Assessing the Effects of Thailand's Greenhouse Gas Mitigation Mechanism on Carbon Footprint and Greenhouse Gas Reduction: A Case Study of a Compound Rubber Factory

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***Abstract*—As countries and organizations worldwide are setting targets for carbon emissions, it is imperative to recognize and address the observable effects of climate change, fostering a collective effort towards mitigating global warming. This study aims to assess the carbon footprint of a compound rubber factory and determine Greenhouse Gas (GHG) reductions in its operations in compliance with Thailand's greenhouse gas mechanism for a compound rubber factory. The assessment adheres to the standards established by the Thailand Greenhouse Gas Management Organization). In 2022, the combined carbon footprint of the factory's three branches was estimated at 26,718.20 tCO_2e. Among the three categories, other indirect emissions (Scope 3) exhibited the largest carbon footprint at 17,779.91 tCO_2e, accounting for 66.55% of the total emissions. This was followed by assessing direct and indirect emissions from electricity (Scope 2), which contributed 581.26 tCO_2e or 2.18% and 8,357.02 tCO_2e or 31.27% of the total emissions, respectively. The carbon intensity per ton of compound rubber was 0.22 tCO_2e/ton for Scopes 1 and 2, and 0.64 tCO_2e/ton when including Scopes 1–3. The factory has implemented activities to reduce GHGs under the Low Emission Support Scheme, such as waste separation for recycling, which reduces GHG emissions by 864.56 tCO_2e (3%), and solar rooftop installations, which cut emissions by 195.53 tCO_2e (2%). These efforts offer valuable insights for minimizing environmental impacts while delivering economic and operational benefits.**

***Keywords*—carbon footprint for organization, greenhouse gas reduction, compound rubber**

I. Introduction

Currently, the planet is facing the effects of climate change, driven by a steady rise in global temperatures [1]. Since 1850, the Earth's average temperature has increased by approximately 0.06°C per decade [2]. This trend is largely attributed to increased levels of Greenhouse Gases (GHGs) in the atmosphere, which mainly emitted from fossil fuel combustion, deforestation, and energy-intensive industrial processes, such as vulcanization, mixing, and curing [3, 4].

To effectively tackle climate change and implement the provisions outlined in the UNFCCC, governments and regulatory bodies should use the GHG Protocol. This widely recognized accounting tool helps businesses, governments, and organizations measure and manage GHG emissions and serve as a basis for developing policies, regulations, and incentives aimed at reducing emissions both nationally and internationally. In Thailand, climate change strategies, policies, plans, and institutional arrangements are developed and managed through the Thailand Greenhouse Gas Management Organization (TGO) [5, 6]. The TGO oversees GHG emissions management, issues guidelines for effective emission reduction, such as the Carbon Footprint of Organizations, and accelerates the development and implementation of GHG reduction initiatives, including the Low Emission Support Scheme (LESS).

Evaluating an organization's carbon footprint is a crucial method for quantifying the greenhouse gas emissions and absorption resulting from its operational activities [7]. This assessment enables the industrial sector to measure the GHG emissions associated with its operations. It accounts for seven types of GHGs, including Carbon Dioxide (CO_2), Methane (CH_4), Nitrogen Monoxide (N_2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulfur Hexafluoride (SF_6), and Nitrogen trifluoride (NF_3), with measurements expressed in tons of carbon dioxide equivalent (tCO_2e). Such assessments lead to the determination of management guidelines aimed at effectively reducing GHG emissions at the factory, industrial, and national levels [8, 9].

The LESS represents a key initiative in Thailand's strategy to mitigate GHG emissions. This scheme is designed to create a framework for reducing GHG emissions by employing social incentives to motivate individuals and communities to engage in emission-reducing activities. It supports this goal by providing guidelines for calculation and issuing certificates to participants, thereby raising awareness and encouraging efforts to reduce emissions. LESS covers a range of activities aimed at cutting GHG emissions, including electricity generation from renewable energy, energy efficiency improvement, transportation with Electric Vehicles (EVs), carbon sequestration LESS covers a range of, and waste management projects [10].

