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Quantifying and Mitigating Carbon Emissions in Long-Span Steel Bridge Construction: Lessons from the Anhsin Bridge in the Ankeng MRT System

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Abstract

Construction materials are the primary source of embodied carbon in long-span bridge projects, particularly for steel-intensive structures. This study presents an empirical construction-stage carbon footprint assessment of the Anhsin Bridge, an asymmetric cable-stayed steel truss bridge in Taiwan. Using the emission factor method in accordance with ISO 14067 and Taiwan Environmental Protection Administration guidelines, a cradle-to-gate (A1–A5 equivalent) system boundary was applied, covering material production, transportation, and on-site construction activities. Total construction-stage emissions were estimated at 55,349 tCO_2e, dominated by structural steel (51.8%), followed by reinforcing steel, concrete, and cement. Material-related emissions accounted for over 90% of the total, highlighting the critical role of material selection in embodied carbon reduction. Three practical mitigation strategies were evaluated using verified project data, as follows: 40% cement substitution with supplementary cementitious materials, optimized steel erection methods, and enhanced reuse of formwork and temporary works. The combined scenario achieved a 7.3% reduction in construction-stage emissions without compromising constructability. The findings demonstrate the effectiveness of material-oriented, constructability-aware strategies for reducing embodied carbon in steel-intensive bridge construction.

Keywords: construction-stage carbon footprint; steel-intensive bridge construction; embodied carbon mitigation; emission factor–based assessment; constructability-driven sustainability

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1. Introduction

Climate change and the associated rise in greenhouse gas (GHG) emissions have become critical challenges for the global construction industry. The built environment contributes nearly 40% of global CO_2 emissions when material production, construction activities, and energy use are considered (IPCC, 2021) [1]. Infrastructure projects represent a significant portion of this impact due to their large scale and intensive use of construction materials. As illustrated in Figure 1, the construction sector accounts for a substantial share of global GHG emissions, underscoring the importance of material-related mitigation strategies.

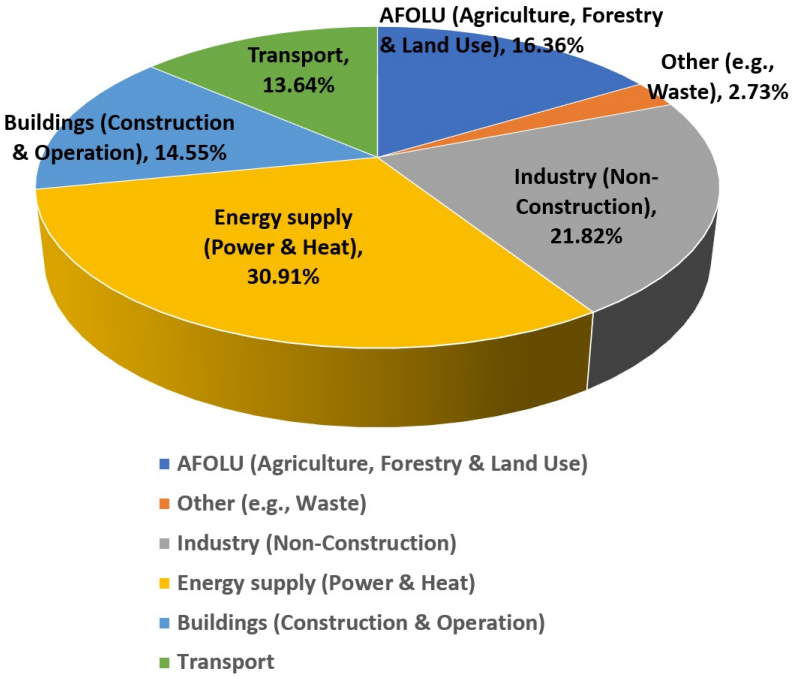

Figure 1. The global distribution of GHG emissions by sector, emphasizing the significant share from construction.

Long-span bridges are among the most material-intensive infrastructure systems, requiring large quantities of cementitious materials, reinforcing steel, and structural steel to satisfy structural safety, durability, and serviceability requirements (Xiao et al., 2025) [2]. Among these materials, structural steel plays a central role in modern bridge engineering. Owing to its high strength-to-weight ratio, excellent ductility, and predictable mechanical behavior, steel enables efficient structural systems capable of spanning long distances with reduced self-weight. These properties allow for slimmer structural members, lower foundation demands, and improved seismic performance.

In addition to its mechanical advantages, steel offers significant constructability benefits. Steel components can be prefabricated off-site with high dimensional accuracy, allowing for modular assembly and rapid erection. Such construction methods shorten project duration, enhance quality control, and reduce on-site environmental disturbance. Steel structures are also highly adaptable to complex geometries, making them particularly suitable for cable-stayed and truss bridge systems. Furthermore, steel exhibits superior recyclability, with high recovery rates at the end of service life, supporting circular construction practices.

Bridges also perform important social, cultural, and symbolic functions beyond their primary role in transportation. As summarized in Table 1, many iconic bridges worldwide are recognized not only for their span length and functional performance but also for their cultural significance. A common characteristic of these landmark structures is the extensive use of steel or steel–concrete composite systems, underscoring the long-established importance of steel as a construction material for long-span bridge applications. In Taiwan, projects such as the Gaoping River Bridge and the Suhua Highway Improvement Project further illustrate how steel-intensive bridge construction contributes to both engineering excellence and national infrastructure development. Although an increasing number of studies have investigated embodied carbon in bridge infrastructure, relatively few have integrated construction-stage carbon quantification with practical mitigation assessment for steel-intensive landmark bridges in Taiwan. While cost considerations remain relevant for

implementation, the present study places primary emphasis on construction-stage carbon quantification and emission reduction potential.

Table 1. A comparison of the world's iconic bridges.

Bridges	Span (m)	Year	Primary Function	Cultural/Symbolic Role
Golden Gate Bridge (USA)	1280	1937	Urban mobility, connectivity	Iconic U.S. landmark, symbol of San Francisco
Sydney Harbour Bridge (Australia)	503	1932	Urban transport, integration	National identity symbol, "Coathanger" landmark
Gaoping River Cable-Stayed Bridge (Taiwan)	330	2000	Highway connectivity	Taiwan's modern engineering showcase
Suhua Highway Improvement Project (Taiwan)	192	2019	Safety, coastal transport	Sustainability-oriented infrastructure project

International sustainability frameworks, such as the Paris Agreement (UNFCCC, 2015) [3], ISO 14067 (ISO, 2018) [4], and PAS 2050 (BSI, 2011) [5], provide standardized methodologies for carbon footprint quantification. Despite these advantages, steel production is energy-intensive and associated with relatively high embodied carbon, particularly in regions where blast furnace–basic oxygen furnace processes dominate manufacturing (Zhao et al., 2025) [6] (Huang et al., 2023) [7]. Previous studies indicate that construction materials typically account for 70–90% of the total embodied carbon in bridge projects, with structural steel and reinforcing steel being the dominant contributors [6,7]. Consequently, understanding the carbon implications of steel use—while recognizing its structural and constructional benefits—is essential for advancing sustainable bridge engineering.

Taiwan has adopted these principles through Environmental Protection Administration guidelines for public construction projects [8]. While life-cycle assessment approaches are widely applied to buildings and infrastructure (Gabriel, 2014) [9], construction-stage emissions deserve particular attention because material selection, fabrication, transportation, and erection methods are largely determined at this phase and offer immediate opportunities for emission reduction.

