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Direct Decarbonization Model for Handling Equipment at Jamrud Terminal Using a Combination Method of Default Emission Factors (DEF) and Direct Monitoring of Greenhouse Gas Emissions (DMGGE)

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***Abstract*— As one of the largest archipelagic countries with a port system that supports more than 90% of its trade volume, Indonesia faces an urgent need to implement the green port concept to minimize environmental impacts, improve energy efficiency, and support national decarbonization commitments. One example is the Tanjung Perak Port, specifically the Jamrud Terminal in Surabaya. This study takes Jamrud Terminal—which provides loading and unloading services for general cargo, passengers, and dry bulk—as a case study. The terminal operates 24 hours a day and thus undoubtedly contributes to pollution, including air pollution from exhaust gas emissions, which are increasing due to a 23.06% growth in vehicle handling activities throughout 2024. Quantifying greenhouse gas (GHG) emissions from the main quay equipment and supporting equipment at Jamrud Terminal is crucial to assess current fossil fuel energy consumption and propose technological interventions to enhance energy efficiency and reduce GHG intensity from fuel usage.This paper aims to identify and calculate the existing direct emissions, analyze the trend of GHG emissions from port equipment, and develop a projection model of GHG emissions from equipment at Jamrud Terminal. The equipment includes Harbour Mobile Cranes, Harbour Portal Cranes, Excavators, Forklifts, Mobile Sweepers, Wheel Loaders, and Generators, with data sourced from primary records of fuel consumption supplied during the 2022 to 2024 period. GHG emissions projection is modeled using the Default Emission Factors method and the Direct Monitoring of Greenhouse Gas Emissions (DMGGE) approach. The results show that from 2022 to 2024, Jamrud Terminal emitted approximately 7.1 tons of CO_2eq from stationary combustion and 5,378.88 tons of CO_2eq from mobile combustion.A future decarbonization scenario developed in this study indicates that if the terminal transitions to electrification and the use of alternative energy fuels such as LPG or CNG, CO_2 emissions could be reduced by as much as 98.6%. The results of this paper will be valuable in formulating effective planning, policies, and strategies to reduce GHG emissions from direct sources related to both main and supporting equipment at Jamrud Terminal.**

Keywords— Fuel Consumption, Default Emission Factors (DEF), Direct Monitoring of Greenhouse Gas Emissions (DMGGE), Decarbonization

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I. INTRODUCTION

Maritime transportation is expected to be the most environmentally friendly mode in terms of emissions per ton of cargo transported. However, due to its dominance in global trade market share compared to other modes and the rapid increase in traffic, maritime transportation has become a major source of emissions (IMO, 2020). Congestion has become a chronic issue in most ports, increasing transportation costs and hampering trade growth[1].

Pollutants such as Nitrogen Oxides (NOx), Sulfur Oxides (SOx), Carbon Monoxide (CO), particulate matter (PM), and hydrocarbons (HC) are generated from the combustion of ship fuels. Indonesia is striving to develop its ports into green ports, one of which is Tanjung Perak Port in Surabaya. This thesis focuses on one of its terminals, the Jamrud Terminal, which provides general cargo and dry bulk handling services, as a case study. This terminal operates 24 hours a day and inevitably contributes to air pollution from exhaust gas emissions—originating both from operational equipment owned by PT Pelabuhan Indonesia and external transportation vehicles—thereby contributing to greenhouse gas effects.

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Total emissions and emissions per TEU at Tanjung Perak Port have increased due to a 10% capacity shortfall and frequent berthing delays, where the average vessel size is approximately 1,000 TEUs, yet the average berth duration exceeds 30 hours per ship. This has led to rising port emissions

[2]. The vehicle handling activity at Jamrud Terminal continues to grow annually, with an average increase of 23.06% by the end of 2024. Additionally, there has been a 16.88% increase in ship routes and fleets arriving and departing, causing Jamrud Terminal to significantly impact traffic congestion along Perak Barat and Timur roads. During peak hours, if port activities coincide with cargo loading and unloading from ferries, it can result in severe congestion. This, in turn, leads to uncontrolled fuel consumption and a surge in exhaust gas carbon emission hotspot, stemming from continuously operating fossil-fueled equipment such as ships, cranes, and diesel-powered trucks transporting cargo. These emissions not only degrade air quality but also contradict the Indonesian Government's commitment to carbon emission reduction. This research is conducted to assess the extent of mitigation efforts in transforming Jamrud Terminal into a green port through port management and governanceaimed at minimizing direct exhaust gas emissions, thus achieving greenhouse gas reductions in the Tanjung Perak Port area. In the figure 1, it is shown that the emission trend at Jamrud Terminal experienced a decline from 2022 to 2023, and continued to decrease in 2024. From Figure 4.9, the results of direct emission calculations from mobile combustion in the main quay equipment and supporting equipment at Jamrud Terminal indicate a value of 5,371.78 tons of CO_2 equivalent. The calculation is based on the total consumption of B30 and B35 biodiesel fuel that occurred during 2022–2024.
Observing the linear trend line of anthropogenic mobile combustion emissions, a significant decrease is evident from 2022 to 2023, with an increasingly larger gap between emission values in the same months of 2022 and 2023. However, in the 2024 linear trend of anthropogenic mobile combustion emissions, early in the year emissions were lower than both previous years (2022 and 2023), but in mid-2024, there was a fluctuating upward trend, exceeding the 2023 emission levels and reaching the 2024 emissions level. The variation in emissions between years, especially during the transition from B30 to B35 biodiesel fuel, resulted in a significant reduction in emissions.

This study will analyze how port policies affect the mitigation of greenhouse gas emissions at Jamrud

intensity without yielding proportional operational productivity.