The compound rubber industry in Thailand is a significant sector of the national economy, significantly both domestic markets and international exports. As one of the world's leading global producers and exporters of natural rubber, Thailand's rubber compound sector is essential for converting raw rubber into value-added finished products [11]. Compound rubber is created by blending various additives with raw rubber to achieve specific chemical and physical properties suitable for different applications. This material is utilized in a variety of industries, such as consumer goods, automotive, aerospace, construction, electronics, and medical fields [12].

While extensive studies have been conducted on the carbon footprint associated with rubber production and plantations in various countries, there is a notable lack of research on the carbon footprint of compound rubber factories, which play a

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crucial role in the rubber industry supply chain. This study aims to provide guidelines for assessing GHG emissions within the rubber compound industry. The carbon footprint for rubber products could vary depending on the sourcing and processing practices of the compound rubber. Sustainable processing methods can help mitigate the carbon footprint of these products. Furthermore, Thailand's GHG mitigation mechanisms could provide a model for similar initiatives in other countries.

Therefore, this study aims to assess the carbon footprint of a compound rubber factory in Thailand. Furthermore, it employs the GHG mechanism to quantify emission reductions achieved through the organization's activities under the LESS.

II. Materials and Methods

A. Study Area

The study focused on a compound rubber factory in Rayong Province, Thailand, and studied three of its branches. The operations within a factory begin with the preparation of raw materials, following by mixing and compounding, where various additives are introduced to achieve specific properties. Subsequently, the compounded rubber undergoes shaping and curing to meet the required standards. The production process relies heavily on machinery and energy consumption. Finally, the factory completes its process with careful packaging and shipping to deliver finished compound rubber products that cater to various industrial needs. Primary data of the compound rubber factory is shown in Table 1.

Table 1. Primary data of the compound rubber factory

Physical location	Branch I	Branch II	Branch III
Factory horsepower (HP)	3,786	8,268	7,043
Compound rubber production (tons/year)	10,928	14,194	16,377
Number of employees	198	212	200
Working hours (hr)	24	24	24
Annual operating (days/year)	300	300	300

B. GHG Emission Assessment

1) Assessment boundary

When establishing organizational boundaries, a company adopts an operational control approach for consolidating its GHG emissions. Using this approach [7], the company accounts for 100% of the emissions from operations over which it or its subsidiaries have control.

The next step involves defining its operational boundaries, which includes identifying and categorizing from its activities. This encompasses direct emissions from company operations (Scope 1), such as those from electricity generation, heat or steam production, energy use, transportation within organizations, and fugitive emissions, as well as indirect emissions from purchased electricity, heating, and cooling (Scope 2). Additionally, Scope 3 covers significant emissions from sources outside the company's direct control, including the production of purchased materials and fuels, water usage, transport-related activities, and waste disposal. Fig. 1 provides an overview of emission sources and the boundaries of factory GHG emissions in relation to Scopes 1, 2, and 3.

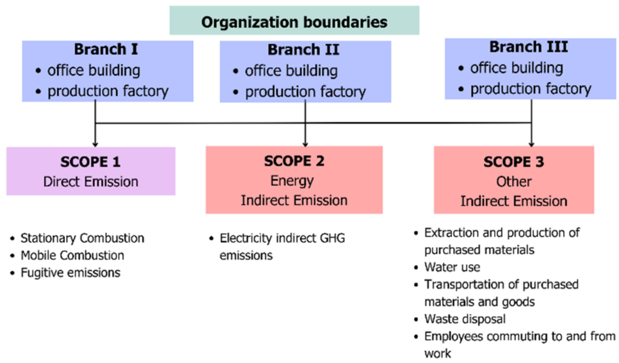

Fig. 1. Overview of emission sources and organizational boundaries.