Existing research in Taiwan has primarily focused on highways, tunnels, and earth-retaining structures, where concrete dominates material use (Shau, 2019) [10]; (Liu et al., 2023) [11]. Comparatively fewer studies have examined long-span bridge projects characterized by extensive use of structural steel, stay cables, and prefabricated steel components. In such projects, construction-stage decisions related to material sourcing, steel fabrication, erection sequencing, and temporary works can significantly influence embodied carbon while also affecting safety, quality, and constructability.

The Anhsin Bridge, a single-pylon asymmetric cable-stayed steel truss bridge constructed as part of the Ankeng Light Rail Metro system in New Taipei City, Taiwan, provides a representative case for investigating the material-driven carbon footprint of long-span bridge construction. The bridge incorporates large quantities of structural steel, reinforcing steel, composite deck systems, and temporary steel works, making it particularly relevant to research at the intersection of construction materials and sustainability. The overall research framework adopted in this study is presented in Figure 2, outlining the systematic process used to quantify emissions and evaluate mitigation strategies.

Accordingly, this study aims to quantify the construction-stage carbon footprint of a steel-intensive bridge, identify material-related emission hotspots, and evaluate practical reduction strategies that are compatible with current construction practice. By focusing on construction materials—particularly the performance, constructability, and recyclability of steel—this research provides empirical evidence to support the more sustainable use of steel and composite materials in long-span bridge engineering.



Figure 2. The overall research framework and sequential structure of this study.

This study adopts an empirical approach to construction-stage carbon footprint assessment, based on verified project records, detailed material inventories, and established emission factors. No numerical structural optimization or advanced computational modeling is involved. The novelty of this study lies in three key aspects. First, it delivers a construction-stage-focused carbon footprint assessment of a steel-intensive landmark bridge in Taiwan, addressing a gap in existing bridge-related carbon studies that predominantly emphasize full life-cycle or building-scale analyses. Second, it evaluates material-oriented mitigation scenarios using verified, project-level construction data, enabling realistic comparison of emission reduction strategies. Third, this study explicitly integrates constructability considerations—such as erection methods and temporary works—into a carbon assessment, thereby providing practical decision-support insights for sustainable long-span bridge construction.

2. Literature Review and Methodology

Over the past two decades, carbon management in civil infrastructure has become a central research and policy concern. The IPCC (2021) [1] identifies the built environment as a major contributor to greenhouse gas (GHG) emissions, with infrastructure projects—bridges, highways, and tunnels—accounting for substantial embodied carbon (Xiao et al., 2025) [2]. Global initiatives such as the Paris Agreement (UNFCCC, 2015) [3] and ISO 14,067 (2018) [4] have established international standards, while Taiwan has committed to net-zero by 2050 through EPA guidelines (2010) [10].

Recent studies provide practical insights. Bechtel Ltd. (2021) [12] emphasized how contractors integrate sustainability into performance strategies. Hao et al. (2020) [13] showed that BIM-based prefabrication can cut material-stage emissions, while Juenger et al. (2019) [14] highlighted the potential of supplementary cementitious materials (SCMs). Bai et al. (2024) [15] and Cao et al. (2024) [16] confirmed that bridges are especially carbon-intensive, with Bannazadeh et al. (2012) [17] reporting significant reductions in an EU cable-stayed bridge through material substitution. Heenkenda et al. (2022) [18] stressed innovation capacity, Ricchiuti et al. (2024) [19] reviewed adoption barriers, and Tu et al. (2020) [20] proposed market instruments such as tradable green certificates. At the national level, MOTC (2022) [21] highlighted the integration of carbon metrics

into infrastructure statistics, while Taiwan's Comprehensive Carbon Reduction Action Plan (National Development, 2025) [22] set sectoral strategies for the 2050 net-zero target. Figure 3 shows the evolution of carbon management initiatives since 2000.

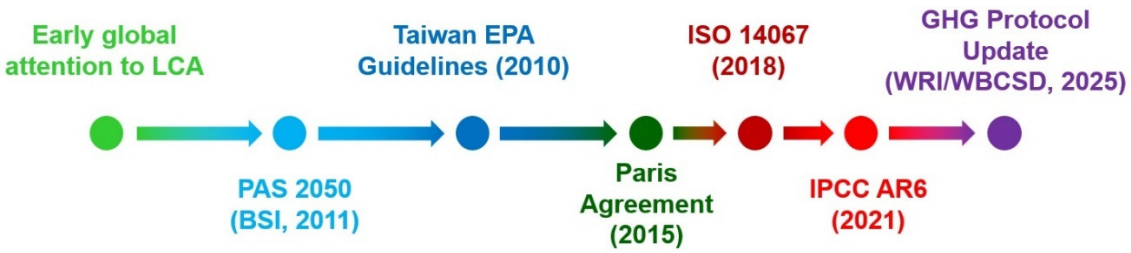

Figure 3. Evolution of carbon management initiatives (2000~2025).

Robust methodologies are critical for consistent assessment. Internationally, PAS 2050 (BSI, 2011) [5], the GHG Protocol (WRI/WBCSD, 2025) [23], and ISO 14067 (2018) [4] dominate, while Taiwan localized them through EPA guidelines (2010) [10]. These rely on the emission factor method, where the carbon footprint is expressed as follows:

$$CFP = \Sigma(ADi \times EFi) \quad (1)$$

Here, AD_i denotes activity data and EF_i represents the corresponding emission factor. Process-based life-cycle assessment (LCA) is widely applied due to its methodological transparency and calculation precision, while hybrid input–output approaches can be used to capture upstream emissions beyond the immediate system boundary (Gabriel, 2014) [9]. For bridge projects, however, process-based LCA methods remain the most practical and widely adopted due to data availability and implementation feasibility (Huang et al., 2023) [7].

Recent research has increasingly applied LCA to bridge and transport infrastructure. Cao et al. (2024) [16] quantified the carbon footprint of expressway bridges over the full life cycle and analyzed emission composition and reduction pathways at the network scale, while Qian et al. (2025) [24] compared life-cycle carbon emissions of conventional reinforced-concrete-beam bridge types. Other studies have focused specifically on steel or composite bridge systems. For example, Ruck et al. (2023) [25] examined embodied carbon in tied-arch steel bridges, Zhang et al. (2024) [26] developed an LCA framework for steel bridge deck pavements, and Almeida et al. (2025) [27] compared the environmental impacts of reinforced concrete and steel–concrete composite bridges. Complementary research has further explored the influence of steel recycling ratios and alternative structural schemes on bridge life-cycle carbon performance.

Recent research has highlighted the importance of constructability-oriented design and structural optimization in improving the sustainability and material efficiency of steel structures. Cucuzza et al. (2024) [28] proposed a constructability-based design framework for steel structures that integrates fabrication and erection considerations from truss elements to full-scale industrial applications, demonstrating how early-stage design decisions can enhance construction efficiency and structural performance. Similarly, Grubits et al. (2025) [29] investigated topology optimization of steel members considering plastic-limit behavior and beam–column connection conditions, showing that optimized structural layouts can improve material utilization and structural efficiency. These studies indicate that structural configuration, connection detailing, and constructability-oriented design approaches play an important role in improving resource efficiency and supporting more sustainable steel-intensive infrastructure systems.

