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Assessing carbon dioxide emissions for long-span cable stay bridge of railway construction project

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Abstract

The purpose of this study was to assess the quantity of greenhouse gas emissions associated with the long-span cable stay bridge of railway construction project. The amount of greenhouse gas in term of carbon dioxide equivalent (CO₂-eq) emission was calculated from the construction project of a double-track railway cable stay bridge across the Mae Klong River in Thailand. Then, the results of the calculation were classified according to work types such as bored pile, foundation, column and pier head, pylon and segment, prestressed wire and cable. The study also included the emission of machinery and material transportation on the site, from cradle to gate and gate to gate. Both national and international database of carbon dioxide emissions coefficients were applied. The results showed that total CO₂-eq emission emit 10,144,522 kg CO₂-eq or 29,837 tons CO₂-eq per kilometer. The types of work that emit the most carbon dioxide is pylon and segment which accounted for 36.0%. Meanwhile, the CO₂-eq emission from bored piles, footing, column and pier head, prestressed wire and cable, and transportation of machinery and material within site accounted for 23.0%, 18.0%, 10.0%, 9.5%, and 3.5%, respectively. To sum up, the CO₂-eq emission is caused by up to 89.0% of construction materials production.

Keywords: Greenhouse gas assessment, Carbon dioxide emission, Low carbon project, Railway bridge project, Railway infrastructure

1. Introduction

The increasing amount of greenhouse gas has resulted from the economic development since the industrial revolution has led to various environmental problems, one of which is drastic climate change. Such a problem is becoming more and more extreme with the rapidly increasing temperature and is responsible for the rising sea levels and melting polar ice caps. As a result, it is predicted that many coastal cities will be under water in a century or more according to how human greenhouse gas emission behavior [1, 2]. One of the sources of global greenhouse gas is the infrastructure construction [3]. According to the International Energy Agency [4], greenhouse gas emission from construction industry accounted for 39.0% of all the global emissions and 11.0% came from the production of building materials. Now, Thailand is seeing a lot of infrastructure development projects as the national government is implementing the 20-year national strategic development plan (2018-2027) resulting in various development projects including telecommunication, mass transit, double-track railways, and airports. According to the study of Chang & Kendall [5], activities such as the production of building materials, the transport of the materials, and the use of energy during the construction of infrastructure are a cause of the large amount of greenhouse gases.

The empirical researches on greenhouse gas emissions for construction projects have been conducted on both horizontal and vertical construction project in Thailand. For example, Jiamvoraphong [6], who studied greenhouse gas emissions from residential building projects, compared precast concrete construction with conventional construction and found that precast concrete buildings emitted more greenhouse gases than conventional concrete ones due to the greater use of concrete materials and reinforcement steel in precast concrete construction. Rungreuangthanaphol [7] and Liwthaisong et al. [8] studied the release of greenhouse gases from the construction of residential buildings as well as during occupancy. However, the number of studies of greenhouse gas emissions from construction projects within the country is still limited, despite the many infrastructure development projects currently underway in Thailand as part of the 20-year national strategic plan. These projects are potential sources of significant greenhouse gas emission. The policies and studies of sources of emission are currently not put in place. Future emissions of greenhouse gases from infrastructure construction projects may increase uncontrollably.

Therefore, this research aims to study the release of greenhouse gases from infrastructure construction projects by examining the case of the dual-track railway for long-span cable stay bridge over the Mae Klong River in Thailand. This project is being developed to enhance the transportation infrastructure for railway transportation and the development of the transportation network. The study was divided into three parts: 1) material production, 2) material transportation, and 3) construction stage. The study aims to identify the main causes of greenhouse gas emissions and propose ways to reduce these emissions.

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2. Materials and methods

2.1 Related researches

The carbon emissions from infrastructure construction and vehicle manufacturing are studied [3, 9-25]. Carbon emission assessment in infrastructure construction has been widely investigated at the international level, particularly through life cycle assessment (LCA) approaches applied to bridges, highways, and rail systems. Previous studies have demonstrated that material production - especially cement and steel - accounts for the largest share of embodied carbon in bridge construction, often exceeding emissions from on-site activities [5, 26, 27]. Research in Europe and East Asia has further highlighted the importance of construction method selection, structural design optimization, and transportation distance in reducing overall greenhouse gas emissions [20, 28].

In the context of railway and long-span bridges, recent international studies have focused on comparing alternative structural systems, material substitution, and low-carbon construction technologies to mitigate emissions throughout the construction phase [29]. These studies consistently emphasize that data-driven carbon accounting at the project level is critical for supporting sustainable infrastructure decision-making.

In Thailand, empirical research on greenhouse gas emissions from construction projects remains relatively limited. Existing studies have mainly focused on residential buildings and conventional building projects [6, 7]. While these studies provide important baseline emission factors and methodological insights, there is a notable research gap concerning large-scale infrastructure projects such as railway bridges, which are increasingly promoted under Thailand's national development strategy.

Therefore, this study contributes to the existing international literature by applying internationally recognized carbon assessment methods to a long-span cable-stayed railway bridge in a developing-country context, thereby enhancing the comparability of results while addressing region-specific construction practices and data limitations.

2.2 Assessing of CO₂ emission

To analyze the data, calculations were made for greenhouse gas emissions in kilograms of carbon dioxide equivalent (kg CO₂-eq) based on the IPCC Guidelines for National Greenhouse Gas Inventories [30]. These guidelines can be applied in various ways and variables to enable countries with different data to calculate emissions according to the same IPCC standard [30]. During construction, the equation was used, and calculating greenhouse gas emissions from the production of building materials was done by multiplying the material usage quantity by the greenhouse gas emission factor as shown Equation 1 [31].

$$E_{m,GHG} = \sum_i (Q_m \times EF_{mi,GHG}) \quad (1)$$

In the equation, $E_{m,GHG}$ is the total amount of greenhouse gases emitted during the production of construction materials, Q_m the amount of materials used in the construction project measured in units, and $EF_{mi,GHG}$ the emission factor of greenhouse gases from the construction materials measured in kg CO₂-eq/Unit.

Additionally, the transportation distance of materials is multiplied by the weight of the load of the trip as shown in equation 2, and then multiplied by the emission factor of greenhouse gases from transportation for each respective material as in equation 3.

$$Q_t = D_i \times W_i \quad (2)$$

$$E_{t,GHG} = \sum_i (Q_t \times EF_{ti,GHG}) \quad (3)$$

E_{t,CO_2} represents the total amount of greenhouse gases emitted during transportation of construction materials, Q_t the amount of materials transported to the construction project measured in ton-kilometers, and $EF_{ti,GHG}$ the emission factor of greenhouse gases from transportation according to the types of transport. Meanwhile, Q_t or the amount of material transported can be obtained from equation 2, D_i is the distance of material transportation, and W_i is the weight of materials that can be transported per trip.