2) Data collection

Permission was granted for primary data collection from three branches of the compound rubber factory. The data, covering the factory's operations from January to December 2022, includes various records necessary for estimating resource consumption, such as fuel consumption, raw material usage, electricity, and water. The study involved collecting and reviewing documents related to each emission scope, as shown in Table 2.

Table 2. Data collection from resource utilization of the compound rubber factory

SCOPE		Operational data	Data sources
Scope 1	Stationary Combustion	Fuel combustion consumption in stationary equipment (e.g., generator, fire pump and water pump)	Receipt
	Mobile Combustion	Fuel combustion consumption in mobile sources (e.g., factory's car and forklift car)	Receipt
	Fugitive emissions	Hydrofluorocarbons (HFCs) from air conditioning and refrigeration use	Record form
		CO_2 from fire extinguisher and welding tank	Receipt
		Sludge removal of septic tank	Calculation
Scope 2	Electricity indirect GHG emissions	Electrical consumption	Utility bills
Scope 3	Extraction and production of purchased materials	Raw materials consumption (Synthetic rubber and carbon black)	Record form
	Water use	Water consumption	Utility bills
	Transportation of purchased materials and goods	Transport distance	Google map
		Shipping weight	Record form
		Type of transport	Record form
	Waste disposal	Weight of waste disposed to landfills	Record form
	Employees commuting to and from work	Distance from home to work	questionnaire
		Type of fuels	questionnaire

3) Calculating carbon footprint

The carbon footprint is determined by applying equation (1), which involves multiplying the organization's activity data by the relevant emission factors as shown in Table 3. The GHG emissions are expressed in terms of carbon dioxide equivalent (CO_2e) to reflect the total emissions.

$$\text{GHG emissions} = \text{Activity data} \times \text{Emission factor} \qquad (1)$$

Table 3. Emission factors

Source	EF	Unit	References
SCOPE 1 - Stationary Combustion			
Motor gasoline	2.1894	$kgCO_2e$/ liter	[13]
LPG	3.1134	kg CO_2e/ kg	[13]
SCOPE 1 - Mobile Combustion			
Motor Gasoline	2.2394	kg CO_2e/ liter	[13]
Gas/ Diesel Oil	2.7406	kg CO_2e/ liter	[13]
SCOPE 1 - Fugitive emissions			
Refrigerants – R32	677	kg CO_2e/ kg	[13]
Refrigerants – R410a	1,725	kg CO_2e/ kg	[13]
Refrigerants – R134a	1,300	kg CO_2e/ kg	[13]
SCOPE 2			
Electricity, grid mix	0.4999	kg CO_2e/kWh	[13]
SCOPE 3			
Synthetic rubber	3.5138	kg CO_2e/ kg	[14]
Carbon black	2.6200	kg CO_2e/ kg	[15]
Transportation (10-wheel vehicle)	0.0454	kg CO_2e/tkm	[14]
Transportation (6-wheel vehicle)	0.0547	kg CO_2e/tkm	[14]
Transportation (4-wheel vehicle)	0.1411	kg CO_2e/tkm	[14]
Transportation (Air Freight)	1.0990	kg CO_2e/tkm	[14]
Transportation (Sea Freight)	0.0107	kg CO_2e/tkm	[14]
Waste	2.9300	$kgCO_2e$/tkm	[14]

4) Assessment data quality level

The uncertainty data assessment is a crucial step for evaluating data quality, including both activity data and emission factors. This process provides insights into the reliability of the data, which is essential for managing data quality effectively.

The quality of data collected from various activities and emission factors can differ, resulting in inconsistent data quality across the dataset presented in Table 4. To address these discrepancies, the uncertainty assessment was assessed using a reliability rating system, which categorized the data into different levels for both data collection and emission factors. By considering the data quality across all activities, the overall data quality can be summarized in Table 5 [8].