Despite these advances, systematic reviews indicate that bridge LCA studies continue to face limitations related to regionalized emission data, construction-stage-focused

assessments, and applications based on real project records, particularly for long-span and iconic bridge structures. Recent efforts integrating building information modeling (BIM) with LCA have enabled more rapid estimation of bridge-related carbon emissions; however, many such applications still rely on generic databases rather than detailed contractor-verified data. Against this background, the present study contributes a construction-stage, material-oriented carbon assessment of a steel-intensive cable-stayed truss bridge based on verified project data and evaluates practical mitigation strategies within Taiwan's specific policy and supply-chain context. Table 2 summarizes the major standards commonly adopted in carbon footprint studies.

Table 2. Comparison of international standards for carbon footprint assessment.

Standard/Guideline	Year	Scope	Application in Infrastructure	Notes
PAS 2050 (BSI)	2011	Product life cycle	Widely used in Europe for materials and goods	Early benchmark for CFP
GHG Protocol (WRI/WBCSD)	2011	Corporate/product	General framework, less specific to construction	Flexible but broad
ISO 14067 [4]	2018	Product carbon footprint	Adopted worldwide, including Taiwan	Most authoritative
Taiwan EPA Guidelines	2010	Product/service	Used for public works and procurement	Based on emission factors

Research has examined highways, tunnels, slopes, and bridges. Zhao et al. (2025) [6] found material emissions represented over 80% of highway totals, while Shau (2019) [8] showed concrete and reinforcing steel dominated Taiwan's Suhua Highway Improvement Project. Liu et al. (2023) [11] demonstrated that alternative retaining methods can reduce emissions and costs. For bridges, Xiao et al. (2025) [2] showed higher embodied emissions than road projects due to steel and cables, while Huang et al. (2023) [7] reported 10–20% reductions through material substitution and equipment optimization. Despite these advances, gaps remain: few studies isolate the construction stage, evaluate cost implications, or address Taiwan's landmark bridges. Figure 4 compares selected infrastructure studies, showing the disproportionately high emissions of bridges [8,10,15,23].

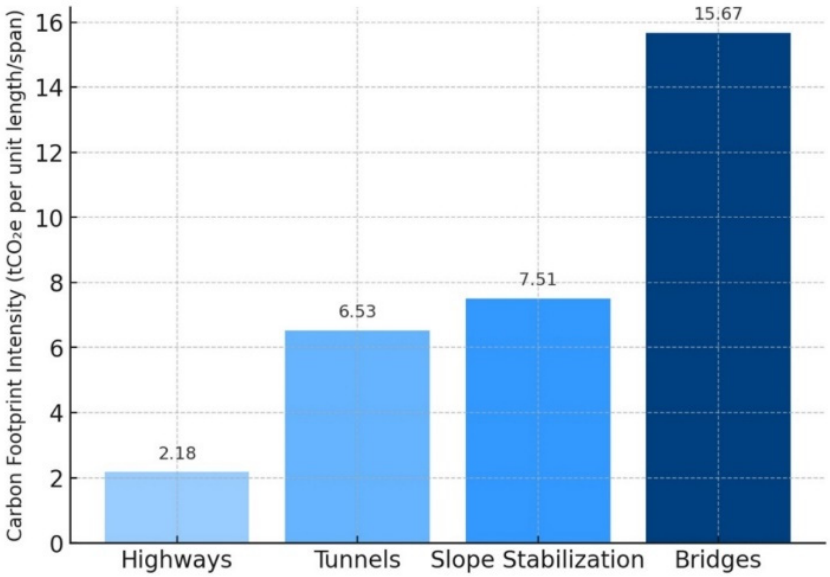

Figure 4. The comparative analysis of carbon footprints from selected infrastructure studies.

This study applies the emission factor method to assess the construction-stage carbon footprint of the Anhsin Bridge. The detailed system boundary definition, functional unit, and inventory scope are described in Section 3.

Three scenarios were evaluated against the baseline: (1) 40% substitution of cement with SCMs, (2) optimized erection methods to reduce temporary works, and (3) enhanced formwork reuse. Table 3 presents the emission factors applied in this study.

Table 3. Selected emission factors for bridge construction materials.

No.	Material/Activity	Unit	EF (kg CO_2e/unit)	Source
1	Portland cement	ton	981	1. Taiwan EPA (2010) [10] 2. Taiwan CCRAP (2025) [22]
2	Concrete	m^3	341	
3	Fly ash	ton	12	
4	Ground granulated slag	ton	35	
5	Reinforcing steel	ton	835	
6	Structural steel	ton	2420	
7	Stay cables (steel strands)	ton	2707	
8	Paint (protective coating)	ton	1330	
9	Diesel fuel (equipment)	liter	3.29	
10	Electricity (Taiwan grid)	kWh	0.606	

This methodological framework ensures comparability with international studies while appropriately reflecting Taiwan's local industrial and regulatory context, thereby enabling a robust evaluation of mitigation strategies for sustainable bridge construction. Electric-arc-furnace (EAF) production routes, recycled-content differentiation, and supplier-specific environmental product declarations (EPDs) were not applied in this study due to limited availability and traceability for large-scale structural steel used in public bridge projects; this limitation is explicitly acknowledged.

Although advanced numerical approaches, such as topology optimization, have been widely explored in structural engineering research, they are beyond the scope of the present work. Instead, this study emphasizes material-oriented carbon assessment based on empirical project data and the evaluation of practical mitigation strategies during bridge construction.

3. Methodology

This study employed a structured methodology to quantify the carbon footprint of the Anhsin Bridge during the construction stage, integrating ISO 14067, PAS 2050, the GHG Protocol (2025), and Taiwan EPA guidelines to ensure both comparability and policy relevance. The process followed five tasks: define boundaries and functional unit, collect activity data, select emission factors, calculate emissions, and evaluate mitigation scenarios. Figure 5 presents the overall methodological flow and sub-activities.

The system boundary of this study was defined as a construction-stage cradle-to-gate boundary, functionally equivalent to modules A1–A5, in accordance with ISO 14067 and the Taiwan Environmental Protection Administration carbon-footprint-calculation guidelines. The boundary encompasses material production (A1–A3), transportation to site (A4), and on-site construction activities (A5), including equipment operation, temporary works, and site energy use. Downstream stages—namely, operation, maintenance, and end-of-life—were excluded, as the analysis focuses specifically on identifying construction-stage mitigation opportunities.

The assessment is empirical in nature and focuses on construction-stage carbon accounting. Included materials comprise cement, aggregates, supplementary cementitious materials (SCMs), reinforcing and structural steel, cables, and asphalt, together with construction equipment use and temporary works. The functional unit of the analysis is the

entire Anhsin Bridge. A detailed summary of system boundary inclusions and exclusions is provided in Table 4.