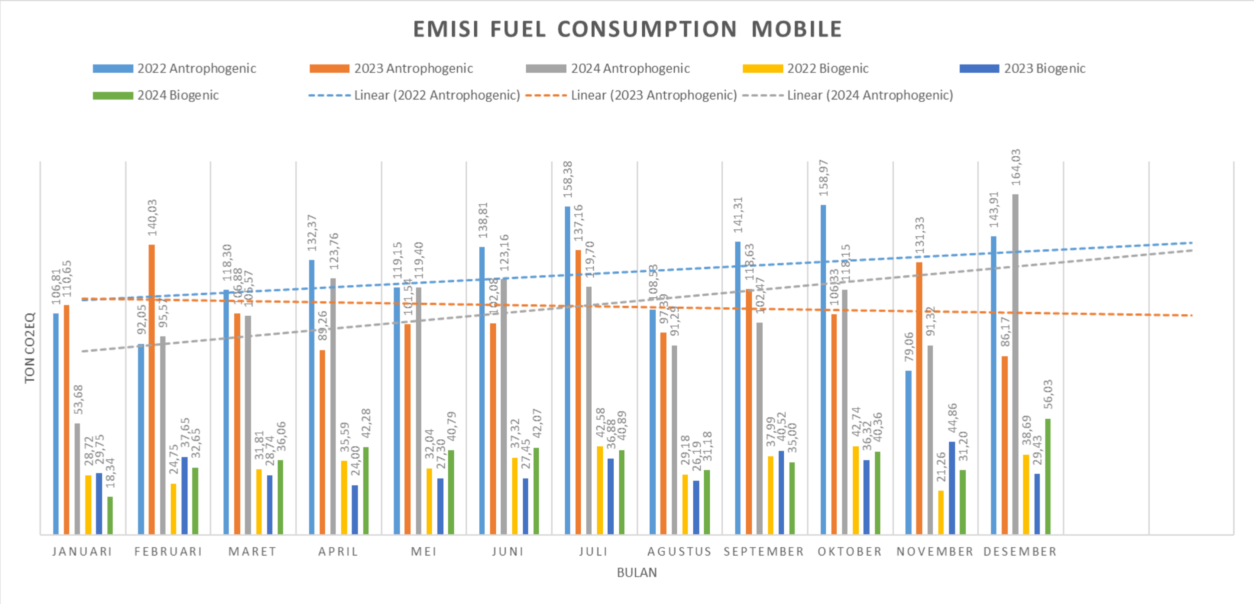
Port productivity becomes ineffective when congestion restricts access to and from the terminal, ultimately lowering port performance as equipment becomes idle for extended periods while continuing to consume fuel, with no corresponding movement in transport cycles. One mitigation effort implemented by Jamrud Terminal management was the preparation of three separate buffer zones around the terminal starting on October 15, 2024, to serve as temporary holding areas. These are intended to ease traffic queues during surges in cargo handling activity.

However, regarding the emissions themselves, it is evident that Jamrud Terminal becomes a primary

Terminal. Hinterland transport emissions are recognized as part of the port's responsibility, and considering these emissions is crucial for achieving efficiency in the overall intermodal transportation chain[3]. These emissions also contribute to climate change and pose health risks to port workers, which may ultimately affect job satisfaction and reduce overall port operational efficiency[4]. In recent years, the demand for dry bulk cargo trade at Jamrud Terminal has increased, along with cargo and passenger handling activities, placing additional pressure on port scheduling for dry bulk, general cargo, and passenger terminals.

The most effective and cost-efficient way to relieve such scheduling pressures quickly is by optimizing the overall scheduling of various port resources. Vessel scheduling on shipping routes and cargo operations at berths and storage yards are often treated as separate tasks. However, a plan that comprehensively meets the needs of port management can only be effectively developed through integrated scheduling of these various resources[5].

This study is expected to identify strategies to reduce carbon emissions through the implementation of decarbonization scenarios tailored to the specific exhaust gas emission profiles of each equipment unit at Jamrud Terminal, using the Default Emission Factors (DEF) and Direct Monitoring of Greenhouse Gas Emissions (DMGGE) methods—as applied in power generation based on the Guidelines for Greenhouse Gas Inventory Calculation and Reporting in the Energy Sector – Electricity Subsector, issued by the Directorate General of Electricity, Ministry of Energy and Mineral Resources.



II. METHOD

Port carbon footprint is a critical step in understanding the most impactful activities in ports and designing reduction strategies to meet ambitious targets set by the International Maritime Organization (IMO), namely reducing greenhouse gas (GHG) emissions by 50% by 2050 (compared to 2008 emission levels). Recognizing the importance of decarbonization, several ports in recent years have started reporting their carbon emissions.

The carbon footprint has become an important metric in understanding contributions to climate change, helping individuals and organizations identify actions to reduce GHG emissions, such as transitioning to renewable energy, increasing energy efficiency, or reducing resource consumption. As part of global efforts, the carbon footprint is often used to set emission reduction targets within the sustainability and climate change mitigation frameworks.

Greenhouse gases (GHGs) are gases in the atmosphere, both naturally occurring and anthropogenic, that absorb and emit infrared radiation, causing the greenhouse effect. Various human activities, especially since the pre-industrial era, have driven increased GHG emissions into the atmosphere, raising their concentrations. This has led to problems of global warming and climate change. As a response, the Earth Summit in Rio de Janeiro, Brazil, in 1992 produced the United Nations Framework Convention on Climate Change (UNFCCC), which aims to stabilize GHG concentrations in the atmosphere at a level that does not harm the climate system.

The Indonesian Government, through Law No. 6 of 1994, has ratified the Climate Change Convention, thereby officially binding itself to the obligations and benefiting from the support opportunities offered by the UNFCCC. One of the obligations of countries that have ratified the Climate Change Convention is to provide national GHG inventories, using the established methodology. The results must then be reported in the National Communication (NatCom) document along with other relevant information.

At the 13th Conference of the Parties (COP-13 UNFCCC) in Bali in 2007, a new agreement was made concerning long-term cooperative action between developed and developing countries to implement appropriate measures to reduce emission levels. In line with this, the President of Indonesia at the G-20 meeting in Pittsburgh, USA, on September 25, 2009, declared Indonesia's commitment (non-binding) to reduce GHG emissions by 26% by 2020 independently and up to 41% with international funding.

At COP-17 in Durban, it was agreed that developing countries (non-Annex 1), including Indonesia, must submit Biennial Update Reports (BUR) to the COP, either as separate reports or as part of their National Communication. At COP-21 in Paris in 2015, Indonesia increased its commitment to reduce GHG emissions by 29% below BaU by 2030 independently, and up to 41% with international support. This commitment is included in Indonesia’s first Nationally Determined Contribution (NDC) under the Paris Agreement, which aims to strengthen the global response to the threat of climate change by limiting global warming to well below 2°C above pre-industrial levels. As of May 2018, the Paris Agreement has been ratified by 176 countries, representing 88% of global GHG emissions. Indonesia ratified it through Law No. 16 of 2016.