Table 4. Score of data reliability rating

List	Level of data quality		
Data collection	Score = 6	Score = 3	Score = 1
	Automation system	Meter and Bill	Estimated value
Emission Factors	Score = 4	Score = 3	Score = 2
	From quality measures	From producer	From national level
	Score = 1		
	From International level		

Table 5. The overall level of data quality.

Level	Level of data score	Explanation
1	1–6	Uncertainly: high Quality: bad
2	7–12	Uncertainly: medium Quality: medium
3	13–18	Uncertainly: low Quality: good
4	19–24	Uncertainly: low Quality: excellent

C. GHG Reductions under LESS

1) Data collection

This research examines how Thailand's GHG mitigation mechanisms, specifically under the LESS, contribute to reducing GHG emissions. The study focuses on mitigating GHG emissions by implementing waste separation for recycling and utilizing renewable energy from solar rooftops. Data collection for this study involved compiling records related to each of these activities, as detailed in Table 6.

Table 6. Primary data of Data collection from each activity

Activity	Operational data
Waste separation for recycling	Weight of recycled waste (kg); paper, plastic and steel
Renewable energy from solar rooftops	Electricity produced/used from renewable energy (kWh)

2) Calculating GHG reductions

The GHG reductions under LESS can be calculated using equation (2). The unit of GHG reduction is in tCO_2e.

$$\text{Emission Reduction} = \text{Baseline Emission} - \text{Project Emission} \quad (2)$$

To assess the impact of waste separation for recycling, the baseline emissions were calculated using equation (3). This involved multiplying W, the total weight of recycled waste (in kg), by the relevant emission factors for recycling ($EF_{recycle}$). These factors represent the emissions avoided by recycling waste instead of dumping it in landfills.

$$\text{Baseline Emission} = \left(W \times EF_{\text{recycle}}\right) \quad (3)$$

For renewable energy from solar rooftops, the baseline emissions can be calculated using equation (4) by multiplying Elc_re, the total electricity produced from renewable energy (kWh) with EF_{elc}, the emission factors for electricity. In contrast, project emissions were calculated using equation (5) by the total electricity used for the power generation system or for carrying out activities (Elc) multiplied by emission factors for electricity (EF_{elc}).

$$\text{Baseline Emission} = (Elc\_re \times EF_{elc}) \quad (4)$$

$$Project\ Emission = (Elc \times EF_{elc}) \quad (5)$$

III. Result and Discussion

A. Carbon Footprint Assessment

Based on historical data on activities that contribute to GHG emissions at the compound rubber factories, the GHG emissions for the year 2022 were successfully evaluated. The results of this evaluation are provided in Table 7.

Fig. 2 presents a summary of GHG emissions for 2022 from each scope. For Branch I, the emissions were 210.24 tCO_2e for direct emissions (Scope 1), 1,878.58 tCO_2e for electricity (Scope 2), and 3,718.70 tCO_2e for indirect emissions (Scope 3), representing 3.62%, 32.35%, and 64.03% of the total emissions, respectively. In Branch II, direct emissions (Scope 1) amounted to 179.96 tCO_2e, electricity-related emissions (Scope 2) were 3,070.31 tCO_2e, and indirect emissions (Scope 3) totaled 12,858.87 tCO_2e, accounting for 1.12%, 19.06%, and 79.82% of the total emissions, respectively. For Branch III, direct emissions (Scope 1) were 191.06 tCO_2e, emissions from electricity (Scope 2) were 3,408.14 tCO_2e, and indirect emissions (Scope 3) were 1,202.34 tCO_2e, representing 3.98%, 70.98%, and 25.04% of the total emissions, respectively.

