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Life-Cycle Greenhouse Gas (GHG) Emissions Calculation for Urban Rail Transit Systems: The Case of Pernambuco Metro

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Abstract: In recent years, the issue of climate change has gained significant attention and become a focal point of discussion in various sectors of civil society. Governments, individuals, and scientists worldwide are increasingly concerned about the observed changes in climate patterns, often attributed to the rising levels of greenhouse gases. In this context, the main objective of this study is to assess the greenhouse gas emissions associated with the railway system in the state of Pernambuco, Brazil, and compare them with other national case studies, aiming to obtain greenhouse gas emission parameters specific to the railway system and propose mitigation models to address this environmental impact in the air. To achieve this goal, a comprehensive life cycle assessment (LCA) methodology was employed to examine the life cycle of the Pernambuco Metro. This involved conducting an inventory of resource inputs and emissions using actual observed data. Additionally, a comparative analysis of greenhouse gas emissions across different urban rail transport systems is presented to provide valuable contextual insights. The study findings reveal that the total greenhouse gas emissions from the Pernambuco rail system amount to 6170.54 t CO_2e. Considering a projected total service life of 50 years, the estimated greenhouse gas emissions for the entire life cycle of the system's operation and maintenance reach 308,550 t CO_2e. The interdisciplinary nature of this research highlights the significance of studying the atmospheric effects of the Pernambuco railway system as a crucial parameter for designing strategies and technologies aimed at reducing air pollution within the region. Through quantifying and analyzing the greenhouse gas emissions of the Pernambuco rail system, this study provides valuable insights that contribute to addressing concerns related to climate change and promoting sustainable practices. It underscores the importance of developing effective strategies to mitigate air pollution and facilitates informed decision-making for the future of urban transportation systems.

Keywords: climate change; air pollution; life cycle; rail system; greenhouse gas emissions

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1. Introduction

According to the 2020 UN report, the world's population is growing at a rate of 1.1%, and at this rate, the organization projects that the world will have 8.5 billion inhabitants by the year 2030. With the increase in population comes the need for greater consumption of natural resources and, consequently, an increase in pollution caused by this consumption [1]. Faced with this fact, humans understand the need to develop consumption methods that have lesser impacts on the environment. However, effective ways to reduce the damage caused by pollution are still lacking.

Humans are demanding more and more natural resources every day, and the increasing demand raises concerns about how the impact of their consumption affects emissions of greenhouse gases into the atmosphere and how the waste generated by their activities may be directly linked to climate change. With the growing population, the consumption of goods and services in large urban areas requires more resources in terms of energy and land [2]. In the background of this huge population mobility, the global outbreak of the COVID-19 pandemic in 2020 prompted people to reconsider privates vehicles utilizing more polluting technologies and affecting health through affecting population mobility and local air pollution levels [3].

Anthropogenic climate change is a widely discussed topic worldwide, leading to international agreements such as the Kyoto Protocol and the National Policy on Climate Change established via Law No. 12.187/2009, which commits Brazil to reducing greenhouse gas (GHG) emissions. The recent global pact at the 21st Conference of the Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC) in Paris aims to strengthen the world's response to the threat of climate change and enhance countries' capacity to deal with the impacts of these changes [4].

The need to improve energetic efficiencies and to reduce pollution caused by transportation have gained importance because decarbonization has been identified as a crucial worldwide concern. The transport sector, being the largest producer of greenhouse gases (GHGs) in many countries, is recognized as a key factor in achieving climate mitigation targets [5,6].

These climate change discussions in recent years have raised concerns among governments, the population, and scientists worldwide, emphasizing the need for action. Climate change may be related to increased concentrations of GHGs, primarily carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6) [7], although other gases also have this property.

In addition, the transport sector is also responsible for the emission of local pollutants such as NOx, CO, and particulate matter (PM). Global and local pollution issues are mainly due to the diffusion of diesel internal combustion engine powertrains in heavy-duty segments. Then, to understand which powertrain and fuel technologies are most capable of shrinking the carbon footprint of transport—and not only the emissions from the tailpipes, but also from fuel and electricity production and vehicle manufacturing—is important for policymakers and investigators [8].

In 2019, the CO_2 emissions of the Brazilian transport sector totaled 201 Mt CO_2e; over 2005–2019, its emissions increased by 42%, the second-highest increase after electricity and heat with a 58% increase [9,10]. Only the transport sector is responsible for about 35% of the consumption of fossil fuels and for over 48% of GHG emissions in the country [11].

Transportation systems are responsible for a significant portion of CO_2 emissions and greenhouse gas emissions. According to Li Ye [12], transportation emissions of air pollutants and greenhouse gases are continuously increasing. Ingrao [13] argues that transportation should never be overlooked, as it would mean neglecting significant environmental impacts. One of these means of transportation is railway systems, widely used worldwide but also with their environmental impacts.

It is a fact that humans are fully aware that they need to take action to reduce the effects of their consumption, and a change in consumption patterns is urgent. Efforts are needed to improve the environment and address mental issues associated with the movement of goods from one place to another, especially over long distances.

Many countries are setting reduction targets, and one of the key sectors is transportation, which needs to become more sustainable. The European Union aims to reduce greenhouse gas emissions by at least 60% by 2050 [14]. Sweden aims to achieve net-zero greenhouse gas emissions in the country by 2045, and for this, stakeholders in transportation planning, construction, and infrastructure need to reduce their impacts by half by 2030 [14,15]. Life cycle assessment (LCA) in the transportation sector is becoming more widespread, and the studies conducted so far have often referred to the results obtained as a measure of the transportation flow, usually expressed as a specific weight moved over a particular distance, i.e., t-km [13].