To support these obligations and commitments, the government has issued Presidential Regulation No. 61/2011 on emission reduction action plans and Presidential Regulation No. 71/2011 on GHG inventories. In accordance with Perpres 71/2011, the Ministry of Environment and Forestry (MoEF) issued Ministerial Regulation No. P.73/MenLHK/Setjen/Kum.1/12/2017 on the Guidelines for the Implementation and Reporting of GHG Inventories on December 29, 2017.

Indonesia is obligated to submit national GHG inventory reports to the UNFCCC regularly. For this, the MoEF, as the National Focal Point, submits the National

Communication (NatCom) every four years and the Biennial Update Report (BUR) every two years.

According to Perpres 71/2011, GHG inventory at the sectoral level is the responsibility of the relevant ministries/agencies, with reports submitted to MoEF at least annually. In practice, ministries/agencies submit activity data to the MoEF for use in calculating the national GHG inventory.

Ports play a vital role in global and regional trade, but are also major sources of GHG emissions. According to recent studies, ship operations alone contribute about 47% to 80% of total emissions in port areas, depending on the type of port activities. The remaining emissions come from cargo handling equipment, trucks, and energy usage in the port [6]

GHG emissions from ports are receiving growing attention due to their significant impact on climate change. However, current research in this field remains fragmented, with limited and non-generalizable findings [4]. To address this gap, [6] proposed an integrative framework to systematically review the literature and identify future research directions on port-related GHG emissions. Using the Web of Science database, a bibliometric analysis of 230 documents and an in-depth review of 68 studies were conducted, focusing on emission sources, emission calculations, and mitigation technologies. Key findings are as follows:

1. Research on port-related GHG emissions has grown rapidly since the Paris Agreement, but international collaboration and institutional coordination remain lacking, hindering the development of comprehensive solutions.
2. Inconsistent classification of GHG emission sources across studies causes bias and limits comparability. Reclassifying emissions based on equipment operation location can improve accuracy and harmonization.
3. Activity-based approaches are the main method for emissions assessment but heavily.
4. rely on static emission factor datasets, especially for container ports. Expanding these datasets across various port types, real-time updates of local factors, and integration of alternative energy sources can enhance adaptability and accuracy.
5. Current mitigation strategies focus on technological innovation, energy substitution, and operational optimization. However, barriers such as high implementation costs, slow commercialization processes, and lack of policy support remain major challenges.

To achieve zero-carbon port operations, future research should prioritize integrating technical innovation with economic and policy frameworks. A multidisciplinary approach is essential.

2.1 Quantification of Carbon Emissions In Maritim Ports

Various approaches are currently available for the inventory and reporting of greenhouse gas (GHG) emissions covered by the United Nations Framework Convention on Climate Change (UNFCCC). The most widely used approaches include PAS 2050 (2011), the GHG Protocol, and ISO 14064-1:2018 (Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals). Publicly Available Specification (PAS) 2050, published by the British Standards Institution, is applied by organizations aiming to assess GHG emissions from products and services. This standard outlines requirements for assessment, such as system boundary definitions, GHG emission sources, data requirements, and calculation results.

Similarly, the Greenhouse Gas Protocol (GHG Protocol), developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), is designed to assist organizations in inventorying and managing GHG emissions. The protocol includes a wide range of applications and is widely used in both voluntary and mandatory reporting programs, such as the Global Reporting Initiative (GRI). This method is specifically designed to enable port authorities to calculate and report their Carbon Footprint accurately. It has been validated by selected ports and environmental experts, with the ultimate goal of distributing this method to all ports and making it freely available[7].

In line with this, the international standard ISO 14064-1:2018 (Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals) establishes principles and requirements for quantifying and reporting GHG emissions and removals at the organizational level. The standard includes requirements for designing, developing, managing, reporting, and verifying an organization's GHG inventory. Although there are some differences, particularly in the ways carbon emissions are collected and reported, all of the aforementioned approaches share the same goals and general scope of application.

Moreover, all of these approaches are based on a life cycle thinking foundation, in accordance with ISO 14040:2006 and ISO 14044:2006. However, due to the general scope of these applications, none of the approaches provide specific recommendations for assessing GHG emissions in seaports. Such assessments are often more complex because seaports involve a variety of activities and supply chains with different physical boundaries and specific requirements. To overcome these limitations, several initiatives have been developed by port authorities that provide specific guidance and recommendations for assessing carbon footprints in seaports, based on the aforementioned general approaches.

Greenhouse gas emissions arise from both mobile and stationary sources when fuel is combusted (WPCI, 2010). Mobile sources at Jamrud Terminal are categorized into two groups: Main Wharf Equipment and Support Equipment. The Main Wharf Equipment at Jamrud Terminal includes Harbour Mobile Cranes and Harbour Portal Cranes, while the Support Equipment includes Excavators, Wheel Loaders, Road Sweepers, and Forklifts.

Stationary sources constitute the second category of GHG emission sources found at ports. Typically, they contribute significantly less to total GHG emissions than mobile sources. Emissions from stationary sources originate from fixed, specific, identifiable, and localized facilities that use combustion processes. In this context, based on the condition of equipment at Jamrud Terminal, the Genset (Generator Set) is categorized as Support Equipment because of its role as a backup power source for operational electricity needs.

2.2 Carbon Footprint Calculation

In general, the total calculation of greenhouse gas (GHG) emissions at ports is given by the sum of all activity data considered within the port, multiplied by their respective emission factors, as follows:

The emission factor (EF) is a "representative value that attempts to relate the quantity of a pollutant released into the atmosphere with an activity associated with the release of that pollutant" (EPA). In the context of GHG emissions, EF allows the conversion of activity data—such as energy and/or fuel consumption estimates—into CO_2 equivalent.

The GHG Protocol recommends using specific values for emission factors whenever possible. This is primarily because industrial processes and/or fuel compositions may vary over time and across regions (for example, for electricity production, the emission factor should be obtained from the specific electricity supplier at the port). However, if it is not feasible to determine an activity-specific emission factor, default values published by general sources (such as the IPCC, GHG Protocol, and others) may be used.