Table 7. GHG emissions in 2022 from each branch of the compound rubber factory

Source	GHG Emissions (tCO_2e)			Total	Level of data score
	Branch I	Branch II	Branch III		
SCOPE 1				*581.24*	
Stationary combustion	0.25	0.12	0.06	0.43	2
Mobile combustion	178.28	136.95	136.14	451.37	2
Fugitive emissions	31.70	42.89	54.85	129.44	1
SCOPE 2				*8,357.03*	
Electricity indirect GHG emissions	1,878.58	3,070.31	3,408.14	8,357.03	3
SCOPE 3				*17,779.91*	
Extraction and production of purchased materials	3,093.81	11,928.32	626.81	15,648.94	3
Water use	2.29	2.35	3.5	8.14	3
Transportation of purchased materials and goods	452.12	704.20	367.99	1,524.31	3
Waste disposal	70.77	84.92	77.96	233.65	3
Employees commuting to and from work	99.71	139.08	126.08	364.87	1

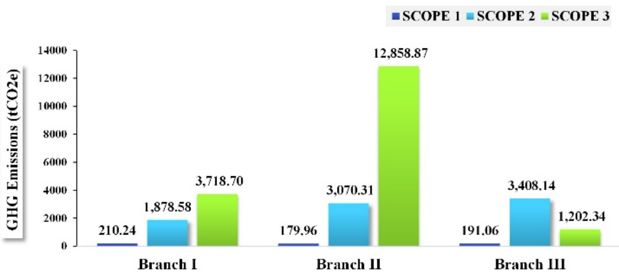

Fig. 2. The summary results of the GHG emissions in 2022 from each scope.

It suggests that, among the three branches, indirect emissions (Scope 3) represent the largest share of the carbon footprint, totaling 17,779.91 tCO_2e, which is approximately 66.55% of the overall emissions. This is predominantly due to the extraction and production of purchased materials, which alone accounts for 15,648.94 tCO_2e, or approximately 88.01% of Scope 3 emissions. A major factor in these significant emissions is the production of synthetic rubber and carbon black, which are the primary raw materials used in rubber compound production, comprising approximately 67.05% of the total material mass used. The transportation of purchased materials and goods contribute approximately 8.57% of the total Scope 3 emissions. According to industry insights, the greater the distance and weight of transported materials and goods, the higher carbon emissions incurred. Similarly previous studies [16–19], this study reveals that raw materials are the source of emissions, with transportation playing a relatively minor role. Additionally, other Scope 3 sources, such as water usage, waste disposal, and employee commuting have minimal impact on overall carbon emissions, a finding consistent with previous research on the carbon footprint of beverage manufacturing [20].

Research [21–23] frequently highlights that a significant portion of the carbon footprint is attributed to electricity consumption (Scope 2). In this study, it was found that the three branches of the compound rubber factory together emitted 8,357.03 tCO_2e from energy use, representing approximately 31.27% of the total emissions. This figure is based on the factory's total annual electricity consumption of 16,717,398.54 kWh in 2022. Based on the company's internal records for 2022, 72% of this electricity was used for production processes, including machinery for mixing, processing, and shaping rubber compounds. The remaining 28% was allocated to lighting, air conditioning, ventilation, and office activities.

The minimal impact of direct emissions (Scope 1) on the overall carbon footprint of a rubber compound factory, accounting for approximately 2.18% of total emissions, is attributed to the absence of combustion processes, chemical reactions, or other activities that release GHG. The emissions primarily originate from internal activities, such as using gasoline for lawnmowers, employing LPG for maintenance work, using vehicles within the factory, and fugitive emissions from factory equipment. These emissions can be mitigated by implementing proactive measures. For example, transitioning to electric lawnmowers and maintenance equipment [24], exploring renewable energy sources such as biogas to replace LPG in maintenance work [25] and upgrading our internal vehicle fleet to include electric and hybrid vehicles can significantly reduce emissions from factory transportation activities [26]. These steps collectively contribute to a substantial decrease in our internal emissions, suggesting our commitment to sustainability and environmental responsibility. Similar reductions in direct emissions have been observed in carbon footprint estimates of the paper industry in China [27].