As for the construction phase, greenhouse gas emissions from the use of diesel fuel and electricity by machinery in the project are included, without considering emissions from fuel production, can be calculated by multiplying the amount of diesel fuel or electricity used by the emission factor of greenhouse gases, as shown in equation 5.

$$FC_i = H_i \times FE_i \quad (4)$$

$$E_{f,GHG} = \sum_i FC_i \times EF_{fi,GHG} \quad (5)$$

FC_i is the amount of fuel or energy consumption of each machine. i in the construction project is measured in liters or kWh, and H_i is the working hours of each machine within the project measured in hours. FE_i is the energy consumption rate of each machine within the project, based on previous studies, $E_{f,GHG}$ the total amount of greenhouse gases emitted from the machines, and $EF_{fi,GHG}$ the emission factor of greenhouse gases of each machine measured in kg CO₂-eq/liter or kg CO₂-eq/kWh.

Greenhouse gas emissions associated with on-site construction activities were calculated based on the consumption of diesel fuel and electricity by construction machinery. Emissions were estimated by multiplying the quantity of fuel or electricity consumed by the corresponding emission factors, following the IPCC Guidelines for National Greenhouse Gas Inventories.

In this study, emission factors for fuel and electricity represent tank-to-wheel (TTW) emissions only. Upstream emissions related to fuel extraction, processing, and distribution (well-to-tank; WTT) were not included in the assessment. This methodological choice was made due to limitations in the availability of consistent, project-level WTT emission data compatible with Thai national emission factor databases, which primarily report direct combustion emissions. Excluding WTT emissions also ensured consistency between on-site construction emissions and the transportation emission factors adopted in this study.

Accordingly, emissions associated with construction machinery reflect direct energy use during the construction phase, while upstream fuel supply chain emissions are outside the defined system boundary.

2.3 Emission factors

A carbon dioxide equivalent or CO₂ equivalent, abbreviated as CO₂-eq is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming [32].

Greenhouse gas emission factors were compiled from both national and international sources to ensure the most appropriate balance between regional representativeness and data completeness. Priority was given to Thai national databases, specifically those published by the Thailand Greenhouse Gas Management Organization (TGO) and the Life Cycle Inventory (LCI) database of the National Metal and Materials Technology Center (MTEC), wherever relevant emission factors were available. These sources were selected to reflect local production technologies, energy mixes, and construction practices in Thailand.

However, for certain construction materials and on-site construction machinery, comprehensive and up-to-date emission factors are not yet fully available in national databases. In such cases, internationally recognized databases, particularly the Inventory of Carbon and Energy (ICE) developed by the University of Bath, were adopted. The use of ICE data in combination with national databases follows common practice in infrastructure life cycle assessment studies conducted in developing-country contexts, where localized data gaps remain a recognized challenge.

To maintain methodological consistency, all emission factors applied in this study were defined on a cradle-to-gate basis and aligned with the IPCC Guidelines for National Greenhouse Gas Inventories. This alignment ensures that differences in geographic origin do not result in incompatible system boundaries. Nevertheless, it is acknowledged that the use of mixed databases may introduce a degree of uncertainty due to variations in temporal coverage and regional assumptions. Accordingly, the calculated emissions should be interpreted as best-estimate, project-level values suitable for comparative analysis within the construction phase, rather than as precise national emission benchmarks.

In summarize, greenhouse gas emission factors, from the related studies were gathered to be used as a database for evaluating greenhouse gas emission. The national database from Thailand Greenhouse Gas Management Organization (TGO) and lifecycle inventory (LCI) of National Metal and Materials Technology Center (MTEC) were selected. Meanwhile, international database was from the Inventory of Carbon and Energy (ICE), University of Bath. The cradle-to-gate emission factors are shown in Table 1, transportation-to-site in Table 2, and gate-to-gate in Table 3 with diesel fuel, used in construction machinery, measured in liters.

Table 1 Greenhouse gas emission factors during the material production.

Materials	Emission factors	Unit	Reference
Reinforcement steel	2.77	kg CO ₂ -eq / kg	[33]
Tying wire	2.77	kg CO ₂ -eq / kg	[33]
Wooden formwork	8.63	kg CO ₂ -eq / kg	[34]
Steel	2.89	kg CO ₂ -eq / kg	[33]
Prestressed wire and cable	3.02	kg CO ₂ -eq / kg	[33]
PVC pipes	2.1415	kg CO ₂ -eq / kg	[2]
Fill sand	0.0037	kg CO ₂ -eq / kg	[2]
Steel sheet	3.27	kg CO ₂ -eq / kg	[33]
Concrete	240.00 – 451.00	kg CO ₂ -eq / m ³	[2]

Table 2 Greenhouse gas emission factors during the material transport.

Types	Emission factors	Unit	Reference
16-ton 10-wheel truck with crane, on-road, 50% Load	0.0957	kg CO ₂ -eq / t-km	[2]
16-ton 10-wheel truck with crane, on-road, full Load	0.0514	kg CO ₂ -eq / t-km	[2]
16-ton 10-wheel cement mixer truck, off-road, full Load	0.0611	kg CO ₂ -eq / t-km	[2]
32-ton 18-wheel semi-trailer truck, on-road, full Load	0.0449	kg CO ₂ -eq / t-km	[2]

Table 3 Greenhouse gas emission factors during the construction stage.

Machines	Emission factors	Unit	Reference
Excavator PC200	2.9790	kg CO ₂ -eq / liter	[2]
Vibratory hammer PC400	2.9790	kg CO ₂ -eq / liter	[2]
80-ton crawler crane	2.9790	kg CO ₂ -eq / liter	[2]
25-ton mobile crane	2.9790	kg CO ₂ -eq / liter	[2]
Crane truck	2.7403	kg CO ₂ -eq / liter	[2]
Tower Crane	0.4999	kg CO ₂ -eq / kWh	[2]
Concrete pump and vibrator	9.0000	kg CO ₂ -eq / m ³	[35]

Note: Due to insufficient data of greenhouse gas emission factor within the country, the data from the relevant study from overseas were used [35].