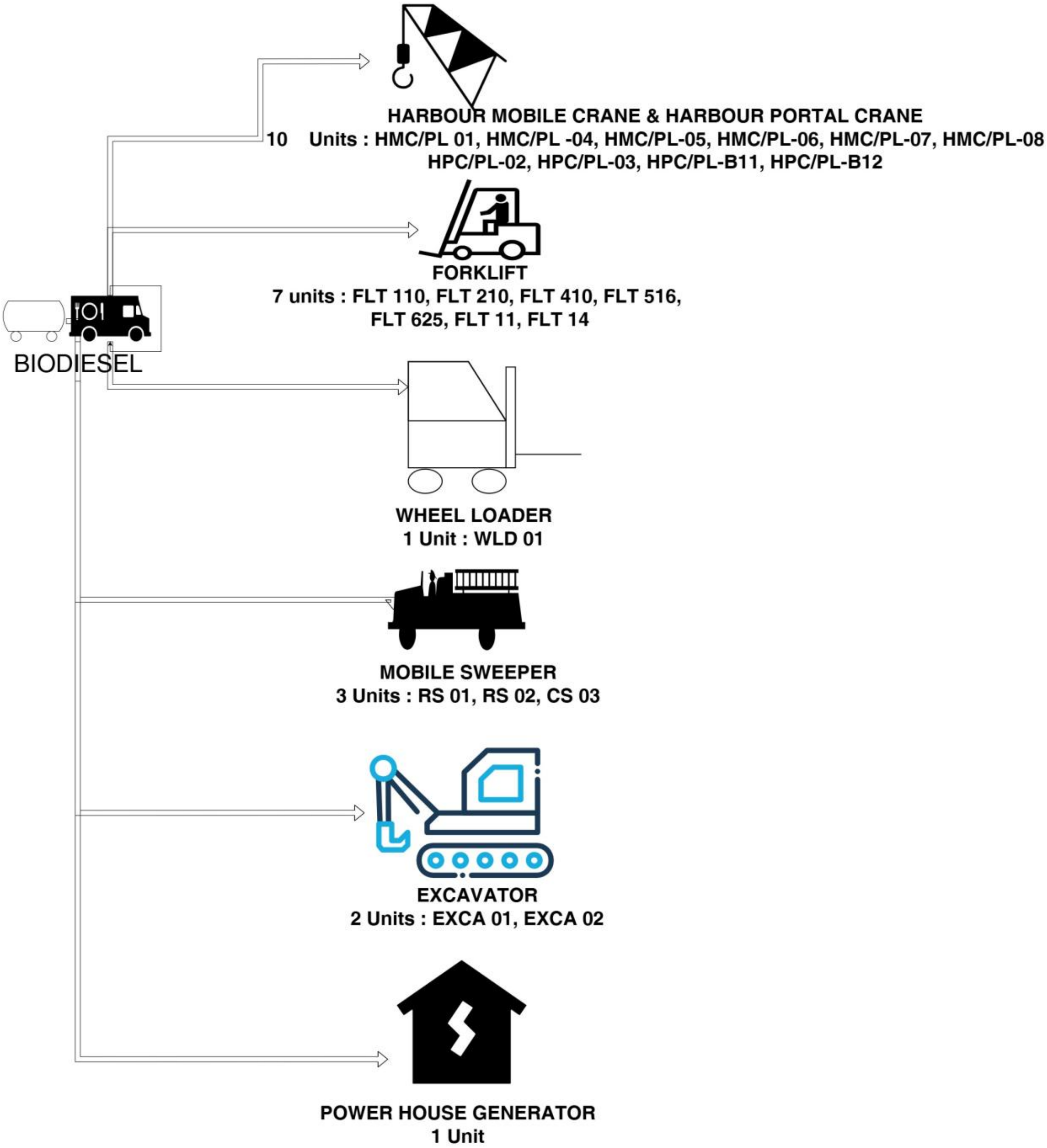


Figure. 2. Fuel Energy Maping Terminal Of Jamrud

Nevertheless, as seen in equation (1), different emission factor sources can cause significant variability in results. Therefore, the source of the emission factors must also be identified.

To produce a quality and verifiable GHG inventory, the inventorying process must adhere to five fundamental principles: Transparency, Accuracy, Completeness, Comparability, and Consistency, commonly abbreviated as TACCC.

After defining the scope and selecting the formula to be used, a practical, user-friendly, and freely available tool has been developed to calculate the Carbon Footprint at ports. This tool is specifically designed to enable port authorities to accurately calculate and report their carbon footprint[7].

$$CF = \Sigma \text{ (Data Aktivitas x Faktor Emisi)} \quad (1)$$

The tool provides options to select the most applicable scopes for each port. Additionally, it allows normalization of the total annual emissions by total tonnage handled or annual TEUs, with the aim of comparing results across ports on
a standardized basis. In this tool, all emission sources listed in standard guidelines (such as IPCC, GHG Protocol, and WPCI) are considered.

Completing this Excel-based tool is estimated to take around 20 minutes (if data are available), and consists of three steps:

- Step 1: Enter general data such as port name, country, and total port cargo.
- Step 2: Select the relevant scopes to be included in the calculation, then input the required data to obtain the final results.
- Step 3: Press the results button to generate a report of total CO_2 equivalent emissions, as well as emissions by capacity (carbon footprint) and by scope. The report can be saved as a PDF.

It is important to note that if data are unavailable for certain sources or if specific activities are not relevant to a particular port, those sections can be left blank. The program will still function, and users can proceed to complete other parts of the tool.

2.3 Greenhouse Gas Emission Reduction Strategies

Several Greenhouse Gas Emission Reduction Strategies:

1. Shore Power (Cold Ironing)

Ships can connect to onshore electricity sources while docked, eliminating the need to run fossil fuel-powered generators. The main challenges involve infrastructure costs and system compatibility.

Shore Power, also known as cold ironing, shoreside power, shore-to-ship power, alternative marine power, or onshore power supply, is a system that delivers electricity from land to a docked ship. This system reduces the use of auxiliary engines onboard, helping minimize direct greenhouse gas (GHG) emissions and other pollutants such as nitrogen oxides, sulfur oxides, and particulate matter, as well as noise pollution [8]. As a result, shore power has become a key decarbonization strategy in the maritime sector over the past few decades [9].