Besides purchased goods and services, it is essential to note that carbon emissions from transportation encompass both mobile combustion (Scope 1) and the transportation of purchased materials and goods (Scope 3). Therefore, organizations should prioritize developing and implementing comprehensive management plans focused on reducing transportation-related emissions. Promoting the use of low-emission vehicles, such as EVs, plug-in hybrid EVs, and hydrogen fuel cell vehicles, can significantly reduce GHG emissions. Although these vehicles have higher initial costs, they generally incur lower operating and maintenance expenses over their lifespan. Many regions offer government incentives and subsidies to reduce the purchase price, making these vehicles more affordable and attractive to consumers [28–30]. Furthermore, investing in the development of complementary electric charging and hydrogen refueling infrastructure will support both short and long-distance travel needs [31]. This infrastructure, combined with initiatives to encourage carpooling and ride-sharing, can further reduce carbon emissions from transportation [31]. Additionally, integrating renewable energy sources into the power supply for EVs enhances overall emission reduction efforts [32]. Addressing the challenge of carbon emissions requires a collective and strategic approach to achieve meaningful reductions.

Lastly, in comparison to carbon intensity, which refers to the amount of carbon emissions per unit of production, the carbon intensity for Branch I, Branch II, and Branch III (Scopes 1 and 2) was 0.19, 0.23, and 0.22 $tonCO_2e/ton$, respectively. Additionally, when including Scopes 3 emissions, the carbon intensity values for these branches were 0.53, 1.13, and 0.29 tonCO_2e/ton, respectively, as shown in Fig. 3. The total carbon intensity across the three branches was 0.22 tCO_2e/ton for Scopes 1 and 2, and 0.64 tCO_2e/ton when Scope 3 is included. Carbon intensity qualifies the GHG emissions per unit of production. For Scopes 1 and 2, a carbon intensity of 0.22 tCO_2e/ton reflects the direct emissions from sources owned or controlled by the company (Scope 1) and indirect emissions from the electricity purchased and consumed by the company (Scope 2). However, including Scope 3 emissions significantly increases the carbon intensity to 0.64 tCO_2e/ton. This rise is due to the substantial indirect emissions associated with the transportation of purchased materials and goods, as well as the extraction and production of these materials. These findings emphasize the importance of addressing not only direct and energy-related emissions but also broader value chain emissions to achieve meaningful reductions in the overall carbon footprint.

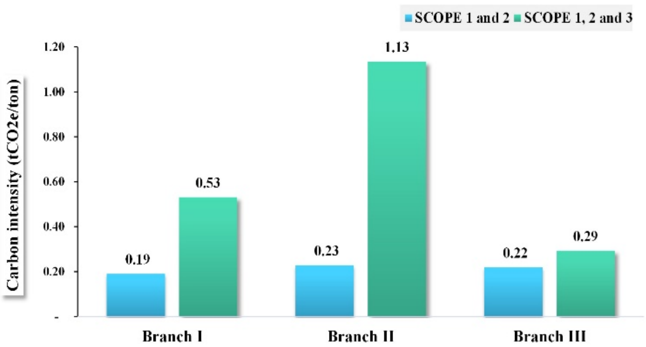

Fig. 3. Carbon intensity from each branch.

When comparing the carbon footprint of rubber compounds to other types of rubber, such as concentrated latex, STR 20, and RSS [33], the carbon footprint for rubber compounds stands at 0.64 tCO_2e/ton, which is significantly higher than that of other rubber products. This disparity can be attributed to the comprehensive assessment of this study, which encompasses entire rubber compound production process and all potential carbon sources within the organization. In contrast, the carbon footprint for other types of rubber is primarily calculated on a product-specific basis, with a focus primarily on energy consumption and the utilization of synthetic fertilizers.