To understand the true impacts of emissions, it is crucial to comprehend how goods and services are consumed by society and measure the resulting effects. Inventories are conducted to assess the environmental impact of activities known to be polluting and environmentally harmful, emitting high levels of CO_2 and greenhouse gases (GHGs), and generating solid waste. These inventories employ tools such as life cycle assessment to provide a more precise understanding.

Li Ye [12] suggests that one of the primary methods for evaluating the environmental impacts of railway transportation is studying its life cycle, which consists of four distinct phases: material extraction and processing, infrastructure construction, vehicle manufacturing, and system operation and maintenance, including end-of-life. Through quantifying these impacts throughout the railway life cycle using data from each stage, strategies can be developed to reduce costs and emissions [16–19].

Recent studies, including the one conducted by Rempelos, Preston, and Blainey [16,20], have evaluated and compared the life cycle GHG emissions associated with the four most common types of sleepers in the UK railway network. Additionally, Chipindula [21] conducted a study on the Dallas to Houston route, which is the busiest corridor among the 18 traffic corridors in Texas. The aim was to assess the environmental impact of the high-speed rail (HSR) system along this corridor throughout its life cycle through estimating CO_2 and GHG emissions per vehicle and dividing them by the number of passengers and kilometers traveled. A thorough analysis of emissions composition and sources was conducted for each life cycle phase to compare the current railway system with the potential HSR system. Results showed that HSR has 27% lower energy use compared to passenger cars [22].

To identify the most resource-intensive and waste-generating phase of the railway system, it is essential to have a comprehensive understanding of resource consumption throughout the entire life cycle. Through quantifying the CO_2 and GHG emissions during the operation phase, significant efforts can be directed towards reducing emissions from rail transport. It is crucial for the pace of technological advancements in transportation infrastructure construction to surpass that of the average urban economy, ensuring the consistent reduction of energy and carbon footprints in new projects [23].

The effects associated with transport emissions differ across regions, technologies, fuel, and modes, but there are three overarching goals: electrification via hybridization, batteries, and fuel-cell technologies; increasing the number of public transport services; or replacing fossil fuels with their green counterparts (biofuels or synthetics). To understand the true impacts of emissions, it is crucial to comprehend how goods and services are consumed by society and measure the resulting effects. Inventories are conducted to assess the environmental impact of activities known to be polluting and environmentally harmful, emitting high levels of CO_2 and greenhouse gases (GHGs), and generating solid waste. These inventories employ tools such as life cycle assessment to provide a more precise understanding [11,24,25].

The methodology of life cycle assessment (LCA) has been employed in several transport studies, applied to different transport modes such as road [25,26], rail [24,27], maritime [28], inland waterways [29], and air transport [30]. Globally, researchers have conducted varied studies from a life cycle perspective in the field of rail transport, with the aim of measuring the main sources of environmental impacts, emissions, and costs. One study developed a comprehensive component-based life cycle assessment model in France [6], with clear and reusable life cycle inventories (LCIs) for high-speed rail (HSR) infrastructure components.

Life cycle analysis (LCA) is used for the identification and quantification of material, energy, and emissions across all stages of the system and enables the identification of appropriate mitigation measures [10]. An LCA of a light rail trip would include the direct effects (moving the train), ancillary effects (e.g., evaluating the total greenhouse gas emissions from constructing the infrastructure and dividing it by the total number of trips), and supply chain effects (e.g., evaluating the greenhouse gas emissions from mining materials for train manufacturing and dividing it by the total number of trips served in the train's lifetime) [31,32]. Policymakers should take into consideration how policies might affect overall vehicle miles traveled, the number of vehicles on the road (i.e., traffic congestion), the availability and utilization of alternative modes of transport, and possible solutions to enhance the environmental benefits and mitigate the potential economic implications of a policy.

In light of all the facts mentioned, mapping the GHG emissions of the railway system in Pernambuco, Brazil, will aid the region in managing the environmental impacts of public transportation while improving environmental sustainability and aligning with state development goals. Through economically characterizing activities associated with increased mobility and reduced environmental impact, it becomes possible to understand the process of sustainable development within the public transport system, considering local peculiarities and potentialities. This understanding will guide the design of measures and public policies to address national environmental concerns [33–35].

Furthermore, this study will contribute to the theoretical and methodological framework concerning the environmental impacts of public transport activities and the development of public policies for railway infrastructure. The field of environmental impact and sustainability in the railway system remains largely unexplored, despite mechanical engineering, engines, fuels, maintenance, and urban train transportation planning being the main research areas within global railway research [27]. It highlights the need for further research in this area.

Considering interdisciplinarity as a guiding principle, this research project aims to explore the atmospheric impacts of the railway system. Its ultimate purpose is to conduct a greenhouse gas emissions inventory of the railway system in Pernambuco, Brazil, comparing it with other national railway systems, and proposing mitigation models to reduce this environmental impact. In this way, the study aims to provide strategic data for policymakers, urban planners, and other stakeholders, with the goal of promoting improvements in the railway system, mitigating air pollution, and enhancing the quality of life for future generations.

2. Materials and Methods

2.1. Study Area

The rail passenger transport system in the Metropolitan Region of Recife (RMR) directly serves the municipalities of Recife, Cabo, Jaboatão dos Guararapes, and Camaragibe, as shown in Figure 1. The rail system consists of three lines implemented in the central and southern corridors of the RMR: the electrified Central and South lines, which operate as metropolitan trains, and the Diesel line, powered by diesel traction and with the characteristics of a suburban train.

Currently, with 28 stations and a length of 39.5 km, the electric metro system in Recife transports approximately 94,000 passengers per day. The Recife metro operates on a double-track, exclusive line, electrified at 3000 Volts, with overhead wire power supply through a pantograph. It utilizes an ATC (Automatic Train Control) system with remote control for traffic and power management. The rolling stock consists of 25 electric trains, each comprising 4 cars.