Since shore power typically relies on the national grid, its effectiveness in reducing emissions varies by region. For instance, shore power can reduce emissions by up to 99.5% in Norwegian ports, about 85% in France, and only 9.4% in the U.S., due to differences in electricity generation methods—Norway uses hydropower, France uses nuclear, and the U.S. relies largely on coal and natural gas (Hall, 2010). Thus, when developing and promoting shore power, it's crucial to consider the GHG emissions of electricity generation. For ships at berth, suitability for shore power should be based on energy mix and docking duration—not solely on tonnage or displacement[11].

However, technological barriers have hindered widespread adoption. For instance, the U.S., Canada, and Brazil use 60 Hz electrical systems, while China, most of Europe, and India use 50 Hz, requiring shipowners to adapt to different systems systems [12].

Port authorities also face significant financial challenges, including expanding power capacity (e.g., building substations and transformers), operations, and maintenance. At Shekou Port in Shenzhen, building shore power facilities cost $2.2 million, limiting profitability (Wan et al., 2021). Subsidies are therefore essential. A case study in a five-berth Chinese container port found shore power to be economically unviable when electricity prices exceeded $0.3/ kWh [14].

To improve financial feasibility, construction subsidies and environmental operation incentives are needed. While carbon trading is insufficient alone, increased revenue from power sales can improve return on investment [15].

Even with strong carbon taxes, subsidies, and high energy prices, detailed analysis of vessel docking patterns, energy demand, and environmental benefits remains essential (Bullock et al., 2023). Efficient scheduling of shore power use considering berth availability, infrastructure, ship arrival randomness, and environmental benefits is recommended [17].

2. Fuel Switching and Alternatives

Encouraging the use of low-carbon fuels such as LNG, biodiesel, hydrogen, or ammonia. LNG offers short-term reductions, while hydrogen and ammonia show long-term potential. A study by Geerlings & Van Duin (2011) found that blending 30% biofuel with diesel in Rotterdam could reduce CO_2 emissions by approximately 26%.

3. Electrification of Port Equipment

Providing electricity from terminal power houses to Harbour Mobile Cranes and Harbour Portal Cranes previously powered by diesel gensets. These diesel-powered, wheeled cranes offer flexibility but can be modified to connect to the grid.

Electrification involves installing cable reel systems to connect to electrical panels and motors. A case study at Ningbo Port showed that electrifying wheeled cranes could reduce GHG emissions by up to two- thirds [19].

After conversion, cranes operate mainly on electricity, using diesel only to move between zones not covered by cable systems (Yu et al., 2019). However, energy switching delays can reduce operational efficiency, so proper electric motor selection is vital [21].

Due to financial constraints, Jamrud Terminal often cannot electrify all cranes simultaneously. Operating diesel and electric cranes together without smart scheduling may even increase emi emissions [22]. Joint scheduling optimization—based on cargo arrival time and truck allocation—can reduce emissions [23], and must consider port layout, berth, and vessel routing [5].

4. Renewable Energy Integration

Installing solar panels, wind turbines, and storage systems to power port facilities and shore power.

A case study showed that using lithium-ion batteries and supercapacitors during transition to shore power could reduce GHG emissions by up to 55% [24].
Providing shore power via renewable sources like hydrogen, solar, and wind also boosts competitiveness [25].

5. Port Logistics Optimization

Using digital technologies (AI, IoT, digital twins) to improve efficiency, reduce waiting times, and minimize fuel use.

Shorter operation durations have more impact on emission reductions than carbon taxes or resource allocation policies [26].

Compact terminal layouts can cut container truck transfer distances—e.g., Rotterdam Port saw up to a 70% CO_2 reduction from layout optimization [18]. Optimizing quay layout, crane distribution, and accounting for vessel schedule uncertainties is key to reducing wait times and emissions [27].

Even as Jamrud Terminal electrifies equipment like cranes, some ports (e.g., in Taiwan) face short-term hurdles due to high procurement costs [28]. Reducing idle time of support equipment and ships remains effective.

Evidence from Yangshan Deep-Water Port in Shanghai shows a 23% crane idle rate—highlighting significant energy and emission savings potential [29].

Switching from manual to automatic mooring can cut docking time from up to 90 minutes to 30 seconds, reducing emissions by ~33 tons/year [9]. Efficient berth scheduling reduces vessel idle time and improves operational efficiency [30].

Inefficient marine traffic flow increases anchorage times and GHG emissions. Coordinated scheduling of port and vessel operations—considering slow steaming emissions—can reduce ship emissions by 8.0%–11.9% [31].

6. Modal Shift in Transportation

Encouraging modal shifts from trucks to rail or inland waterways for more sustainable hinterland distribution.

III. Results And Discussion

The calculation approach for direct emissions quantification is carried out using Method 1, the Default Emission Factors (DEF) approach, based on fuel consumption activity data, and combined with Method 4, Direct Monitoring of Greenhouse Gas Emissions (DMGGE), using CEMS (Continuous Emission Monitoring System), in accordance with the methods specified in ISO 14064-1:2018 (Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals) and Australia's National Greenhouse and Energy Reporting (NGER) as references to help address the issues in this study.

Data collection is conducted through historical records of fuel oil usage as recorded in the fuel consumption reports for each main quay equipment and supporting equipment in the technical division of Jamrud Terminal. The nature of this data acquisition can be categorized as primary data since the transaction records of fuel refueling for each piece of equipment at Jamrud Terminal are based on measurements using a fuel flowmeter recording system operated by PT Pelindo Energi Logistik and PT Lamong Energi, in accordance with the fuel supply cooperation agreement for all Pelindo Group equipment.

Furthermore, the actual fuel consumption data for each main quay equipment and supporting equipment at Jamrud Terminal is calculated using a bottom-up approach, as described in the "Guideline for Greenhouse Gas Inventory Calculation and Reporting in the Energy Sector" – Electricity Subdirectorate, Directorate General of Electricity, Ministry of Energy and Mineral Resources (2018). Based on Method 1 and Method 4, and by referring to the explanations of each method in the IPCC 2006 Guidelines and elaborated in ISO 14064-1:2018 and National Greenhouse and Energy Reporting (NGER).