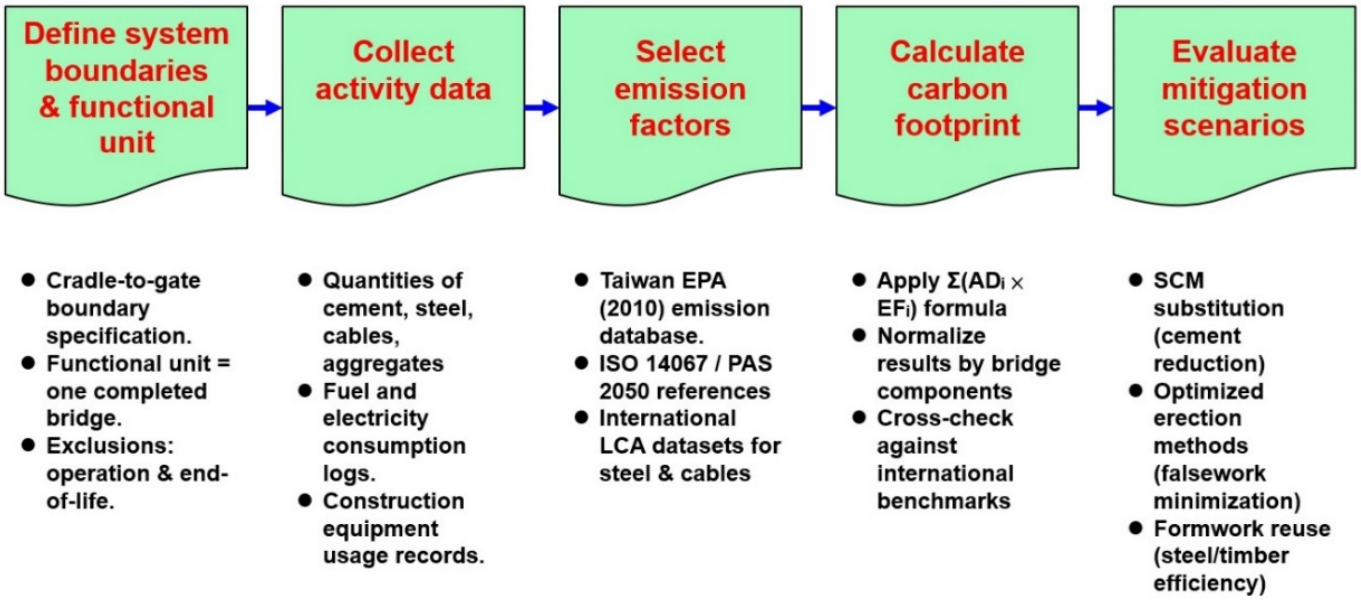

Figure 5. The overall methodological flow and key sub-activities adopted in this research.

Table 4. System boundaries of the study.

Category	Included Activities	Excluded Activities
Materials	Cement, aggregates, fly ash, slag, steel, cables	Long-term recycling, deterioration
Works	Foundations, substructure, superstructure, deck	Operation, maintenance
Equipment	Cranes, trucks, barges, generators	End-of-life disposal
Temporary	Formwork, scaffolding, cofferdams, access bridges	Demolition waste
Energy	Diesel, electricity for site operations	Post-opening use

Items excluded under the cut-off criteria include equipment manufacture, worker commuting, site office operation, and long-term recycling processes. These exclusions are consistent with common practice in bridge construction carbon assessments and are justified by limited data availability and their minor expected contribution to total emissions. Data were primarily sourced from verified project records, including design bills of quantities (BOQs), procurement logs, and contractor reports [28], supplemented by on-site measurements of fuel and electricity consumption and supplier-provided information for cement, steel, and cables adjusted to Taiwan's manufacturing conditions. Cross-checking invoices against daily site logs and delivery records was conducted to improve data reliability.

Key construction inputs included approximately 92,000 m^3 of concrete, 17,500 tons of reinforcing steel, 6800 tons of structural steel, 1200 tons of cables, 0.9 million liters of diesel, and 1.6 million kWh of electricity. Material quantities were obtained from approved design BOQs, procurement records, and contractor construction reports and were validated through comparison with site logs and delivery documentation. Fabrication-related items, such as protective coatings and temporary steel works, were included where documented, while minor fabrication losses, shop welding consumables, and trial assemblies were implicitly captured within recorded procurement quantities, consistent with established practice in construction-stage carbon assessments.

Carbon emissions were calculated using the emission factor method (Equation (1)), which combines activity data with recognized emission factors. Emission factors were adopted from the Taiwan Environmental Protection Administration (2010) [10], the

Comprehensive Carbon Reduction Action Plan (2025) [22], and relevant international databases. The assessment covered cement, concrete, reinforcing and structural steel, stay cables, paint, diesel fuel, and electricity. A complete list of emission factors is provided in Table 3, and Figure 6 illustrates the integration of activity data and emission factors within the calculation framework [4,8,10].

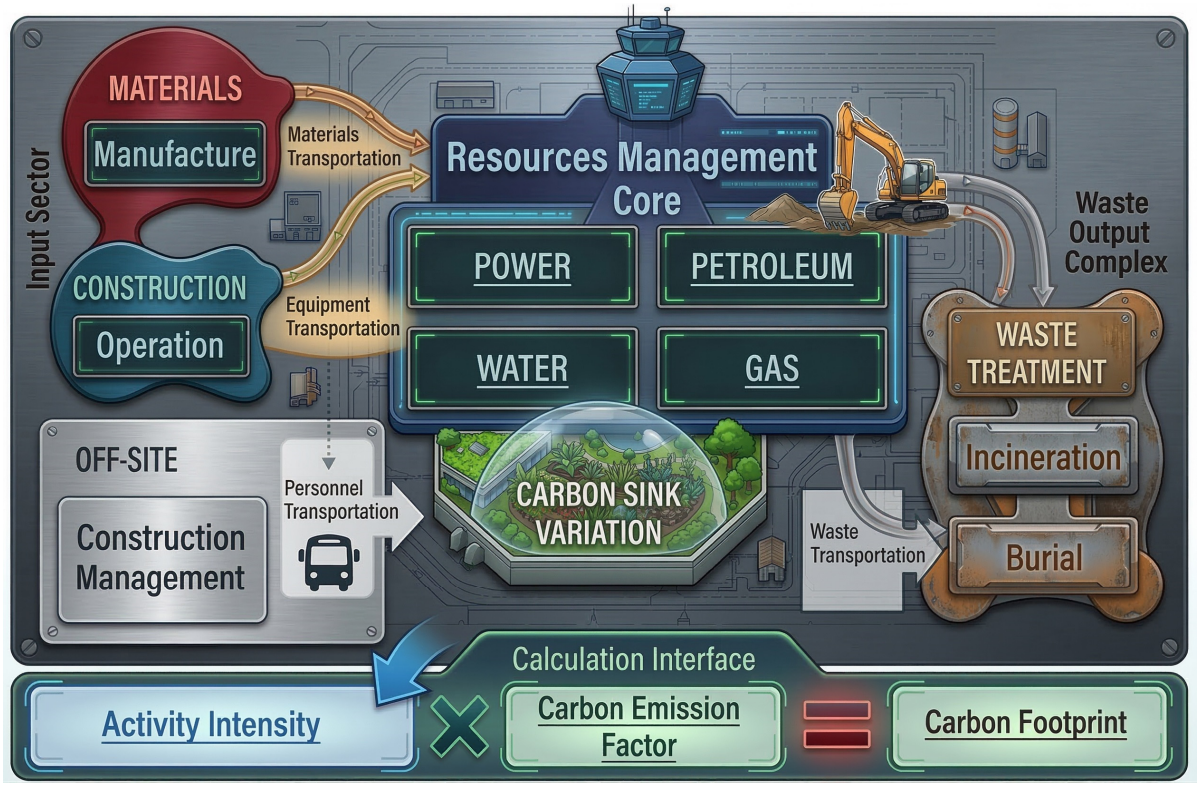

Figure 6. The integration of activity data and emission factors within the calculation process.