The Diesel line, with 8 stations, operates between the city of Cabo, in the municipality of the same name, and the Curado neighborhood, in the city of Recife. With a length of 31.5 km, including 7 km on a double track and 24 km on a single track, the diesel train runs on a shared track with freight transportation and integrates with the electric system (metro) at Curado Station. It has 6 level crossings, and the signaling system is manual (using tokens). The rolling stock consists of 7 light rail vehicles (LRVs) [36].

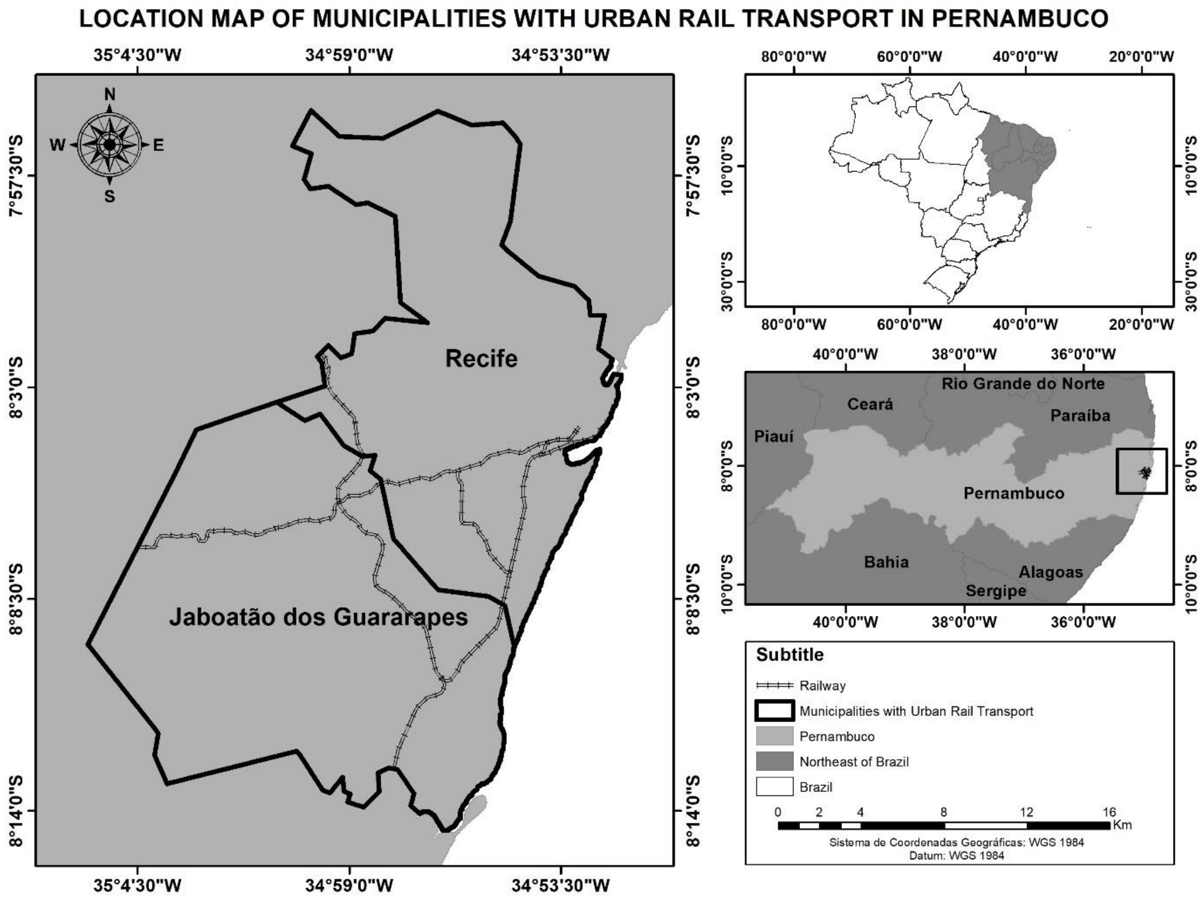

Figure 1. Geographic location of the Pernambuco urban railway.

2.2. Method

The chosen approach for investigating greenhouse gas emissions throughout the life cycle is the quantitative method, which enables a comprehensive inventory. This calculation will consider associated resource inputs such as materials, fuels, and equipment [37,38].

The methodology employed, known as life cycle assessment (LCA), is globally recognized for quantifying emissions across the entire life cycle of specific products or systems [39–41]. However, the initial definition of this methodology was intended for general application across various product types.

LCA is based on international standards like the ISO 14040 series, which establish principles and requirements for conducting life cycle studies. These standards outline the stages of LCA, including defining the study's objective and scope, data collection, the assessment of environmental impacts, and the interpretation of results [12,16,21].

In this specific life cycle study, we have followed the framework developed based on ISO 14040-14043, which provides principles, requirements, and guidelines for conducting a reliable life cycle analysis [42,43]. This framework is widely accepted and ensures consistency and quality in the obtained results.

It is important to note that the urban rail transit system does not fit solely into the category of a product, cooperation, or isolated project. Conducting an LCA in this context presents unique challenges and complexities compared to typical consumer products, requiring specific modeling adaptations [4,44,45].

The urban railway transport system comprises tracks, tunnels, viaducts, power facilities, depots, stations, vehicles, control centers, and more. The calculation will encompass associated resource inputs (materials, fuels, and equipment) and greenhouse gas emissions at each phase, as illustrated in Figure 2.