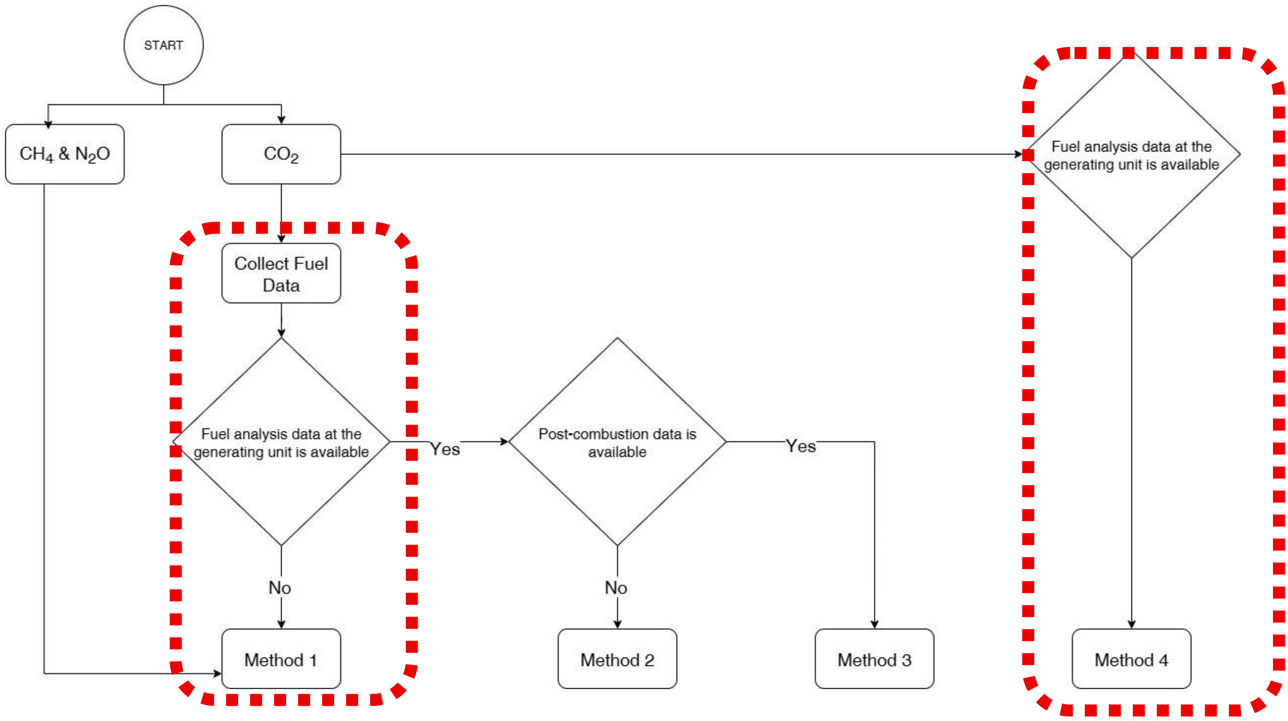


Figure. 3. Flow of Determining the Greenhouse Gas Emission Calculation Method

3.1 Direct Monitoring of Greenhouse Gas Emissions

Direct Emission Monitoring System is a system used to directly measure exhaust gas emissions from their source, such as stacks, engines, or combustion equipment. This system is designed to obtain actual and real-time data on the types and concentrations of pollutants released into the air. The main objectives of the Direct Emission Monitoring System include:

1. Monitoring the performance of the combustion process or exhaust gas production.
2. Early detection of abnormal emission spikes.
3. Obtaining actual and high-precision emission data.
4. Supporting verification-based emission reporting systems (MRV: Monitoring, Reporting, and Verification).
5. Providing data for national/international GHG inventories.

Several models are used for direct emission monitoring, such as:

1. Continuous Emission Monitoring System (CEMS) – Used to measure gas emissions in real time and continuously from combustion sources. Equipped with sensors and data acquisition systems. Commonly used for CO_2, NOx, SO_2, and O_2.
2. Portable Gas Analyzer – Used for periodic/non-continuous emission measurements. Suitable for small sources or field verification.
3. Non-Dispersive Infrared (NDIR) Sensors
4. Fourier-Transform Infrared Spectroscopy (FTIR)
5. Optical Gas Imaging (OGI)

From this system, the amount of direct exhaust gas emissions produced at the port is obtained, which is then used to determine technological modifications such as converting onboard genset engines to electrification of Harbour Portal Cranes and Harbour Mobile Cranes to support decarbonization efforts in achieving the 2030 zero emission target. This transition is aimed at reducing emissions from the current Business As Usual (BAU) scenario. Thus, the management of Terminal Jamrud can plan and implement direct emission reduction initiatives.

3.2 Default Emission Factors

This emission source originates from the combustion of fuel in generators (gensets) at Terminal Jamrud, where the electricity produced by these generators is used for terminal operational activities during emergency conditions. Emissions from stationary combustion can be calculated using the equation (2) & (3) stipulated in Clause 6.3 of ISO 14064-1:2018 as follows:

$$DA_{BBM} = F_{BBM}\ x\ \rho\ x\ NCV x\ 10^{-6} \qquad (2)$$

Where; Jumlah BBM = Amount of Fuel Used (kL); NCV = Net Calorific Value (TJ/Gg); ρ = Fuel Density (kg/m³)

$$EmisiCO2 = DABBM \times FEi \times GWPi \qquad (3)$$

Where Emisi CO_2 = Total CO_2 Emissions (tons CO_2-eq); DA BBM = Activity Data (TJ); FEi = Emission Factor for GHG parameter-i (ton/TJ); GWPi = Global Warming Potential for GHG-i (ton CO_2-eq/ton of GHG-i).