Emission factors for reinforcing steel and structural steel were adopted from the carbon footprint databases issued by the Taiwan Environmental Protection Administration (2010) and updated national policy references in the Comprehensive Carbon Reduction Action Plan (2025). These factors reflect average steel production conditions in Taiwan during the project period, where blast furnace–basic oxygen furnace (BF–BOF) routes remain dominant for bridge-grade steel. The applied structural steel factors represent fabricated bridge members (plates, sections, and truss components) and do not distinguish individual product forms due to the aggregated nature of available national data.

Transportation of construction materials was modeled based on typical supplier locations and delivery practices in Taiwan, following the guidance of Taiwan EPA carbon footprint guidelines. Structural steel and reinforcing steel were primarily transported by heavy-duty trucks, with partial use of barge transport for large prefabricated steel components. Cementitious materials and aggregates were assumed to be delivered by truck from regional suppliers. Overseas shipping was not applicable for the Anhsin Bridge project.

Standard load factors and one-way delivery assumptions were adopted; secondary effects such as backhaul optimization, traffic congestion, idling, and modal switching scenarios were not explicitly modeled due to limited project-level data.

Three reduction scenarios were evaluated. The SCM Substitution Scenario applied a 40% replacement of Portland cement with fly ash and slag. The Optimized Construction Scenario employed barge-mounted cranes to reduce temporary falsework and cofferdams. The Formwork Reuse Scenario increased reuse frequency of steel and timber formwork. Scenarios were modeled by adjusting activity data across multiple sectors and recalculating

emissions. They were contextualized within Taiwan's broader governance framework, including sectoral allocation of reduction responsibilities, progressive verification of 2030 targets, and institutional innovations such as carbon pricing. Figure 7 shows projected carbon emissions in Taiwan by sector, highlighting the 27% reduction target for 2030 and the pathway toward net-zero by 2050 [10,22].

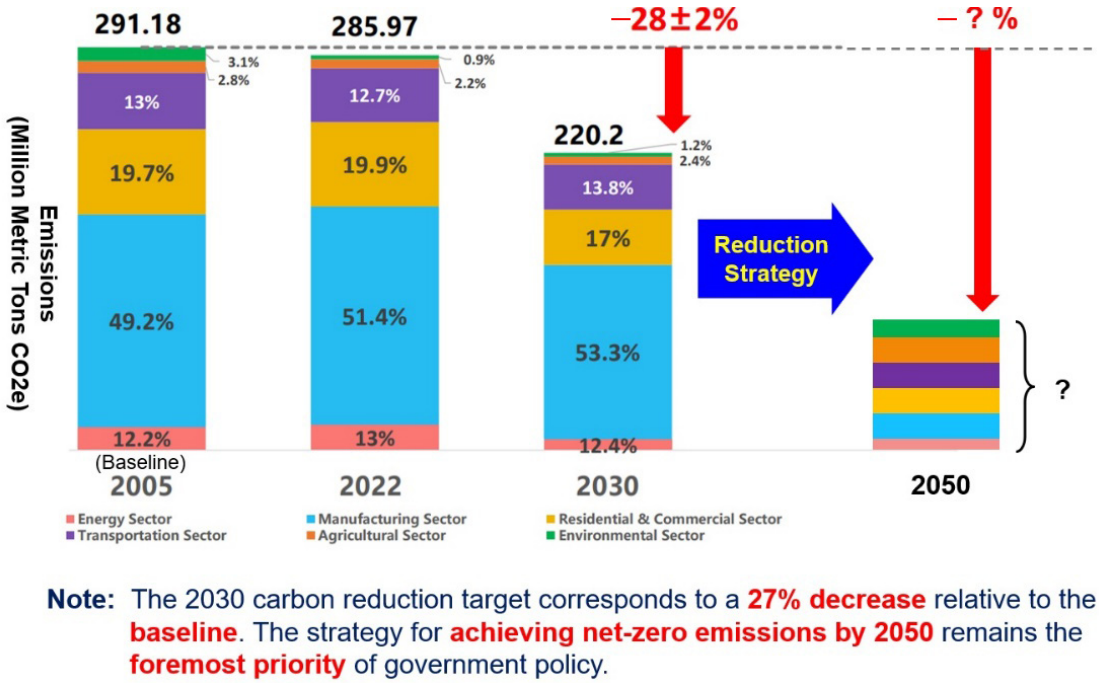

Figure 7. Carbon reduction pathway: 2005 baseline, 2030 target, 2050 net-zero in Taiwan [10,22].

As described in Section 3, the adopted steel emission factors demonstrate adequate temporal representativeness (2010–2025 policy-consistent data), strong geographical relevance (Taiwan-specific industrial conditions), and appropriate technological representativeness for infrastructure-grade steel production. While more granular product- or supplier-level data could further refine accuracy, the selected factors are considered suitable for construction-stage carbon assessment of large public bridge projects.

4. Case Study on Anhsin Bridge of the New Taipei City MRT System

4.1. Project Description

The Anhsin Bridge is a landmark element of the Ankeng Light Rail Metro (LRM) system in New Taipei City, Taiwan. This single-pylon asymmetrical cable-stayed truss bridge spans the Xindian River, linking the Anhsin and Shuangcheng districts, and enhances urban mobility while serving as a visual landmark.

Main features include: cable-stayed design with a steel truss girder, 225 m main span, 136 m steel tower, composite truss deck with dual LRM tracks, fan-type parallel strand cables, and foundations of large-diameter bored piles in alluvial soils. Construction began in 2019 and was completed in 2023 under the New Taipei City Government [14]. Innovative methods included barge-supported heavy lifts, truss-frame assembly, and hydraulic cable tensioning [16]. Figure 8 shows the bridge's location.

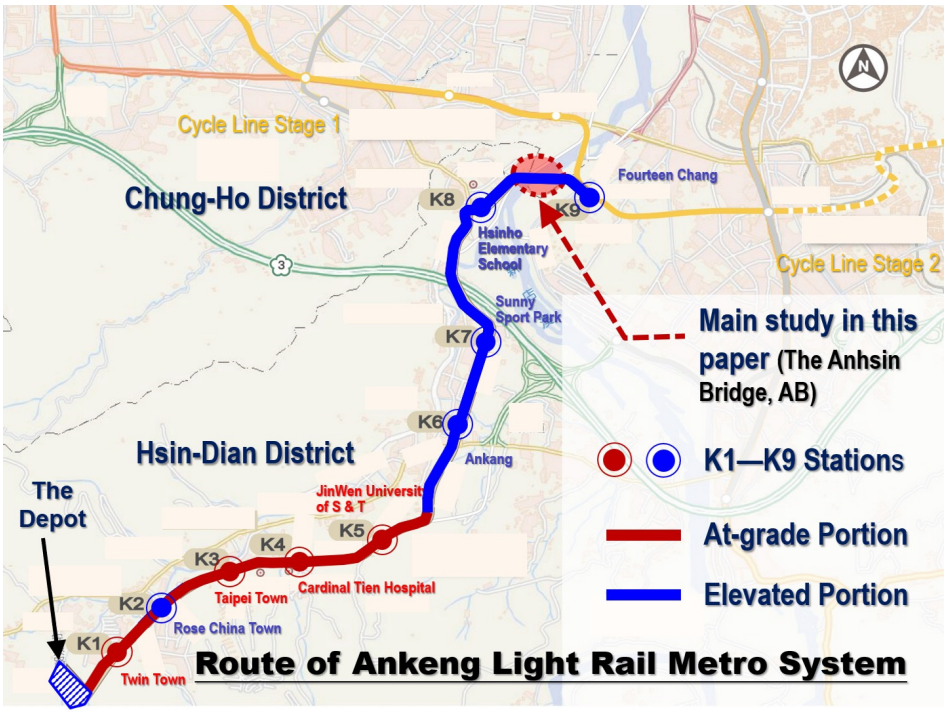

Figure 8. Planned route of the AKLRM project and the location of AB.