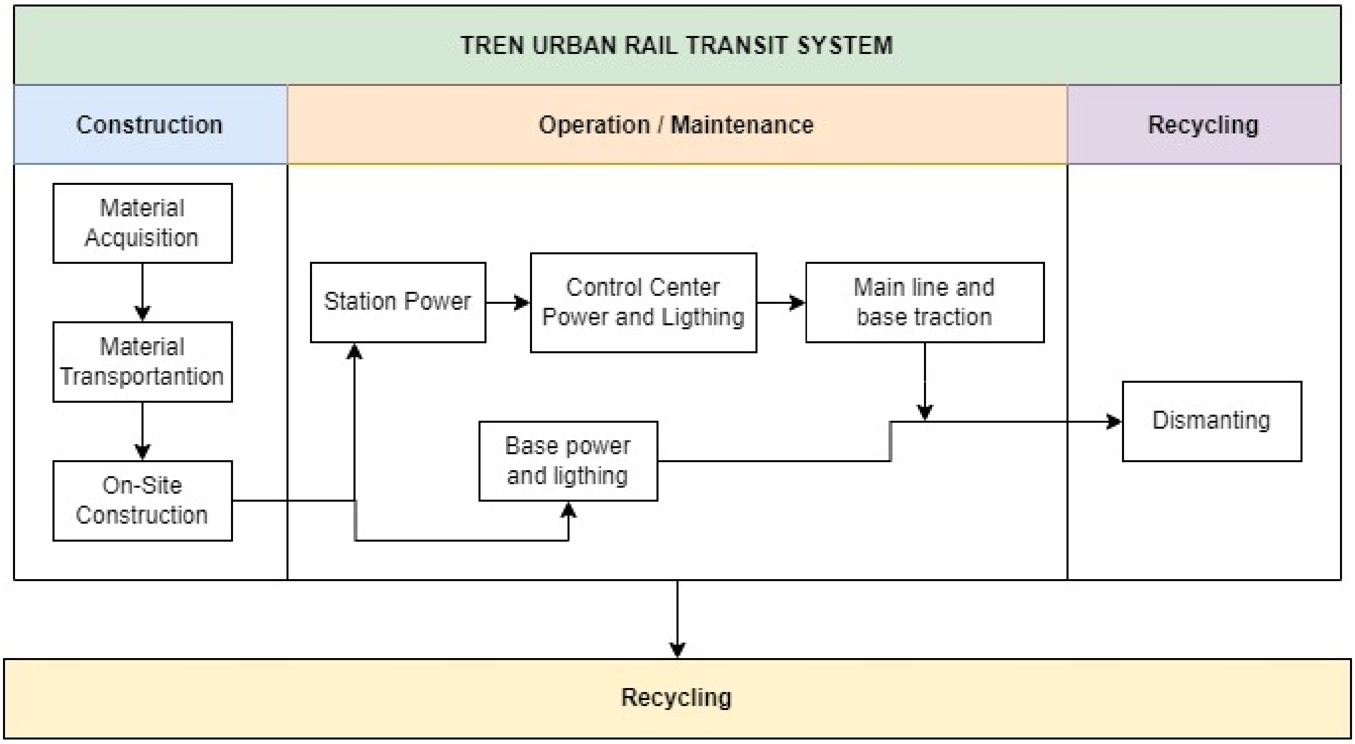

Figure 2. System boundary of GHG emission calculation of the urban rail transit system.

This study provides the total amount of gas emissions for the year 2021. However, to facilitate comparison with other international case studies, the results have been standardized based on passenger-kilometers traveled (PKT) [46].

2.3. Goal and Scope Definition

This study aims to utilize a life cycle assessment methodology to establish the system boundaries of an urban rail transit system. It involves conducting an inventory of resource inputs (such as materials, fuels, and equipment) and emission outputs based on real observed data from the Pernambuco Metro. The obtained results will then be compared with findings from other similar case studies inside Brazil. The urban rail transit system comprises various components, including tracks, tunnels, viaducts, power facilities, vehicle depots, stations, vehicles, and control centers. The calculation process will encompass determining the resource inputs and greenhouse gas (GHG) emission outputs for each phase, as illustrated in Figure 2.

In the case study of the Pernambuco Metro, the functional unit considered is 1 km of construction length with a service life of 50 years. To enable meaningful comparisons with other case studies, the results are standardized per passenger-kilometer traveled (PKT).

2.4. Life-Cycle Inventory Modeling

The methodology used in this study was quantitative and based on the specifications of the Brazilian GHG Protocol Program published by the World Resources Institute (WRI, 2010). The inventory process forms the foundation of the Brazilian GHG Protocol program for accounting, quantifying, and reporting corporate greenhouse gas emissions inventories, following the parameters of ISO 14040-14043, which determine the framework, principles, requirements, and guidelines that should be included in a life cycle study [46].

A study was conducted to identify the sources of greenhouse gas (GHG) emissions within the railway system of Pernambuco, based on the year 2021. The GHG Protocol tool was used for this purpose, following the activity categories and emission factors associated with gases.

The modeling process will focus on calculating the inputs of associated resources (materials, fuels, and equipment) and the outputs of greenhouse gas emissions in each relevant phase. These phases will be categorized into sectors such as maintenance, operation, transport, and material acquisition, allowing for a comprehensive analysis of the emissions throughout the railway system's life cycle.

Life-cycle GHG emissions were estimated using Equation (1), as follows:

$$E = (Q1 + Q2 + Q3 + Q4)/L \quad (1)$$

where

E = GHG emissions by extension of the urban rail transport system (t CO_2e/km);

Q1 = Maintenance Emission Factor;

Q2 = Operation Emission Factor;

Q3 = Transport Emission Factor;

Q4 = Material Acquisition Emission Factor;

L = the length of the rail line (km).