2.4 Methodology

This research aims to identify the major source of greenhouse gas emission from construction projects. The study analyzed the amount of greenhouse gas from the Mae Klong River extradosed bridge construction project by calculating the quantity using the unit 1 kilogram of CO₂ equivalent (CO₂-eq). Uncontrolled variables including machine wear, construction material waste, and the amount of water used within the project site were not considered due to their complications.

In this study, greenhouse gas emissions are quantified using kilograms of CO₂ equivalent (kg CO₂-eq) and normalized by a functional unit of one kilometer of bridge length. This functional unit was selected to enable comparison with existing bridge and railway infrastructure carbon assessment studies, which commonly report construction-phase emissions on a length-normalized basis.

To improve clarity and interpretability, the functional unit is explicitly defined with reference to the physical and functional characteristics of the assessed structure. The case study bridge is a long-span cable-stayed railway bridge designed to carry a double-track railway system, constructed using the balanced cantilever method. The structure is intended exclusively for railway transportation and forms part of a national dual-track railway development project. All material quantities, transportation activities, and construction processes included in the emission calculations correspond directly to these defined structural and functional characteristics.

The adopted functional unit therefore represents emissions associated with the construction of one kilometer of a long-span, double-track cable-stayed railway bridge under the specific design, construction method, and service function considered in this project.

2.4.1 Project information

The project is the first phase of the construction of a dual-track railway from Nakhon Pathom to Hua Hin. It covers the section from Nakhon Pathom to Nong Pla Lai (double-track railway bridge across the Mae Klong River). The project is a large-scale transportation infrastructure development project which aims at improving the transportation network in the southern region. The project is owned by the State Railway of Thailand (SRT) under the Ministry of Transport, with Construction Supervision Consultancy Services as the project controller/consultant and A.S. Associated Engineering (1964) Co., Ltd. as the employer. The contractor is Nawarat Patanakarn Public Company Limited, with a project value of THB 410,530,444 divided into bored pile work (39.17%), footing work (3.44%), column and cross head work (3.01%), pylon and segment work (19.54%), stressing and stay cable work (32.62%), and mobilization equipment work (2.22%).

The structure is a suspension bridge as illustrated in Figure 1. The bridge comprises a three-span structural system, having a total length of 340 m and an overall deck width of 7.64 m, designed to accommodate double-track railway operations. The construction process will use the balanced cantilever method.

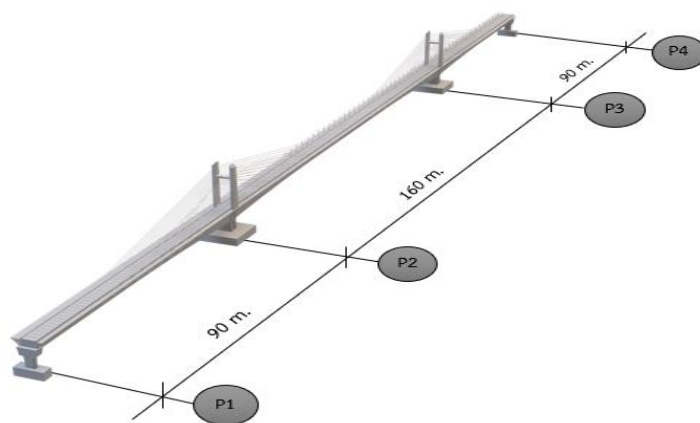


Figure 1 Long-span cable stay bridge of Mae Klong River railway bridge (3D perspective).

The greenhouse gas emissions are calculated by categories and ranks according to the quantity in the main construction categories, including bored piles, footing, column and pier head, prestressed wire and cable, and transportation of machinery and material within site. The calculation also included the three stages according to the research framework: the production of construction materials, transportation of construction material, and construction period as shown in Figure 2. Also, the system boundaries of assessment are shown in Figure 3. The cable stay bridge structure consists of bore pile, footing column, pier head, segment, pylon, prestressed wire and cable.

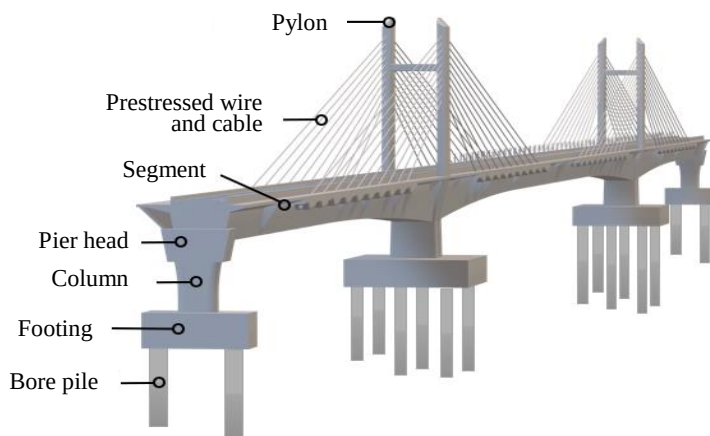


Figure 2 Bridge structure components of cable stay bridge.

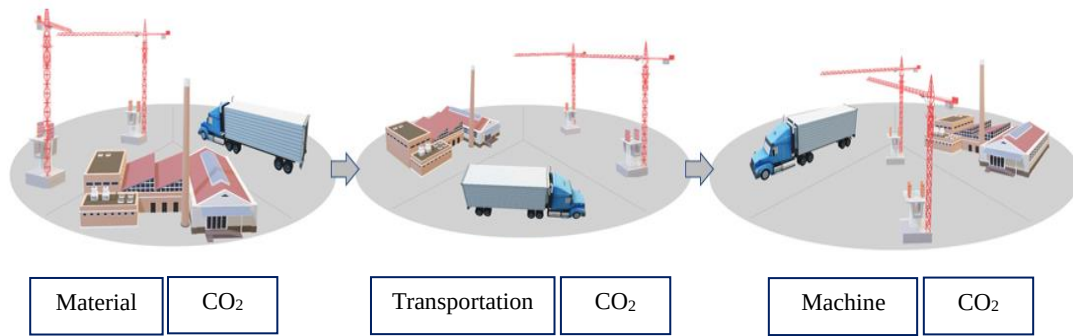


Figure 3 System boundaries of the greenhouse gas assessment.

Figure 3, the assessment encompasses cradle-to-gate material production, transportation of materials and equipment to the construction site, and gate-to-gate on-site construction activities. Operational, maintenance, rehabilitation, and end-of-life stages are excluded from the defined system boundary.