4.2. Major Construction Activities

Construction was executed in five phases with methods tailored to structural and environmental requirements, as illustrated in Figure 9.

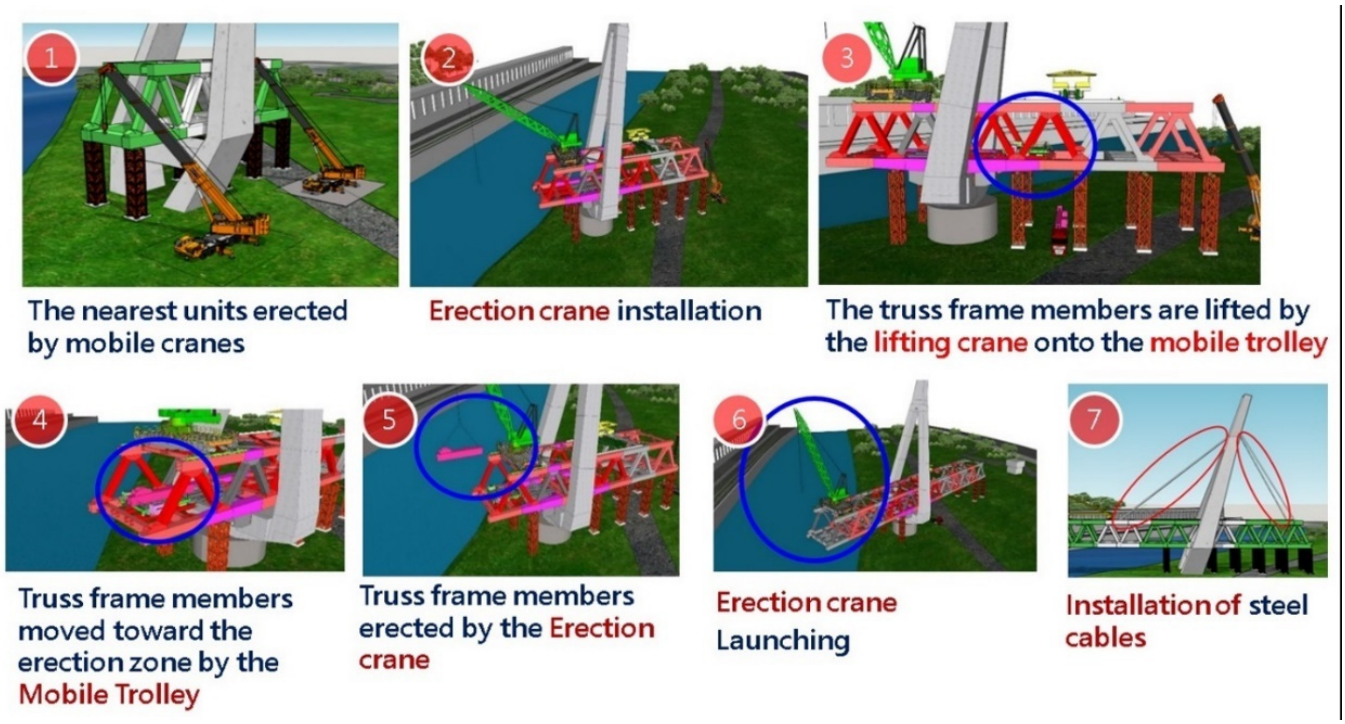

Figure 9. The erection steps of the truss-frame members.

1. Foundation and Substructure—Large-diameter bored piles (2.0 m, depths 35–47 m) formed the base. Cofferdams and jet grouting ensured stability in alluvial soils, and static pile load tests confirmed safety under service and seismic loads.

2. Pylon Erection—The 136 m steel pylon was lifted segmentally using a tower crane (ST-3330), stabilized with tie-in frames and temporary guying. Working platforms improved safety, critical under typhoon conditions.
3. Girder Assembly—Steel truss segments, prefabricated off-site and delivered by barge, were erected sequentially using the truss-frame erection system (TFES), eliminating temporary shoring in the river and reducing ecological impacts [30,31].
4. Cable Installation—Twelve pairs of stay cables (55–73 strands each) were tensioned with hydraulic jacks. Sensors ensured accurate force control, while HDPE sheathing provided corrosion protection [30,31].
5. Deck and Ancillary Works—Concrete deck slabs were cast in situ, integrating dual rail tracks. Ancillary systems included parapets, signaling, lighting, and drainage, with emphasis on formwork reuse [30,31].

The site photos of Anhsin Bridge, including construction stage and after completion are shown in Figure 10.



Figure 10. The Anhsin Bridge (**a**) during construction and (**b**) after completion.

4.3. Carbon Footprint Inventory

Using the methodology in Section 3, construction emissions totaled 55,349 tCO_2e [30].

Material contributions. Structural steel dominated with 32,138 tCO_2e (51.77%), followed by reinforcing steel (15.17%), concrete (13.76%), and cement (9.90%). Stay cables and paint contributed 2.45% and 0.51%, respectively. Equipment and energy added further emissions, as follows: diesel 4.88% and electricity 1.56%. Table 5 and Figure 11 detail the breakdown.

Table 5. Carbon footprint for major items of the Anhsin Bridge construction.

Category	Quantity Used	EF	Emissions (tCO_2e)	Share (%)
Cement	6265 tons	981 kg/ton	6146	9.90%
Concrete	25,060 m^3	341 kg/m^3	8545	13.76%
Reinforcing steel	11,277 tons	835 kg/ton	9416	15.17%
Structural steel	13,280 tons	2420 kg/ton	32,138	51.77%
Stay cables	562 tons	2707 kg/ton	1521	2.45%
Paint	239 tons	1330 kg/ton	318	0.51%
Diesel fuel	920,500 L	3.29 kg/L	3028	4.88%
Electricity	1.6 M kWh	0.606 kg/kWh	970	1.56%
Total			55,349	100%