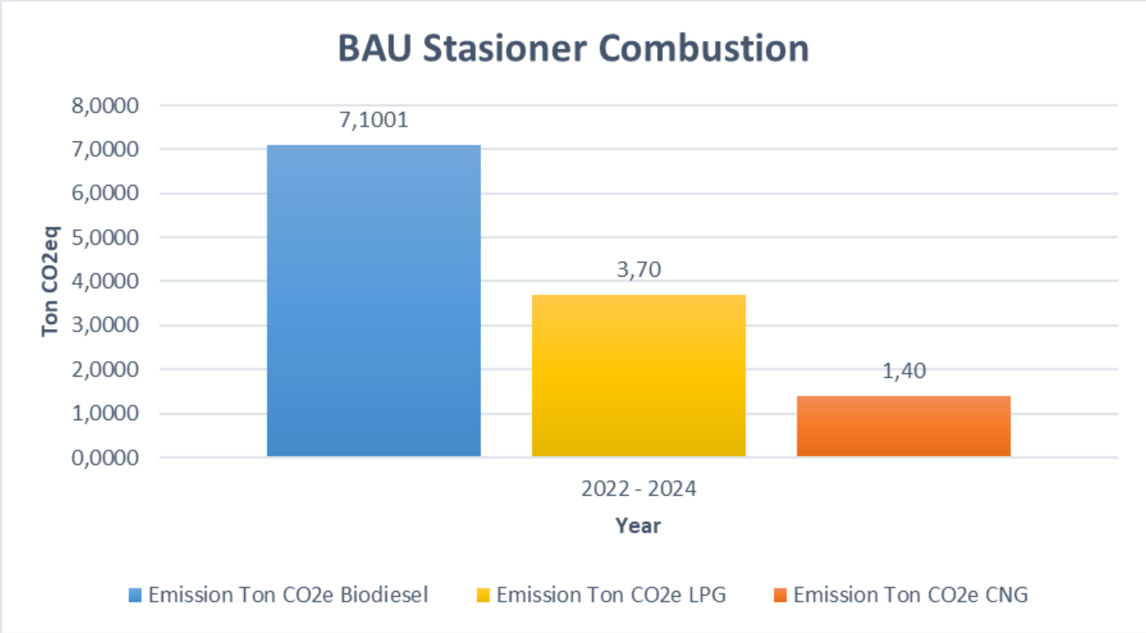


Figure. 4. BAU Stasioner Combustion

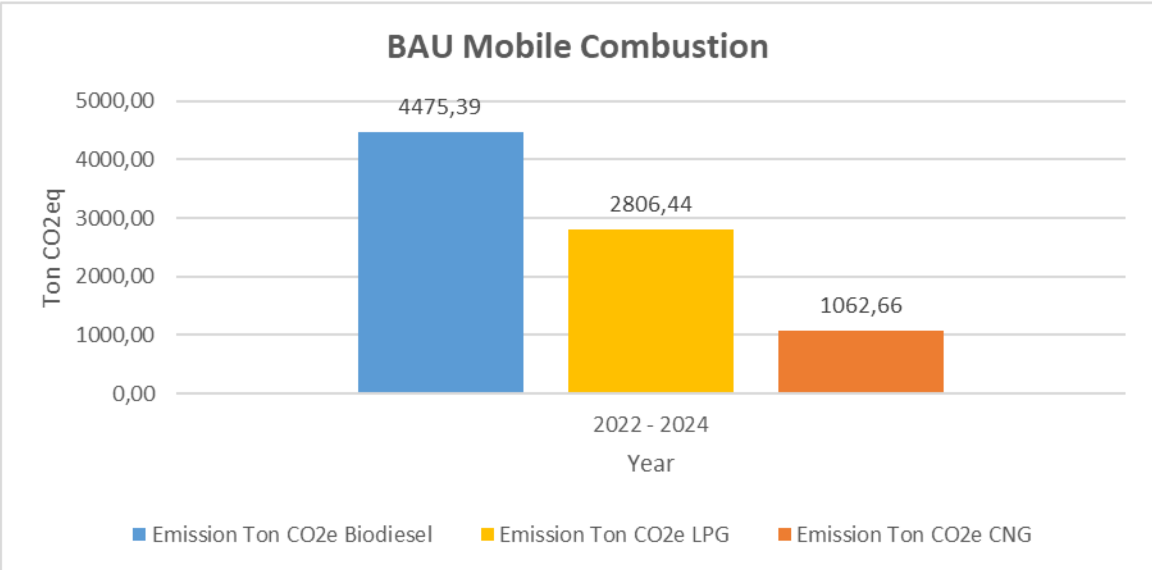


Figure. 5. BAU Mobile Combustion

3.3 Result Analysis Scenario

$$€ = Volume_{bbm} \times \rho_{bbm} \times NCV_{bbm} \quad (4)$$

Where : $Volume_{bbm}$ = Jumlah BBM (Liter); ρ_{bbm}= Density BBM (Kg/liter); NCV_{bbm}= Nilai Kalor Bersih BBM (MJ/Kg)

Figure 4 and Figure 5 need to be explained in the context that the emission reduction curve from the fuel modification scenario modeling shows a significant decrease in direct emissions from the existing baseline, both in stationary combustion and mobile combustion.

If the transition from biodiesel fuel can be optimized by using LPG or even CNG, then the emission value using the DEF method can reach 1.4 tons CO_2eq for stationary combustion (with CNG) and 1,062.66 tons CO_2eq for mobile combustion.

For equipment that is not suitable for electrification—such as supporting operational equipment (Forklifts, Excavators, Road Sweepers, Wheel Loaders, and Gensets)—a technology modification is applied to use CNG or LPG gas fuels instead.

This initiative is outlined in the roadmap targets through 2036, by which time all electrification and gas fuel modifications are expected to be completed.

As a result, the quantified emissions for supporting equipment using mobile or stationary combustion, modified to use CNG or LPG gas fuel, are as follows equation (4).

