect emissions from electricity use, underscoring the urgent need for a cleaner national energy mix to complement ongoing electrification and efficiency measures. The implementation of electric powered heavy equipment and LED lighting demonstrates the tangible benefits of technological innovation in reducing direct emissions and enhancing energy efficiency. Furthermore, integrating GHG inventory results into environmental management systems such as AMDAL and RKL RPL can institutionalize sustainability reporting and improve regulatory transparency. These findings emphasize that achieving low carbon port operations requires not only technological transformation but also

policy alignment, stakeholder collaboration, and investment in renewable energy infrastructure. Consequently, this research contributes to the broader goal of developing resilient and sustainable maritime logistics systems that support Indonesia's long term commitment to the Net Zero Emission 2060 agenda.

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## AUTHORS CONTRIBUTIONS STATEMENT

All authors contributed substantially to the conception, design, and execution of this research. Wanda Gustina Utami, as the corresponding author, coordinated the overall research framework, supervised data acquisition, and led the analysis of greenhouse gas emission inventories using the energy based approach. Indah Yusliga Sari Purba was primarily responsible for data validation, interpretation of emission trends, and drafting the initial manuscript, ensuring the methodological alignment with the GHG Protocol. M. Rizky Ismail contributed to the analytical modeling, comparative assessment of emission scopes, and the formulation of policy recommendations related to decarbonization strategies for sustainable port operations. Chandra Bogireddy provided technical guidance on emission factor standardization, cross-referencing with international methodologies, and critical review of the manuscript to enhance its scientific rigor and global relevance. All authors actively participated in revising, editing, and approving the final version of the manuscript, and collectively agree to be accountable for all aspects of the work.

## CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. All contributions were conducted independently and without any financial, commercial, or institutional influence that could be perceived as a potential conflict. The research was carried out solely for academic and professional purposes.

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