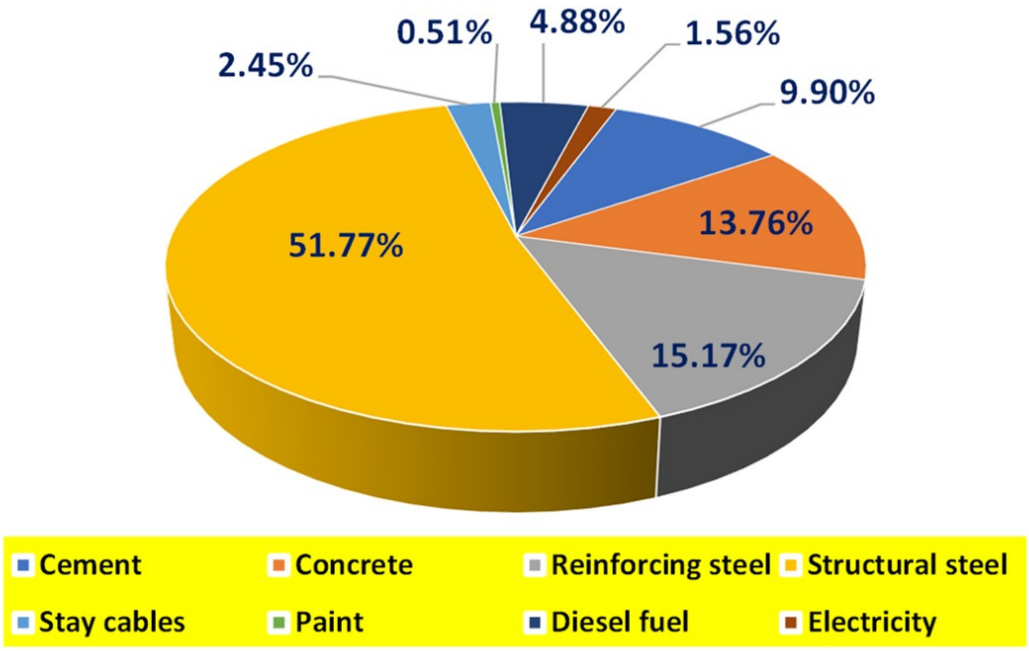

Figure 11. Carbon footprint for major items of the Anhsin Bridge construction by pie chart.

Component-based analysis. Emissions were allocated by structural components, as follows: foundations/substructure 41.50%, tower 21.84%, girder 33.50%, cables 2.62%, and deck/finishing 0.54%. Figure 12 highlights the dominance of the foundation and girder, reflecting their material intensity.

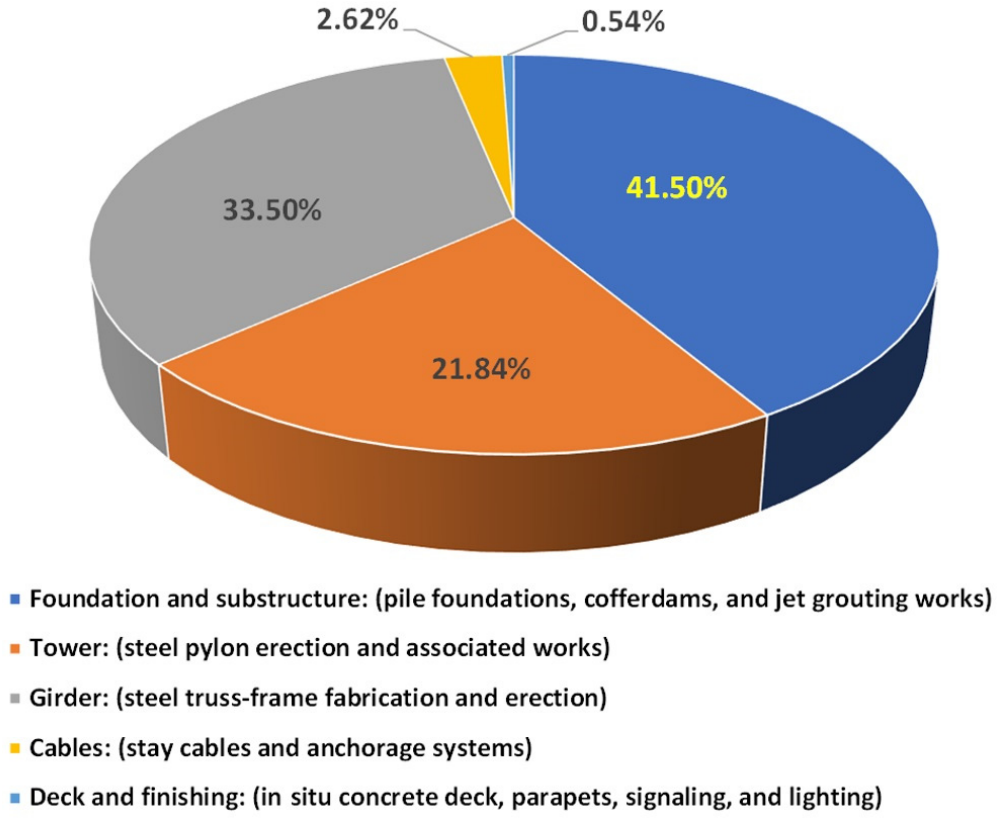

Figure 12. Carbon footprint distribution of Anhsin Bridge construction, showing dominance of each major component.

4.4. Reduction Strategies and Scenario Evaluation

Three reduction measures were tested against the baseline [30]:

1. SCM substitution: replacing 40% of cement with fly ash and slag cut 2458 tCO_2e (−4.4%), with neutral or slight cost savings.
2. Optimized erection: using barge-mounted cranes and TFES reduced cofferdams and diesel consumption, avoiding 1281 tCO_2e (−2.3%). While specialized equipment added cost, ecological and safety benefits were significant.
3. Formwork reuse: increased reuse of steel/timber formwork avoided 309 tCO_2e (−0.6%), cost-neutral but requiring planning.

Combined impact. Together, the three measures reduced emissions by about 4048 tCO_2e (−7.3%). Although modest in percentage terms, the reductions targeted high-emission categories and demonstrated feasible pathways for incremental improvement. Table 6 and Figure 13 summarize the outcomes.

Table 6. Carbon reduction scenarios and qualitative cost–benefit evaluation for the Anhsin Bridge.

Mitigation Strategy	Main Measure	Carbon Reduction (tCO_2e)	Reduction (%)	Cost Impact (Qualitative)	Practical Implications
SCM substitution	40% replacement of Portland cement with fly ash and slag	2458	4.4%	Cost-neutral to slight saving	Mature technology; minimal impact on construction sequence when properly planned
Optimized erection methods	Barge-mounted cranes, reduced temporary works, revised erection sequencing	1281	2.3%	Slight cost increase	Higher equipment and planning cost offset by improved safety and reduced environmental disturbance
Formwork and temporary works reuse	Increased reuse cycles of steel and timber formwork	309	0.6%	Cost-neutral	Requires early planning and coordination; supports circular construction practices
Combined scenario	Integration of all above measures	4048	7.3%	Slight overall cost increase	Achieves meaningful emission reduction while maintaining constructability

The optimized steel-erection scenario involved the use of barge-mounted cranes, reduced temporary falsework, and revised erection sequencing of prefabricated truss segments. These changes led to shorter erection durations and lower diesel consumption. Emission reductions were quantified by adjusting activity data related to temporary steel quantities and equipment fuel use while maintaining identical material volumes for permanent structural components.

The SCM substitution scenario assumed a 40% replacement of Portland cement using fly ash and ground granulated blast furnace slag, consistent with prevailing practice in Taiwan. Mechanical performance and durability requirements were satisfied through established mix design standards. Potential impacts on strength development and curing time were considered qualitatively; however, no significant schedule delays affecting the critical erection path were observed in the case project.