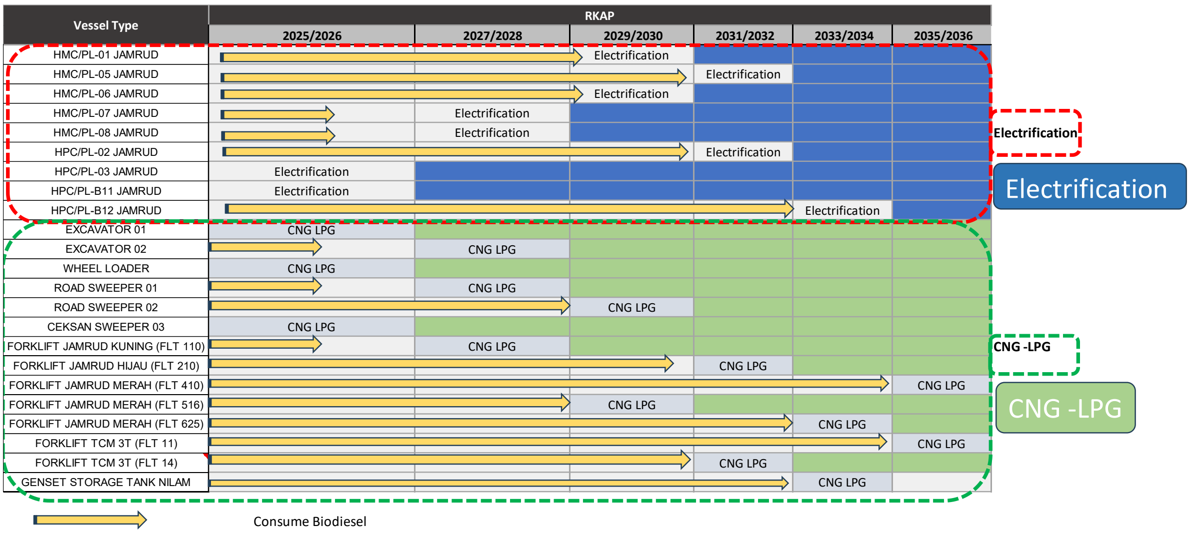


Figure. 6. Scenario Elektrification and Modification CNG/LPG

The transition to using CNG gas fuel yields the best and lowest quantified emission values, with stationary combustion resulting in an emission quantification of 1.4 tons CO_2eq and 72.168 tons CO_2eq for mobile combustion. The direct emissions from mobile combustion of main quay equipment and supporting equipment at Terminal Jamrud amounted to 5,371.78 tons of CO_2eq. This calculation was derived from the total consumption of B30 and B35 biodiesel fuel during the years 2022–2024. Observing the linear trend of anthropogenic mobile combustion emissions from 2022 to 2023 shows a significant decline, with an increasingly large gap in monthly emission values between the two years. However, in 2024, while the early months recorded lower emission levels than both 2022 and 2023, the middle of the year experienced a rather fluctuating upward trend, surpassing the 2023 emissions and eventually approaching 2024's levels. The shift from B30 to B35 biodiesel during this period contributed to a significant reduction in emissions across the years. The scenario developed to decarbonize Jamrud Terminal in the future, if a transition to electrification and the use of alternative energy fuels such as LPG or CNG occurs, would result in a 98.6% reduction in CO_2 emissions.

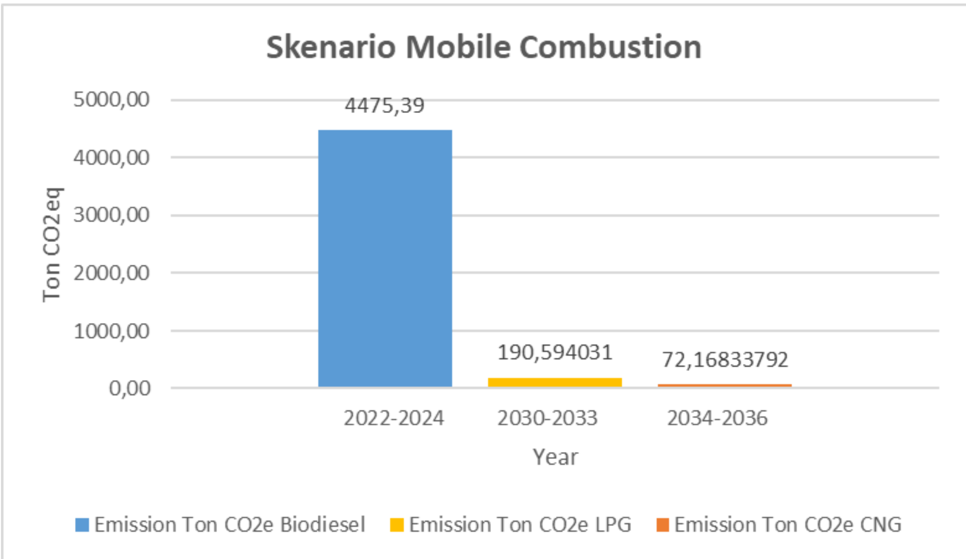


Figure. 7. Scenario Mobile Combustion

IV. CONCLUSION

Based on the results of data collection, processing, and analysis of direct emissions from biodiesel fuel combustion of quay main equipment and supporting equipment at Terminal Jamrud using a combined method of DEF (Default Emission Factors) and DMGGE (Direct Monitoring of Greenhouse Gas Emissions), the following conclusions can be drawn: Terminal Jamrud, during the period 2022–2024, has a quantified emission of 7.1 tons CO_2eq from stationary combustion and 5,378.88 tons CO_2eq from mobile combustion.

The optimal decarbonization scenario for quay main equipment at Terminal Jamrud involves modifying diesel engines powered by diesel fuel into electrified units, which would eliminate emissions from the absence of fuel consumption activities.

The decarbonization scenario for supporting equipment and generators at Terminal Jamrud, through the transition from biodiesel fuel to CNG (Compressed Natural Gas), results in the lowest quantified emissions compared to LPG and LNG, amounting to 72.1 tons CO_2eq. The scenario developed to decarbonize Jamrud Terminal in the future, if a transition to electrification and the use of alternative energy fuels such as LPG or CNG occurs, would result in a 98.6% reduction in CO_2 emissions.

The ongoing modification process of all equipment at Terminal Jamrud, whether through electrification or the transition from biodiesel to gas fuel, should be carried out gradually during 2030–2033 and 2034–2036 to ensure operational activities continue to run smoothly.

Based on the author's observations during data collection, processing, and emission analysis, several suggestions can be recommended for future research. These suggestions include:

The emission calculation analysis using the DEF (Default Emission Factors) method can serve as a reference or guideline for monitoring greenhouse gases based on actual fuel consumption.

Supporting tools for DMGGE (Direct Monitoring of Greenhouse Gas Emissions), such as CEMS (Continuous Emission Monitoring System), can assist in providing real-time data on the quantified emissions produced by equipment.

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