2.4.2 Data collection

The system boundary of this study was intentionally defined to cover cradle-to-gate, transportation-to-site, and gate-to-gate stages, focusing exclusively on the construction phase of the railway bridge project. Specifically, the assessment includes greenhouse gas emissions from (i) the production of construction materials, (ii) transportation of materials and equipment to the construction site, and (iii) on-site construction activities involving machinery, equipment, and energy use.

This boundary selection reflects the primary objective of the study, which is to quantify and analyze construction-stage greenhouse gas emissions for a large-scale railway bridge project in Thailand. In the Thai context, construction-phase emissions - particularly for complex structures such as long-span cable-stayed bridges - remain relatively under-documented compared with building projects and operational-stage assessments. Focusing on this phase enables the identification of emission hotspots associated with material use, construction methods, and logistics under real project conditions.

Life-cycle stages beyond construction, including operation, maintenance, rehabilitation, and end-of-life processes, were excluded from the system boundary due to limitations in long-term performance data and the absence of project-specific information on future maintenance strategies and demolition scenarios at the time of assessment.

Data collection was divided into 4 parts: the secondary data which is greenhouse gas emission factors from studies in the national and international, the construction material data, the transportation data, and the primary data which is construction activity data obtained directly from the construction project.

The construction material data was collected directly from the construction site. The excerpt of the transportation of construction materials is shown in Table 4. Also, the data from the project's material log and partly from the bill of quantity is shown in Table 5.

The transportation data was from the construction site's logbook which reported on which location the materials came from, what distance they were transported for, and what kind of vehicles they were loaded in as shown in Table 6.

Table 4 An excerpt of the transportation of construction materials.

Construction Material	from	Destination	Distance (km)
Ready Mix Concrete	Siam Cement Group PLC (Khao Wang)	N535	14.5
Reinforcement Steel	P.Overseas Steel PLC (Warehouse)	N535	143.0
General Steel	Chonsanglohakit Ltd.	N535	120.0

Note: N535 refers to the construction sites of Nawarat Patanakarn PLC.

Table 5 The quantity of the materials in different types of work.

Materials	Types of work					Unit
	Bored pile	Footing	Column and cross head	Pylon and segment	Stressing and stay cable	
Reinforcement steel	308,504	198,364	165,553	652,989		kg
Wooden formwork		5,281	17,547	64,742		kg
Steel		237,659	9,612	29,240		kg
Tying wire	5,553	3,571	2,980	11,754		kg
Prestressed wire and cable					246,445	kg
PVC pipe					853	kg
Fill sand		1,695,930				kg
Steel sheet					78,200	kg
Lean concrete		37				m ³
35 Mpa. concrete	3,589					m ³
45 Mpa. concrete		853	71			m ³
65 Mpa. concrete			427	2,409		m ³

Table 6 The material transportation and vehicle types.

Construction materials and machines	Distance (km.)	Transportation		
		Vehicles	Fuel	Route
Sheet pile	179	32-ton 18-wheel semi-trailer truck, full load	Diesel	On road
Fill sand	5.4	32-ton 22-wheel semi-trailer truck, full load	Diesel	On road
Lean concrete	14.5	16-ton 10-wheel cement mixer truck, full load	Diesel	On road
Structural concrete	14.5	16-ton 10-wheel cement mixer truck, full load	Diesel	On road
Steel	120	32-ton 22-wheel semi-trailer truck, full load	Diesel	On road
Reinforcement steel	143	32-ton 22-wheel semi-trailer truck, full load	Diesel	On road
Cable	110	32-ton 22-wheel semi-trailer truck, full load	Diesel	On road
Prestressed wired	110	32-ton 22-wheel semi-trailer truck, full load	Diesel	On road
Steel sheet	120	32-ton 22-wheel semi-trailer truck, full load	Diesel	On road
Excavator (PC200)	40	32-ton 22-wheel semi-trailer truck, full load	Diesel	On road
Vibratory hammer (PC400)	40	32-ton 22-wheel semi-trailer truck, full load	Diesel	On road
Tower Crane	139	32-ton 22-wheel semi-trailer truck, full load	Diesel	On road
80-ton crawler crane	139	32-ton 22-wheel semi-trailer truck, full load	Diesel	On road
25-ton mobile crane	139	32-ton 22-wheel semi-trailer truck, full load	Diesel	On road

The construction activity data was used to calculate greenhouse gas emissions during the construction phase (gate to gate) of a project. This refers to the work processes of various machinery within the project. The data were obtained from daily reports of the project as well as estimated machine work rates from previous research in case the data from the construction project was insufficient. For example, data on fuel consumption for bored pile work and concrete work as well as other works were taken from the other studies [36-38] as shown in Table 7.

Table 7 The energy consumption during the construction.

Work categories	Activities	Machines used	Hours of work (hr.)	Energy rate (unit/hr.)	Diesel fuel and electricity consumption	Unit
Bored pile	Curing or boring	Boring Plant	2,744	21.24	58,290	liter
	Boring support	80-ton crawler crane	2,364	17.20	40,650	liter
	Hammering casing	Vibratory hammer PC400	34	12.64	431	liter
	Filling concrete	10-ton cement mixer truck	263	17.50	4,602	liter
Footing	Excavating and refilling	Excavator PC200	2,744	12.64	34,684	liter
	Soil retention	Vibratory hammer PC400	2,184	12.64	27,606	liter
Column and pier head	Lifting reinforcement steel and formwork	25-ton mobile crane	3,216	16.67	53,611	liter
Pylon and segment	Lifting reinforcement steel and formwork	Tower crane	4,384	3.47	15,226	kWh
Transporting materials within site	Transporting materials within site	5-ton truck with crane	4,288	17.50	75,040	liter
Transporting personnel	Transporting personnel	Employee transportation vehicle	4,288	17.50	75,040	liter

3. Results

3.1. Candle to gate

The production of construction materials for the project released 9,031,033 kg CO₂-eq of greenhouse gases. Pylon and segment work emitted the most (3,577,306 kg CO₂-eq), followed by bored pile (2,007,080 kg CO₂-eq), footing work (1,609,932 kg CO₂-eq), stressing and stay cable (970,037 kg CO₂-eq), and column and pier head (866,677 kg CO₂-eq) as shown in Figure 4.

In Figure 5, pylon and segment work accounted for the largest share of emissions due to the use of reinforcement steel (1,841,338 kg CO₂-eq or 51.47%), ready-mix concrete (1,086,564 kg CO₂-eq or 30.37%), and plywood (558,720 kg CO₂-eq or 15.62%).