1) GHG reduction

The GHG reduction analysis focused on organizational activities conducted under the LESS. Each of the three branches of the compound rubber factory, Branch I, Branch II, and Branch III, has adopted waste separation practices for recycling materials such as paper, plastic, and steel. Additionally, Branch II has installed solar rooftops to utilize electricity from renewable sources, leading to a reduction in GHG emissions.

Table 8 shows the calculation for GHG reductions achieved through waste separation activities from January to December 2022. The total reduction in GHG emissions from this initiative at the compound rubber factory amounted to 864.56 tCO_2e.

Table 8. GHG reduction in 2022 from waste separation for recycling

	Branch I	Branch II	Branch III	Total
Weight of paper (kg)	28,638.00	9,528.00	54,196.00	92,362.00
Weight of plastic (kg)	15,141.00	15,601.00	46,802.00	77,544.00
Weight of steel (kg)	16,751.00	20,050.00	105,446.00	142,247.00
GHG reduction (tCO_2e)	208.78	106.87	548.91	864.56

The results highlight the significant potential of waste separation, especially for segregating recyclables, in reducing GHG emissions. Recycling paper, plastic, and steel leads to reductions of 5.66 kgCO_2e/kg, 1.03 kgCO_2e/kg, and 1.83 kgCO_2e/kg, respectively. When compared with recycling initiatives, such as those for paper [34], plastic and metal waste in Bangalore, India, emission reductions vary by material. Specifically, recycling paper products like sheets, newspaper inserts, newsprint, cardboard, and magazines results in emission reductions to 0.98, 1.6 and 0.52 kgCO_2e/kg. Similarly, for plastics, reductions for high-value plastic, PET bottles, and low-value plastic are 0.73, 2.73, and 1.59 kgCO_2e/kg, respectively, while metal waste demonstrates a reduction to 17.2 kgCO_2e/kg. These reductions are calculated by comparing the life cycle emissions of virgin materials with those of recycled materials. However, due to the lack of detailed information on specific waste types, emissions values may vary. It is advisable to separately categorize paper and plastic types for more accurate information. Additionally, recycling offers a range of benefits, including resource conservation, reduction in landfill waste, energy and water savings, and economic gains.

Regarding GHG reduction through renewable energy from solar rooftops, Branch II began using solar rooftop installations in July 2022. The on-grid photovoltaic power system has a capacity of 865 kW. From July to December 2022, Branch II generated 402,578.67 kWh of electricity from these solar rooftops, resulting in a GHG reduction of 195.53 tCO_2e. In 2023, the electricity produced from the solar rooftops increased to 863,057.23 kWh, leading to a GHG reduction of 419.19 tCO_2e, which translates to a reduction rate of 0.49 kgCO_2e per kWh. When compared to the carbon mitigation achieved by photovoltaics (PVs) in Singapore [35], which suggests an emission rate of 0.013 kgCO_2e/kWh, this variation may be attributed to differences in solar energy availability. Such differences are influenced by factors such as latitude, climate, and geography, as well as the varying levels of infrastructure and technological advancements in solar energy systems across different regions.

IV. Conclusion

This study presents an assessment of the carbon footprint and evaluates GHG reductions resulting from activities conducted under the LESS at a compound rubber factory in Thailand. It enhances the understanding of both GHG emissions and carbon intensity at the factory while also detailing efforts to reduce these emissions. In the year 2022, the total estimated carbon footprint for the factory's three branches was 26,718.20 tCO_2e. The majority of these emissions were attributed to indirect emissions (Scope 3), accounting for 66.55% of the total, followed by electricity-related emissions (Scope 2) at 31.27%. Under the LESS program, the factory implemented initiatives to reduce GHG: waste separation for recycling achieved a reduction of 864.56 tCO_2e, and the use of renewable energy from solar rooftops resulted in a reduction of 195.53 tCO_2e.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

P.S: Conceptualization; Methodology; Writing - Original Draft, V.K.: Conceptualization; Supervision; Review & Editing. S.W.: Conceptualization; Supervision; Review & Editing. All authors had approved the final version.

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