Under the relevant category, information on GHG emissions was inputted based on railway data, such as electricity consumption, fuel consumption, releases from air conditioning and fire extinguishers, fossil fuel combustion, material and personnel logistics, and other activities that may emit GHGs.

2.5. Data Collection

This research was conducted as a life cycle study following the structure developed based on ISO 14040-14043, which establishes the principles, requirements, and guidelines for conducting life cycle assessments. To perform the greenhouse gas (GHG) inventory of the railway system in the state of Pernambuco, Brazil, data were collected from various sources:

I. Fuel and traction energy consumption: The Pernambuco railway operates on both diesel and electric energy, depending on the section of the rail network. Therefore, data on traction electricity consumption by trains and the diesel fuel used by light rail vehicles were collected over the course of one year.

II. Maintenance and auxiliary activities: Auxiliary activities related to the railway, such as infrastructure maintenance, station operations, lighting, the refrigeration of facilities, and carbon dioxide fire extinguishers, were considered. Data related to the fuel consumption of auxiliary vehicles, electric energy used in stations and administrative buildings, fugitive emissions from train and facility refrigeration systems, and fugitive emissions from carbon dioxide fire extinguishers, as well as the electric energy used in train maintenance, were collected.

III. Data accuracy: To obtain accurate GHG emission calculations, specific emission factors for each source were considered. For instance, in the case of gasoline, it was taken into account that approximately 27% of this fuel in Brazil is composed of ethanol, while for diesel, the ethanol percentage is around 7%. Therefore, the amounts of ethanol, pure gasoline, and pure diesel were separated to calculate the GHG emissions using specific emission factors for each type of fuel.

IV. Distance traveled: The total distance covered by trains was recorded to calculate emissions per unit of distance and enable comparisons with other railway systems.

V. Demographic and demand data: Data regarding the number of passengers were fundamental to estimate total emissions and calculate emissions per passenger unit.

The data are reliable, up to date, and the calculations adhere to the standards of the Greenhouse Gas Protocol (GHG Protocol), recognized internationally for conducting GHG inventories.

However, there was a limitation in data collection regarding construction materials and building maintenance, which hindered the calculation of GHG emissions associated with the construction and maintenance of the railway infrastructure in Pernambuco. Due to the railway's long history, relevant information on construction materials over the years was lost over time.

In this article there is a summary of all the data collected on traction and building electrical energy consumption, diesel consumption by locomotives and light rail vehicles, fuel consumption of auxiliary vehicles and maintenance logistics, fugitive emissions from refrigeration systems and extinguishers, among other factors already highlighted.

2.6. Calculation Tool

The GHG Protocol tool was created to calculate greenhouse gas (GHG) emissions from all sources within the company and assist in the inventory development process. It was developed using an electronic spreadsheet along with the Visual Basic tool, based on the GHG Protocol methodology. Each spreadsheet was programmed with formulas and emission factors to quantify the emissions, providing information about emissions by scope and summaries [4].

Each greenhouse gas has the capacity to retain heat at a specific intensity, which can be compared to the capacity of carbon dioxide to perform the same function. Therefore, the tool works with a transformation model that converts emissions from different sources into carbon dioxide equivalents (CO_2e) conform Table 1. CO_2e is a metric used to equalize emissions of various GHGs based on their relative importance compared to CO_2 in producing a given amount of energy (per unit area) several years after the emission impulse. The calculation of CO_2e involves conversions, with the global warming potential (GWP) table proposed by the IPCC being the most commonly used [45].

Table 1. Building energy consumption data.

GAS	GWP-100
CO_2	1
CH_4	25
N_2H	298
HFC-125	3500
HFC-134a	1300
HFC-143a	1430
HFC-152a	124
CF_4	7390
C_2F_6	12,200
SF_6	22,880

With the data collected, the spreadsheet was filled, and the calculation tool performed the necessary calculations for equivalent emissions. All data were input into the spreadsheet, which uses the conversion model for each greenhouse gas that is capable of retaining heat at a specific intensity, comparable to the capacity of carbon dioxide [12,35,41].

3. Results

3.1. Case Study: Pernambuco, Brazil

The urban railway transportation system in Pernambuco, Brazil has a rich history spanning over 150 years. The decision by the Brazilian government to repurpose the defunct freight railway for the construction of the urban railway was a strategic one. However, this choice has resulted in a scarcity of reliable information concerning the actual construction process of the urban railway in northeastern Brazil. Consequently, the greenhouse gas emissions inventory pertaining to the railway construction is not addressed within the scope of this particular case study.

Nevertheless, various studies, including the research conducted by Ye Li [12], have consistently indicated that the emissions attributed to railway construction constitute a minor proportion, accounting for less than 5% of the overall life cycle emissions of a railway system. Hence, the absence of construction data does not exert a significant impact on the greenhouse gas emissions inventory analyzed in this study.

3.2. Operation and Maintenance

The energy consumption during the operation and maintenance phases can be categorized into eight sources: fugitive emissions, station energy and lighting, electric traction, diesel traction, base energy and lighting (workshop and administration), control center energy and lighting, transportation, and materials. Tables 2–6 provide a detailed description of the scope of each source, serving as a reference for future life cycle assessment (LCA) studies on urban railway transportation systems.

Table 2. Data on building energy consumption.

	Energy Consumption	Emissions (t CO_2e)	CO_2-Biomass
Electric (building)	8431.12	624.24	-

Table 3. Data on energy consumption per logistics transport.

	Energy Consumption	Emissions (t CO_2e)	CO_2-Biomass
Diesel	8764	20.87	2.04
Gasoline	29,083	45.97	11.26

Table 4. Gases released by the air conditioning and fire extinguisher.