Bored pile work also emitted a significant amount due to the use of reinforcement steel (869,939 kg CO₂-eq or 43.34%) and ready-mix concrete (1,137,141 kg CO₂-eq or 56.66%). In footing work, ready-mix concrete (318,156 kg CO₂-eq or 19.76%), reinforcement steel (559,360 kg CO₂-eq or 34.74%), and concrete formwork (686,835 kg CO₂-eq or 42.66%) were the main sources of emissions while the production of plywood only emitted 45,577 kg CO₂-eq or 2.83%.

The largest emission in column and pier head work was from reinforcement steel (469,213 kg CO₂-eq or 54.14%), followed by ready-mix concrete (218,253 kg CO₂-eq or 25.18%) and plywood (151,433 kg CO₂-eq or 17.47%).

In stressing and stay cable work, the production of prestressed wire (467,775 kg CO₂-eq or 48.22%), stay cable (264,645 kg CO₂-eq or 27.28%), and steel sheet (224,434 kg CO₂-eq or 23.14%) were the biggest sources of emissions. Finally, PVC pipes only accounted for 1.36% (13,183 kg CO₂-eq) of the total emissions.

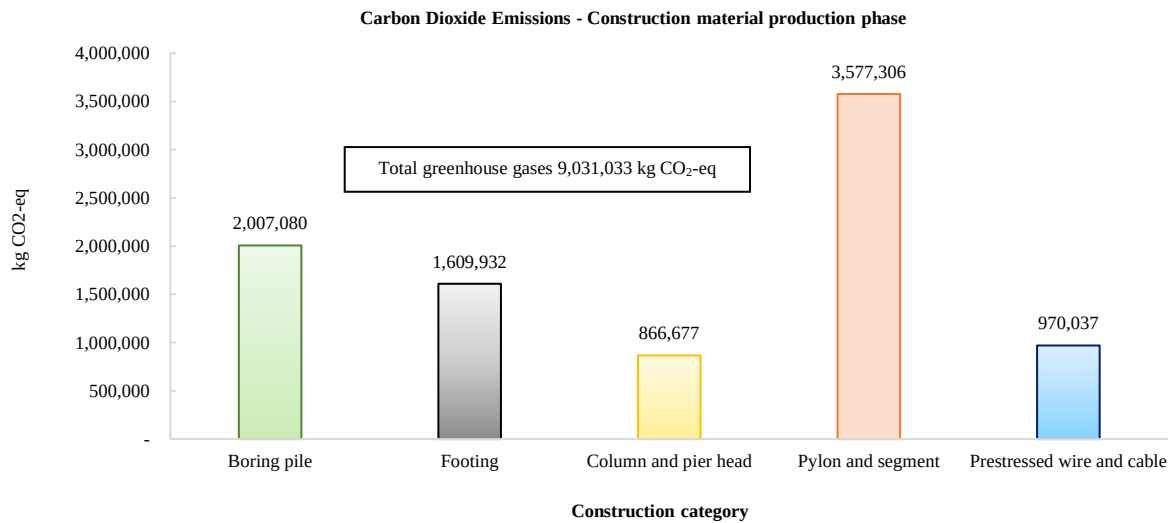


Figure 4 Greenhouse emissions during the material production by work categories (kg CO₂-eq)

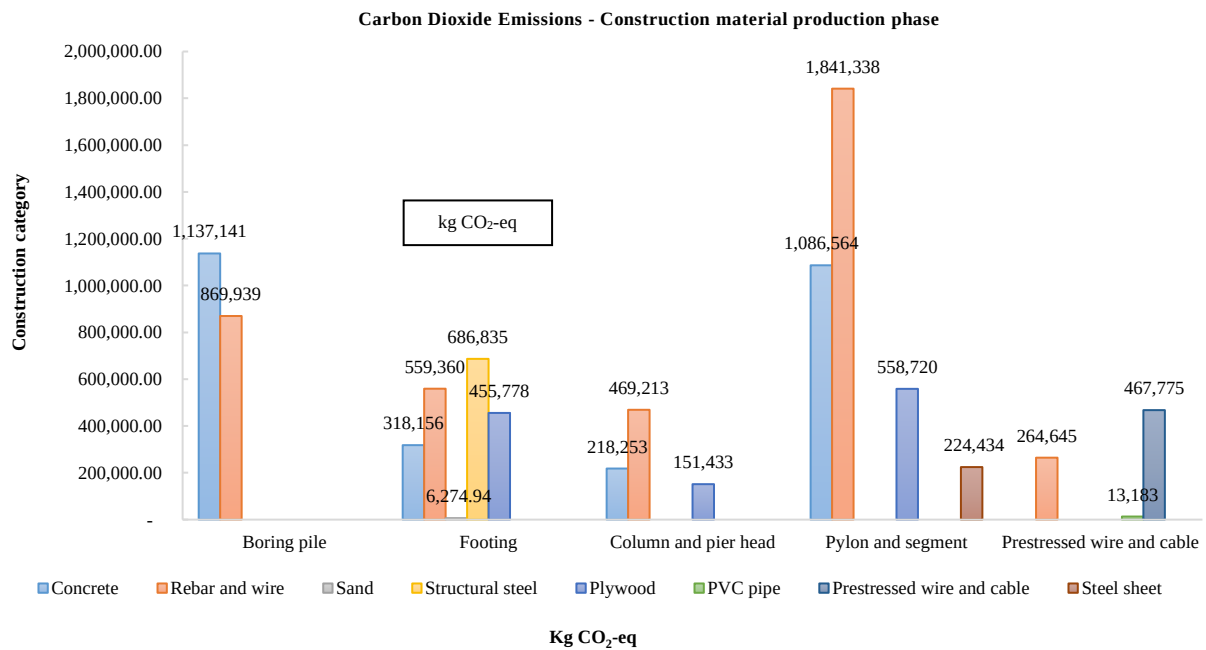


Figure 5 Greenhouse emissions of material production (kg CO₂-eq)

Therefore, in large construction projects where a large amount of construction materials is used, consideration in designing the structure should be given to the selection of construction materials and construction methods, as the greenhouse gas emissions of each material vary. For example, 400 ksc concrete (40 Mpa) has a greenhouse gas emission coefficient of 362.40 kg CO₂-eq/m³, while 300 KSC concrete (30 Mpa) has a greenhouse gas emission coefficient of 271 kg CO₂-eq/m³. Similarly, the choice of construction methods also affects transportation and on-site construction.

3.2 Transportation to site

During the transportation of construction materials, 29,265 kg CO₂-eq of greenhouse gases were released. The bored pile work was found to be the activity that released the most greenhouse gases due to the transportation of a large quantity of ready-mix concrete, with 718 truck trips releasing a total of 9,946 kg CO₂-eq, which accounts for 33.99% of the total emissions. Similarly, in the transportation of pylons and segments, a release of greenhouse gases was a little less due to the transportation of a significant quantity of ready-mix concrete, with 483 truck trips releasing a total of 9,098 kg CO₂-eq, which accounts for 31.09% of the total emissions.

For footing work, there was a release of 5,055 kg CO₂-eq, which accounts for 17.27% of the total emissions. In addition, for activities such as stressing and stay cable work, and equipment procurement and transportation, there were similar amounts of greenhouse gas emissions of 1,997 kg CO₂-eq and 1,889 kg CO₂-eq, respectively, accounting for 6.82% and 6.45% of the total emissions. Lastly, the transportation of columns and cross heads released the least amount of greenhouse gases, with a total of 1,280 kg CO₂-eq, accounting for 4.37% of the total emissions. Most of the transportation involved the delivery of ready-mix concrete to the construction site due to the nature of the structure being cast-in-place. The detail was shown in Figure 6.

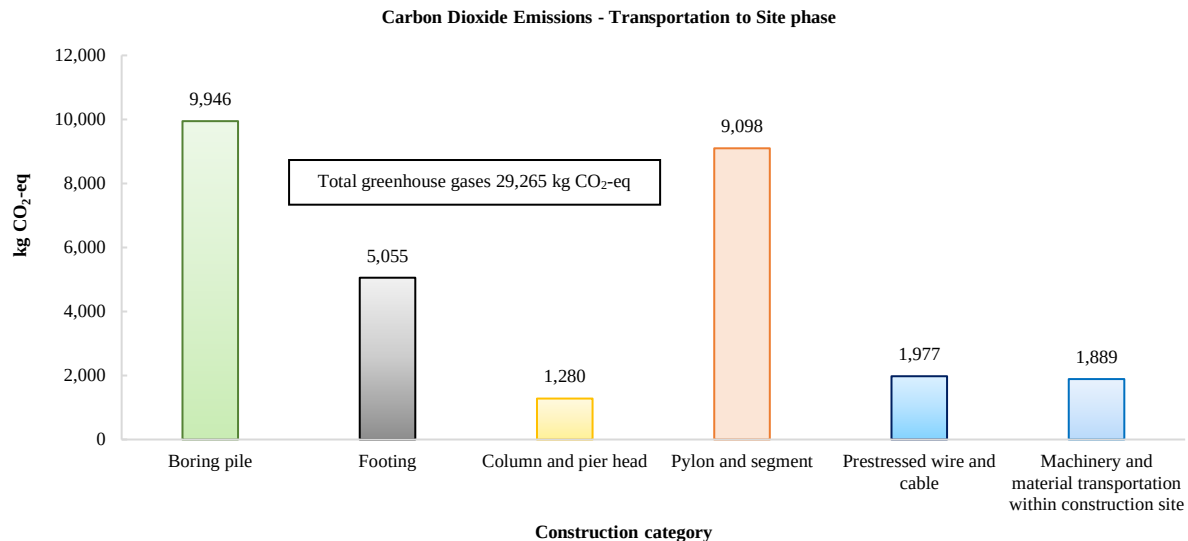


Figure 6 Greenhouse gas emissions during the material construction (kg CO₂-eq)

3.3 Gate to gate

It was found from the analysis of the data obtained during the construction period that a total of 1,084,225 kg CO₂-eq of greenhouse gases were emitted during the construction, with the highest amount of greenhouse gas emissions coming from the transportation of construction materials and personnel within the project, which accounted for 411,264 kg CO₂-eq or 37.93%. This is because the longest working hours were 4,288 hours, which led to the use of 150,080 liters of fuel. The bored pile work was the second biggest source of greenhouse gas emissions, releasing 293,917 kg CO₂-eq, accounting for 27.11% [36]. This was caused by the boring plant, machinery, and an 80-ton crawler crane that consumes a large amount of fuel.

Footing work released 185,562 kg CO₂-eq, accounting for 17.11%, due to excavation, backfilling, sheet piling, and sheet pile removal, which required the use of two excavator PC200s and two vibratory hammer PC400s, all using a total of 62,290 liters of fuel. The installation of columns and cross heads released 164,187 kg CO₂-eq, accounting for 15.14%, due to the use of a 25-ton crane, which used 53,611 liters of fuel. Finally, the installation of pylons and segments emitted 29,294 kg CO₂-eq, accounting for 2.7%, mainly due to the use of a significant amount of ready-mix concrete. The detail was shown in Figure 7.

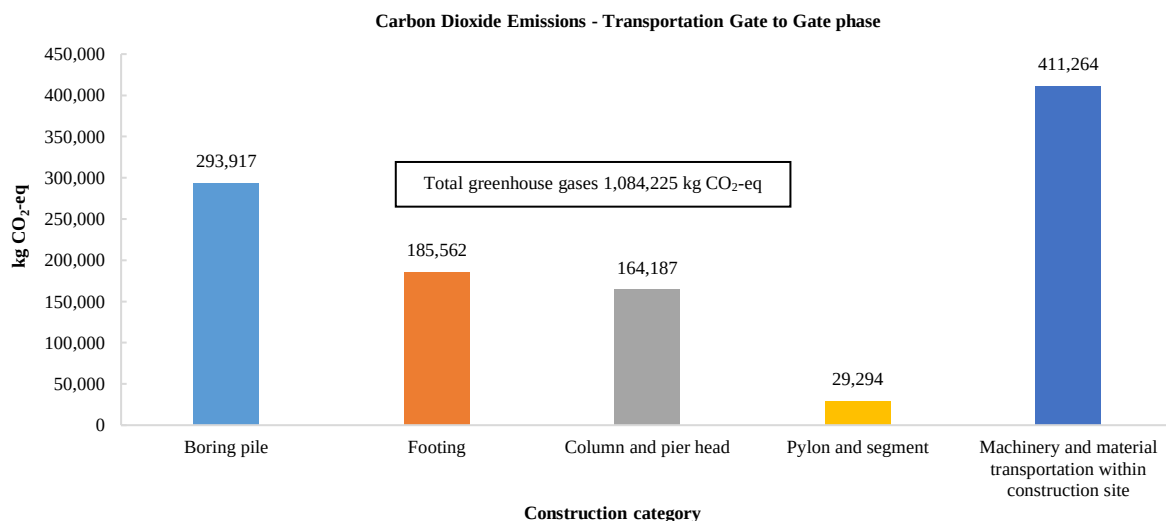


Figure 7 Greenhouse emissions during the construction (kg CO₂-eq).