	Energy Consumption	Emissions (t CO_2e)	CO_2-Biomass
gas garbonic	434	319.42	-

Table 5. Tractive energy data of the electric train.

	Energy Consumption	Emissions (t CO_2e)	CO_2-Biomass
Electric (traction)	51,663,668	3774.70	-

Table 6. Tractive energy data of the diesel train.

	Energy Consumption	Emissions (t CO_2e)	CO_2-Biomass
Locomotive	27,480	1319.61	129.79
Light Rail Vehicles (LRV)	551,491	65.73	6.49

To ensure data availability and accessibility, we have selected 2021 as the base year for estimating the overall emission level during the operation and maintenance phases. Data from the Brazilian urban train company reveals the total energy usage in station facilities and building energy, along with their associated emissions, as presented in Table 3. Additionally, Table 3 also includes information on the total energy and resources consumed in logistic transportation, considering vehicle arrivals and departures, and their corresponding emissions.

Table 4 offers a comprehensive summary of greenhouse gases emitted from air conditioning systems and fire extinguishers employed in the railway system throughout 2021, including the emissions associated with them. Tables 5 and 6 outline the energy consumption for electric and diesel train traction, respectively, with traction energy accounting for approximately 84% of the total greenhouse gas emissions.

The railway system in Pernambuco, Brazil, has a portion of trains powered by diesel traction and another portion powered by electricity. As a result, the emissions from electricity account for 61% of the total emissions, while emissions from diesel traction are around 23%. This differs from most railway systems around the world, which are predominantly powered by electricity (Figure 3).

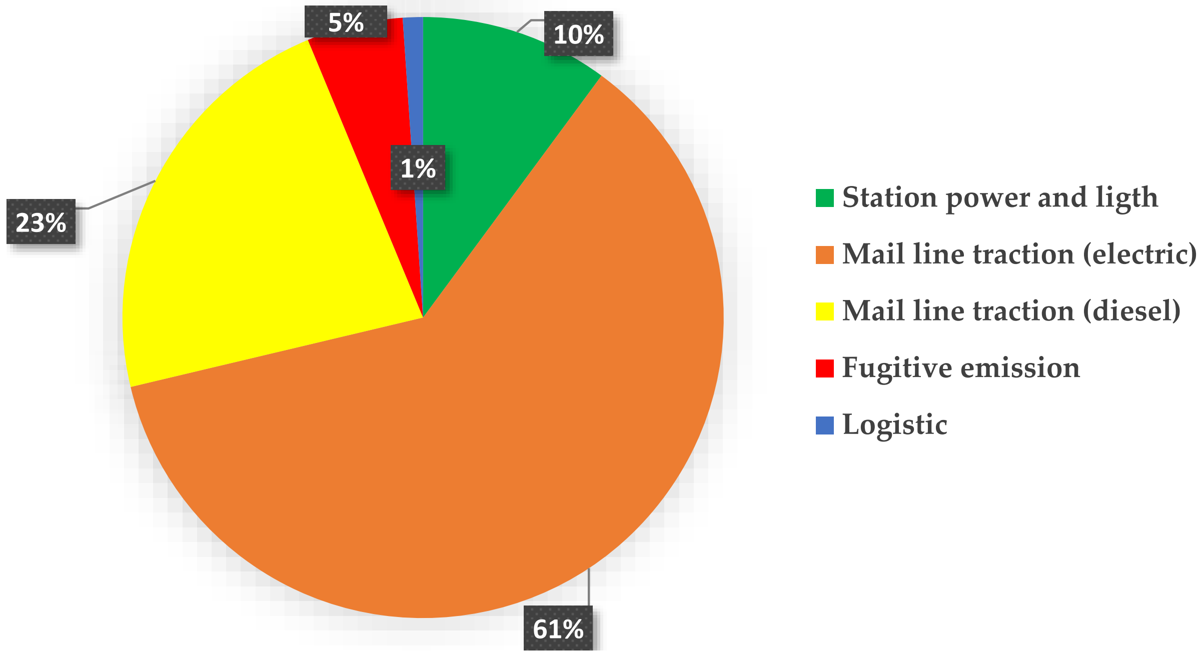

Figure 3. Composition of consumption and emissions.

Although the emissions are not directly generated by the electricity consumed during operation, the LCA calculations encompass greenhouse gas emissions arising from energy generation and transmission processes. In 2021, the average annual electricity consumption for train traction in Pernambuco's railway transportation during the operation phase reached 51.7 million kWh. The corresponding greenhouse gas emissions from electricity utilized for train traction amounted to 3774.70 t CO_2e. For the diesel train system, which consumed 578,978 L of diesel fuel in 2021, the calculated greenhouse gas emissions were 1385.34 t CO_2e.

Through aggregating emissions from other energy sources, the total annual greenhouse gas emissions from operation and maintenance summed up to 6170.54 t CO_2e. Assuming a total service life of 50 years, the estimated total greenhouse gas emissions from the life cycle of operation and maintenance in Pernambuco's railway system amounted to 308,550 t CO_2e.

3.3. Disassembly and Recycling

The development of urban railway transportation in northeastern Brazil occurred relatively late, starting with the opening of the first system in 1985. This involved repurposing some trains from the Rede Ferroviária and acquiring new ones. However, there is currently a lack of reliable data regarding the dismantling and recycling of the urban railway transportation infrastructure in this region of Brazil. As a result, the dismantling process is not addressed in this particular case study.

4. Discussion

4.1. Comparative System

This study aims to emphasize the importance of conducting a comparative analysis of traction emissions, station operation, and infrastructure in different urban railway transportation systems across Brazil. It should be noted that there is limited availability of related studies, and the comparative analysis is conducted within the same scope whenever possible, drawing on data and information from specialized literature and various case studies with diverse local parameters [47].