4. Discussion

The study of the Mae Klong River Extradosed Bridge project was a case study on greenhouse gas emissions from the construction of a railway project. The study estimated the amount of greenhouse gas emissions released during the construction process, categorized by the type of work, including bored pile work, footing work, column and cross head work, pylon and segment work, and stressing and stay cable work, as well as by research boundaries, including the cradle-to-gate stage, transportation to the construction site stage, and gate-to-gate stage.

The study revealed that greenhouse gas emissions from the production of glasshouse gases during the production of construction materials, the transportation of the materials, and bridge building processes amounted to 9,031,033 kg CO₂-eq, 29,264 kg CO₂-eq, and 1,084,225 kg CO₂-eq respectively. Furthermore, the highest amount of greenhouse gas emissions was released during the production of construction materials, accounting for 89.02%. In terms of categories of work, the highest amount of greenhouse gas emissions was

released during the production of materials for pylon and segment work, amounting to 3,615,699 kg CO₂-eq, followed by bored pile work at 2,310,943 kg CO₂-eq, footing work at 1,800,549 kg CO₂-eq, column and cross head work at 1,032,144 kg CO₂-eq, and finally, stressing and stay cable work at 972,035 kg CO₂-eq. The transportation of materials within the site also contributed to greenhouse gas emissions, amounting to 411,264 kg CO₂-eq. In the construction of pylons and segments, a significant amount of construction materials was used, such as reinforcement steel, ready-mix concrete, and wooden formwork, which were more wasteful than other types of work. A lot of reinforcement steel and ready-mix concrete was used in bored pile work as well. This is shown in Figure 8.

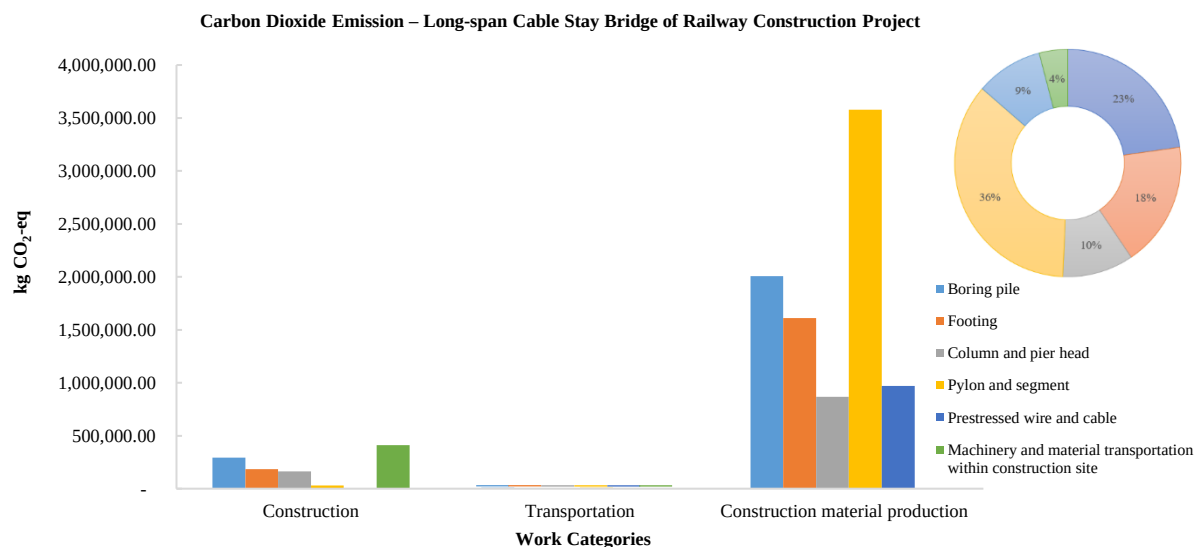


Figure 8 Proportions of greenhouse gas emissions of the entire project by work categories

The results indicate that approximately 89% of total greenhouse gas emissions originate from the production of construction materials. This finding is consistent with international studies on bridge and railway infrastructure projects, which report that material production - particularly cement and steel - typically contributes between 70% and 90% of total construction-phase emissions [5, 26, 28, 39]. The high proportion observed in this study can be attributed to the extensive use of reinforcement steel, prestressed cables, and high-strength ready-mix concrete required for long-span cable-stayed bridge construction.

In contrast, transportation-related emissions accounted for a relatively small share of total emissions. This result can be explained by several project-specific conditions. First, the majority of ready-mix concrete was supplied from nearby batching plants located approximately 14-15 km from the construction site, significantly reducing transport distances compared with projects relying on remote material sources. Second, heavy materials such as steel and concrete were transported using high-capacity trucks operating at or near full load, resulting in lower emissions per ton-kilometer. Finally, transportation was primarily conducted via on-road diesel vehicles with relatively stable routes and minimal congestion. Similar findings have been reported in international case studies where localized material sourcing and efficient logistics substantially reduced transportation-related emissions relative to material production impacts [20, 27].

While material substitution strategies such as geopolymer concrete have been widely recognized for their potential to reduce embodied carbon, their practical application must be evaluated within a regional and project-specific context. In Thailand and other Southeast Asian countries, geopolymer concrete is technically feasible due to the availability of industrial by-products such as fly ash from coal-fired power plants and ground granulated blast-furnace slag from the steel industry. Previous studies have shown that geopolymer concrete can reduce greenhouse gas emissions by approximately 30–60% compared with conventional Portland cement concrete, depending on mix design and curing conditions [40-43].

From a cost perspective, geopolymer concrete may involve higher initial material and quality-control costs due to alkaline activators and limited local supply chains. However, these costs can be partially offset in large-scale infrastructure projects through reduced cement consumption, long-term durability benefits, and economies of scale [44-46]. Importantly, the cast-in-place construction methods used in the Mae Klong River bridge - such as bored piles, pylons, and segments - are generally compatible with geopolymer concrete, provided that appropriate curing regimes and mix control are implemented.

Beyond material substitution, construction method optimization represents a critical and often underexplored pathway for emission reduction. Structural optimization aimed at reducing material quantities, particularly in pylons, segments, and foundation elements, can significantly lower embodied carbon without altering material types. International studies have demonstrated that optimized structural design and construction sequencing can reduce cradle-to-gate emissions by 10–20% in bridge projects [47, 48].

Furthermore, logistics and construction planning improvements - such as maximizing truck load efficiency, sourcing materials from nearby suppliers, and minimizing on-site material handling - can further reduce transportation and gate-to-gate emissions. Although transportation emissions were relatively low in this case study due to short hauling distances, such optimization measures become increasingly important in projects with longer supply chains or imported materials. Consequently, an integrated strategy combining low-carbon materials, construction method optimization, and efficient logistics planning offers the most realistic and scalable pathway for reducing greenhouse gas emissions in large-scale railway bridge construction projects in the region.

This study applied a hybrid emission-factor approach, combining national databases with international sources due to gaps in Thai life cycle inventory data for certain construction materials and on-site machinery. Priority was given to national data from the Thailand Greenhouse Gas Management Organization (TGO) and the National Metal and Materials Technology Center (MTEC), while the Inventory of Carbon and Energy (ICE) was used where local data were unavailable. All emission factors were harmonized to a cradle-to-gate boundary and aligned with the IPCC Guidelines. Although the use of mixed databases introduces uncertainty related to regional and technological differences, the results represent best-estimate values that reliably capture the relative contributions of materials and

construction activities. The dominance of material production emissions is consistent with international bridge and railway studies, indicating that the identified emission hotspots and mitigation priorities remain robust.

While the functional unit of emissions per kilometer of bridge provides a practical and widely used basis for comparison across infrastructure projects, it does not fully capture performance-related parameters such as traffic capacity, service life, load intensity, or long-term operational efficiency. These parameters are particularly relevant for full life-cycle assessments and service-based comparisons between alternative bridge designs or transport systems.

Accordingly, this study focuses specifically on construction-phase greenhouse gas emissions, encompassing material production, transportation to site, and on-site construction activities. Operational emissions, maintenance, rehabilitation, and end-of-life stages were intentionally excluded from the system boundary. As a result, the findings should be interpreted as a construction-stage carbon profile, rather than a comprehensive life-cycle or service-based environmental performance indicator.

The exclusion of well-to-tank (WTT) emissions represents an important limitation of this study. Upstream emissions associated with fuel production, refining, and distribution can contribute a non-negligible share of total construction-phase greenhouse gas emissions, particularly in diesel-intensive activities such as bored pile construction, excavation, and material handling. As a result, the total construction-phase emissions reported in this study may be conservatively underestimated.

However, the methodological choice to exclude WTT emissions was driven by data availability constraints and the need for consistency with Thai national emission factor databases, which predominantly report tank-to-wheel emissions. Similar boundary definitions have been adopted in previous construction-phase carbon assessments where localized WTT data were unavailable or highly uncertain. Importantly, the exclusion of WTT emissions does not affect the relative comparison between work categories, as all construction activities were assessed using the same boundary conditions.

The system boundary of this study is limited to the construction phase, including material production, transportation to site, and on-site activities, to address the lack of empirical data on construction-phase greenhouse gas emissions for large railway bridges in Thailand. As this phase involves large quantities of carbon-intensive materials, it represents a major source of embodied emissions and a key mitigation opportunity. However, excluding maintenance, rehabilitation, and end-of-life stages limits the applicability of the results for full life-cycle decision-making. Accordingly, the reported emissions should be interpreted as construction-stage profiles that support early-stage design, material selection, and construction planning. Future studies should extend the boundary to include downstream life-cycle stages to enable comprehensive life-cycle assessments and service-based comparisons.

Future research could enhance the robustness of construction-phase greenhouse gas assessments by integrating WTT emissions using hybrid life cycle assessment approaches or region-specific fuel supply chain data. Such extensions would be particularly valuable for comparative studies across projects or for full life-cycle evaluations of railway infrastructure systems. Future studies also could extend this work by integrating service life assumptions, traffic demand, and maintenance scenarios to enable emissions to be expressed per unit of transport service (e.g., per passenger-kilometer or ton-kilometer), thereby supporting more holistic infrastructure sustainability comparisons.

5. Conclusion

Based on the assessment of greenhouse gas emissions, the project released a total of 10,144,522 kg CO₂-eq or 29,837 ton-CO₂ eq/km. In the study by Lee et al. [31], which analyzed the greenhouse gas emissions during the production of materials and the construction, it was found that the construction of a high-speed railway project in the bridge category resulted in the emission of 26,445 ton CO₂-eq/km. This was due to the use of a large amount of ready-mix concrete, prefabricated piles, and reinforcement steel. Thus, the approach to reducing greenhouse gas emissions is to reduce the use of construction materials. From empirical research, Chang et al. [16] was found that in the bridge category, the emission of greenhouse gases was 32,204 ton CO₂-eq/km. This was due to differences in construction methods, as well as variations in the quantity and type of construction materials used.

From the study, it was found that the production of construction materials, such as reinforcement steel and ready-mix concrete, is the main source of greenhouse gases. Choosing alternative materials, such as geopolymers, can be one way to reduce the use of construction materials that release high levels of greenhouse gases during production. In the process of producing geopolymers, greenhouse gases are released less compared to regular concrete used in construction, by about 36-56% [38]. Designing and reviewing construction processes is another approach to reducing greenhouse gas emissions. Designing structures to reduce the weight of the upper parts of the structure leads to the smaller size of foundation and columns and as a result can reduce greenhouse gas emissions by up to 12% in the cradle-to-gate stage. Therefore, before construction, it is important to assess greenhouse gas emissions together with alternative design options for construction that is more environmentally friendly [48].

This study assessed greenhouse gas emissions associated with the construction phase of a long-span cable-stayed railway bridge, expressed as kg CO₂-eq per kilometer of bridge length. The functional unit reflects a double-track railway bridge constructed using the balanced cantilever method and intended for national railway service. Within this defined scope, total construction-phase emissions were estimated at 10,144,522 kg CO₂-eq, or 29,837 t CO₂-eq per kilometer.

It is important to note that the results represent construction-phase emissions only and do not account for operational performance, service life, traffic capacity, maintenance, or end-of-life impacts. While such parameters are essential for full life-cycle and service-based evaluations, the present study provides a critical baseline for understanding emission hotspots during the construction stage, which is often the least documented phase of large-scale railway bridge projects in developing-country contexts.

The findings therefore offer valuable insights for designers, contractors, and policymakers seeking to reduce embodied carbon through material selection, structural optimization, and construction method improvements at the project planning and design stages.

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