The results obtained from this comparison can provide valuable insights into the potential for reducing emissions in urban railway transportation systems and contribute to the establishment of emission reduction targets in the Brazilian context. This study compares greenhouse gas emissions (GHE) from urban railway systems, including the metro systems in Recife, São Paulo, and Rio de Janeiro, as well as the urban railway (train) in Rio de Janeiro.

Furthermore, the reasons for data discrepancies among these cities are explored. To facilitate the comparison, emission intensities for each city are standardized per passenger-kilometer traveled (PKT). Standardizing emission intensities per PKT enables fairer comparisons and allows for the identification of areas for improvement in each railway system. This approach takes into account both the number of passengers transported and the distance traveled, thus providing a more equitable evaluation of environmental performance [7].

Therefore, this comparison of emissions standardized per PKT in different urban railway systems offers valuable insights into disparities and provides important information for the development of more sustainable and emission-efficient transportation strategies. In 2021, the total GHE from electricity and diesel consumption for traction in the metro system of Pernambuco amounted to 5160.04 tCO_2e, based on a total of approximately 32 million passengers, resulting in traction emissions of 4 g CO_2e/PKT.

In 2016, the total GHE from electricity consumption for traction in the metro system of Rio de Janeiro reached 14,963 tCO_2e. With a total passenger volume of approximately 245 million, traction emissions were measured at 5.5 g CO_2e/PKT. The total traction emissions in 2016 for the railway system in Rio de Janeiro were 22,273 tCO_2e, with a total passenger volume of 182 million [48,49]. Hence, traction emissions on the Rio de Janeiro railway amounted to 5.6 g CO_2e/PKT [50]. According to the governance report of the metro system of São Paulo in 2022, traction emissions for the São Paulo metro were 6 g CO_2e/PKT [45,51]. In Figure 4 presents the comparison of traction emissions per PKT in these three locations.

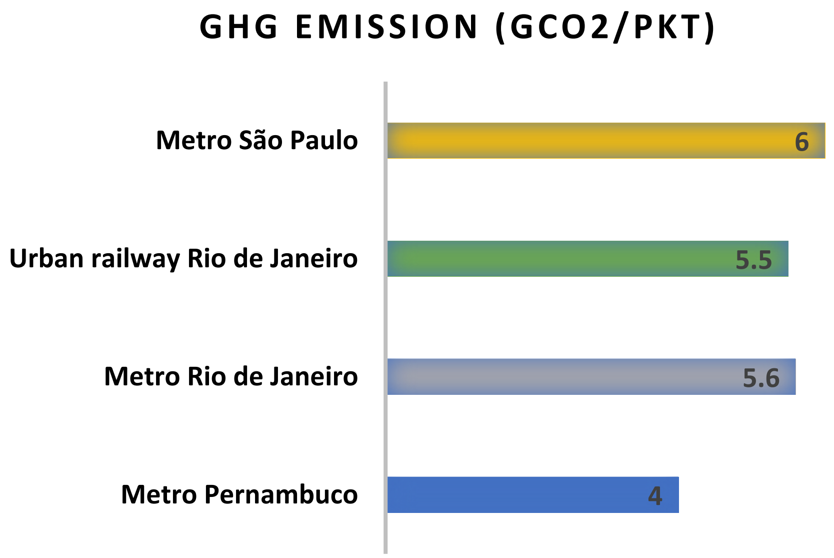

Figure 4. Traction emission per PKT.

Based on these results, Pernambuco exhibited the lowest traction emissions per PKT, while the São Paulo metro had the highest emissions per PKT. Traction emissions are influenced by factors such as train characteristics, track conditions, and operational modes, among others. However, since these contributing factors are not the main focus of this study, they were not detailed within this research.

These results can be attributed to three factors: the carbon intensity of electricity supply, passenger volume, and the efficiency of electricity use in urban railway transportation. The adopted greenhouse gas emission factors for electricity were similar across the case studies. However, there are notable differences in train flow between the Pernambuco metro and the metros in Rio de Janeiro and São Paulo, with much longer intervals between trains in Pernambuco. Additionally, the Pernambuco metro has a smaller network extension compared to Rio de Janeiro and São Paulo.

Typically, higher passenger occupancy rates result in lower emissions per PKT. However, this pattern does not hold true for the São Paulo metro due to its extensive railway network, which serves a larger population than the other three systems being compared.

It's important to note that the data for Rio de Janeiro is from 2016, predating the data from the other systems. The relatively high emissions in Rio de Janeiro may be partially explained by the lack of available energy-saving technologies at that time.

Greenhouse gas (GHG) emissions in railway systems can vary considerably due to various factors that affect the operation and infrastructure of these systems. One of the main influences is the type of energy used to power the trains, which has a significant impact on the total emissions of the railway system [35,52]. In the case of the Pernambuco subway, it stands out from other systems compared in this article because it uses a combination of electric and diesel energy, with the latter being a fossil fuel with high GHG emissions.

Furthermore, the number of passengers and freight transported via railway systems has a direct impact on GHG emissions [41]. Highly busy systems with high demand, such as São Paulo's, may show greater efficiency in terms of emissions per passenger-kilometer. However, this efficiency is not reflected when comparing São Paulo's system with other railway systems with lower passenger flow, such as Rio de Janeiro's, for example. This discrepancy can be partly explained by the energy efficiency of train engines, which directly influences GHG emissions. More modern and energy-efficient trains tend to emit fewer GHGs per kilometer traveled compared to older and less efficient trains. Additionally, operational factors such as the use of traffic control technologies, efficient operating practices, and proper maintenance also play a significant role in reducing GHG emissions in railway systems.

However, to fully understand the specific differences between São Paulo's system and others, it is essential to conduct a detailed scientific investigation within that particular system. This would allow for the identification of factors that may be related to the high GHG emission rate in this specific system.

It is crucial to emphasize that GHG emissions are influenced by a combination of several factors. Therefore, for a comprehensive assessment of GHG emissions in compared railway systems, it is necessary to consider all relevant variables and conduct a thorough investigation to analyze and compare each of them. The existence of this gap in the current article highlights the importance of future research that can fill this knowledge gap and enhance our understanding of the environmental impact of railway systems.

4.2. Mitigation of GHG Emissions

Mitigating greenhouse gas (GHG) emissions in railways is essential to reduce the environmental impact of this transportation sector.

In the railway system of Pernambuco, electric energy is the main source of GHG emissions, as demonstrated in graph 01. Adopting electrified railway systems, using renewable sources such as solar energy, can significantly decrease GHG emissions. Installing solar panels on station rooftops can significantly reduce electricity consumption, taking advantage of the abundant sunlight in the northeast region of Brazil, where Pernambuco is located.

Currently, Pernambuco's light rail operates on diesel energy, a fossil fuel with high GHG emission potential. Replacing this fuel with renewable energy can substantially cut down on GHG emissions. A study by Mariko, which analyzed the feasibility of photovoltaic energy for Brazilian light rail, revealed that installing photovoltaic systems on the rooftops of the fleet operated in Brasilia's railway could save around BRL 800,000 and reduce CO_2 emissions by 540 tons over 10 years [53].

Efficient electricity use plays a crucial role in reducing energy consumption and emissions in urban railway transportation. Recycling is an effective method to save energy, as demonstrated by Delhi's metro. Electricity generated during train braking is repurposed for other operational modes, resulting in nearly 35% of Delhi Metro's electricity consumption being regenerated by the system [54].

Additionally, managing energy consumption in stations and administrative buildings can further decrease GHG emissions. Mariko's research, which implemented a conscious and sustainable energy consumption program in a Brazilian Northeast railway system, achieved a 56% reduction in monthly electricity consumption and over 50% in GHG emissions [55]. Applying energy-saving techniques like this can be beneficial in reducing traction emissions in Brazilian railway systems.

Improving the energy efficiency of Pernambuco's light rail is an important form of mitigation. This can be achieved through engine modernization, traction system enhancement, route and speed optimization, and the use of more efficient technologies. As demonstrated by Dariusz Kurczyński [52], a modern engine with a common rail system, powered by biodiesel RME (rapeseed methyl ester) and its blends with diesel, can reduce average concentrations of carbon monoxide, hydrocarbons, and particulate matter.

5. Conclusions

The objective of this research was to calculate greenhouse gas (GHG) emissions throughout the entire life cycle of the railway system in Pernambuco, Brazil, using real observed data. Additionally, a comparative analysis was conducted to understand the level of emissions in the national context and provide guidance for future emission reduction efforts. This analysis also aimed to provide concrete data on environmental impact to policymakers, urban planners, and other stakeholders who seek to promote improvements in the railway system towards a sustainable railway system for future generations.

The results showed that the total GHG emissions for the entire life cycle of the Pernambuco railway system, considering its construction length, amounted to 6170.54 metric tons of CO_2 equivalent (tCO_2e). With a lifespan of 50 years, the projected emissions are estimated to reach 308,550 tCO_2e.

These findings offer valuable insights into the environmental impact of the railway system in Northeast Brazil, serving as a basis for identifying areas that need improvement and guiding future actions to reduce GHG emissions. However, due to the railway system's construction over 150 years ago, using the cargo transportation system of the federal railway network, there is a lack of concrete data on the quantity of construction materials used, making it impossible to calculate GHG emissions during the construction phase.

The urban railway system in Pernambuco differs from the rest of the country as it combines trains powered by electricity and diesel. When compared to other national systems in the operation and maintenance phase, the traction emissions of the Pernambuco railway system were 4 g CO_2e per passenger-kilometer traveled (PKT), which is competitive with the emissions of the São Paulo and Rio de Janeiro metros and the Rio de Janeiro railway. This is noteworthy considering the higher passenger volume in the latter systems. However, there is still significant potential for energy savings in the operation phase, particularly in stations and central buildings that could utilize solar energy. The northeastern region of Pernambuco, located close to the equator, receives abundant sunlight throughout the year, making solar energy a viable renewable option [55]. Implementing more efficient ventilation structures in metro stations and using energy-saving lighting solutions like LED lights can effectively reduce emissions from these stations [53].

For future research, it is recommended to conduct a more detailed comparative analysis that takes into account system boundaries, GHG accounting methods, and datasets from different case studies. This approach will provide a comprehensive and accurate understanding of emissions in diverse contexts.

Furthermore, the development of a comprehensive estimation tool and a standardized benchmark applicable to various areas, equipment types, structures, and techniques would be highly beneficial. This would facilitate the collection and analysis of consistent and comparable data, enabling a more precise assessment of GHG emissions in different railway systems.

This report provides, in addition, real-world experience and guidance from government and industry with years of experience in inventory. A comprehensive life cycle model of the entire railway system was developed. This report is meant as a complement to policymakers' efforts and provides, in addition, real-world experience and guidance from government and industry with years of experience in the charging space. Given the role of the railway system in Pernambuco's economy, especially as it relates to the distribution of goods and the provision of services, the Fuels Institute is dedicated to informing comprehensive discussions about the various policy options available to balance the various needs of the market while achieving significant reductions in transportation emissions.

In conclusion, conducting more in-depth analyses, improving tools, and establishing enhanced benchmark standards will contribute to the assessment and management of GHG emissions in the railway sector. This will allow for the identification of areas for improvement and the development of effective strategies to reduce emissions.

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