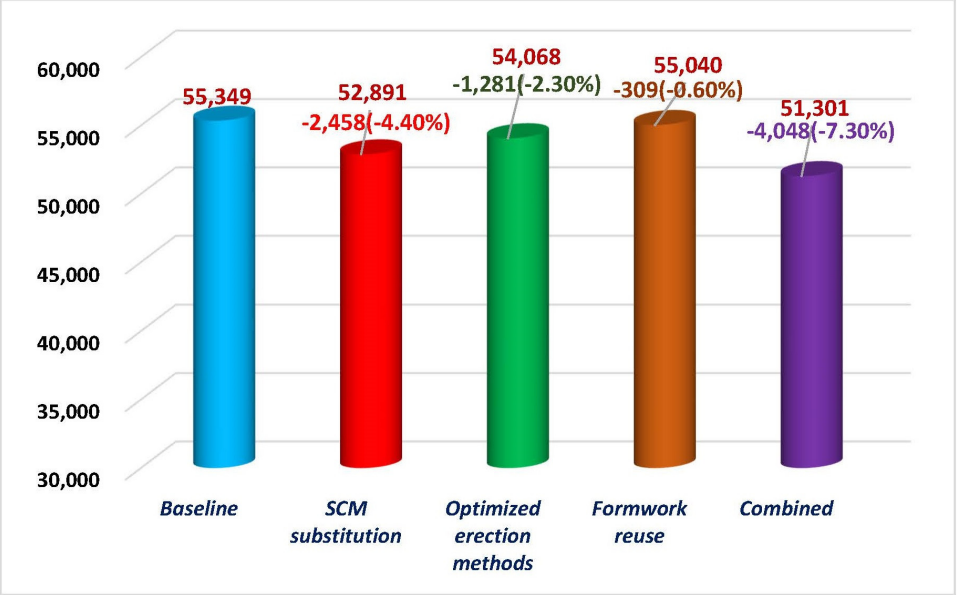

Figure 13. Baseline and reduction scenarios: SCM, erection, reuse, and combined effect.

5. Discussion and Findings

5.1. Interpretation of Carbon Footprint Results

The inventory analysis presented in Section 4 indicates that total construction-stage emissions for the Anhsin Bridge amount to 55,349 tCO_2e. Material production dominates the overall carbon footprint, with structural steel as the largest contributor (51.77%), followed by reinforcing steel (15.17%), concrete (13.76%), and cement (9.90%). Collectively, these materials account for more than 90% of total construction-stage emissions. Additional contributions from stay cables (2.45%) and protective coatings (0.51%) are comparatively minor.

Energy use associated with construction activities contributes a smaller share of emissions, with diesel fuel accounting for 4.88% and electricity for 1.56% of the total. Although these proportions are relatively modest, they highlight potential opportunities for improving logistics efficiency and increasing the use of low-emission or electrified construction equipment.

From a structural component perspective, foundations and substructure works contribute the largest share of emissions (41.50%), followed by the truss girder system (33.50%). The tower accounts for 21.84%, while emissions associated with stay cables (2.62%) and the bridge deck (0.55%) remain limited. These results confirm that steel-intensive structural elements play a decisive role in shaping the embodied carbon profile of long-span bridge construction.

Two key insights emerge from this analysis. First, structural form exerts a strong influence on construction-stage emissions. The asymmetrical cable-stayed truss configuration adopted for the Anhsin Bridge increases steel demand, thereby elevating embodied carbon intensity. Second, incremental improvements in material selection and construction methods—such as supplementary cementitious material (SCM) substitution and extended reuse of temporary works—can achieve meaningful emission reductions without fundamentally altering structural performance. These findings are consistent with broader life-cycle assessment research emphasizing the importance of robust inventories and methodological transparency in infrastructure carbon evaluation (Finnveden et al., 2009) [31].

Recent studies further demonstrate that steel structural design decisions significantly affect constructability and material efficiency, which in turn influence embodied carbon

outcomes. Constructability-oriented design approaches show that appropriate member configuration and erection planning can reduce material waste and enhance construction efficiency, while research on structural optimization highlights the role of rational steel member layouts and connection detailing in improving material utilization [28,29].

5.2. Comparative Insights with International Bridge Projects

Benchmarking shows that the Anhsin Bridge's emissions align with international cases. Bai et al. (2024) [15] reported 70,000–95,000 tCO_2e for Japanese bridges, while Hao et al. (2020) [13] identified 8–15% reductions via material substitution in Asian projects. Bannazadeh et al. (2012) [17] documented ~20% reductions in a European bridge through high SCM substitution and recycled reinforcing steel.

Taiwan's outcomes were constrained by limited recycled steel and higher emission factors from domestic blast-furnace production, despite established guidelines (EPA, 2010) [10]. This highlights a gap between policy and practice.

Table 7 compares bridge projects internationally. With 55,349 tCO_2e and a main span of 180 m, the Anhsin Bridge records 307 tCO_2e/m, lower than an earlier estimate (433), and closer to peers such as the Tatara Bridge (327) and EU case (357), though still higher than Korea's Incheon Bridge (393).

Table 7. Comparative carbon footprint intensities of long-span bridges.

Project/Country	Type	Total CO_2e (t)	Main Span (m)	Intensity (t/m span)	Reduction Strategies Applied
Anhsin Bridge, Taiwan	Cable-stayed truss	55,349	180	**307**	SCM substitution, optimized erection, formwork reuse
Incheon Bridge, Korea	Cable-stayed	90,500	230	393	SCMs, optimized erection
Tatara Bridge, Japan	Cable-stayed	72,000	220	327	Recycled steel, energy-efficient cranes
EU Case (Bannazadeh et al., 2012) [17]	Cable-stayed	75,000	210	357	High SCM substitution, recycled steel

5.3. Evaluation of Reduction Scenarios

Three scenarios were analyzed against the baseline of 55,349 tCO_2e.

- SCM substitution reduced by 2458 tCO_2e (−4.4%), being the most impactful strategy. This mirrors global evidence, but wider adoption faces supply constraints and conservative construction practices.
- Optimized erection methods cut 1281 tCO_2e (−2.3%). Benefits extended beyond carbon savings, including reduced hydrological disturbance, shorter duration, and better safety, though costs increased slightly.
- Formwork reuse avoided 309 tCO_2e (−0.6%). Though small in effect, it is cost-neutral and supports circular practices.

Together, the three measures achieved 4048 tCO_2e (−7.3%), a modest share of the total but significant in targeting high-emission categories like cement and diesel. These results illustrate that even incremental measures can set foundations for broader adoption of sustainable practices.

5.4. Policy and Practical Implications

The findings hold implications for both policy and practice in Taiwan.

Policy. (1) Innovation capacity should be strengthened through government support for SCMs, low-carbon steelmaking, and electrified equipment. (2) Performance-based specifications should replace prescriptive standards to allow greater flexibility in sustainable materials. (3) Supply chains for SCMs, recycled steel, and alternative fuels need investment. (4) Public works should integrate sustainability metrics into MOTC's statistical framework, aligning projects with Taiwan's 2030 and 2050 goals.

Practice. (1) Design choices should explicitly include embodied carbon alongside cost and safety. (2) Construction logistics, including optimized erection and reduced temporary works, can enhance efficiency. (3) Lessons from the Anhsin Bridge should be codified into guidelines for wider dissemination.

Broader lessons. Achievable reductions (~7.3%) remain insufficient to align with net-zero goals. Deeper change requires systemic innovation in material production (e.g., green steel, alternative binders), expanded SCM supply, and stronger integration of carbon accounting into procurement. This is consistent with research highlighting the role of innovation, construction-phase sustainability, and policy instruments in enabling sectoral transition.

Figure 14 illustrates a progressive pathway to carbon neutrality, combining project-level strategies with sector-wide transformations in materials, electrification, and policy [22,31].

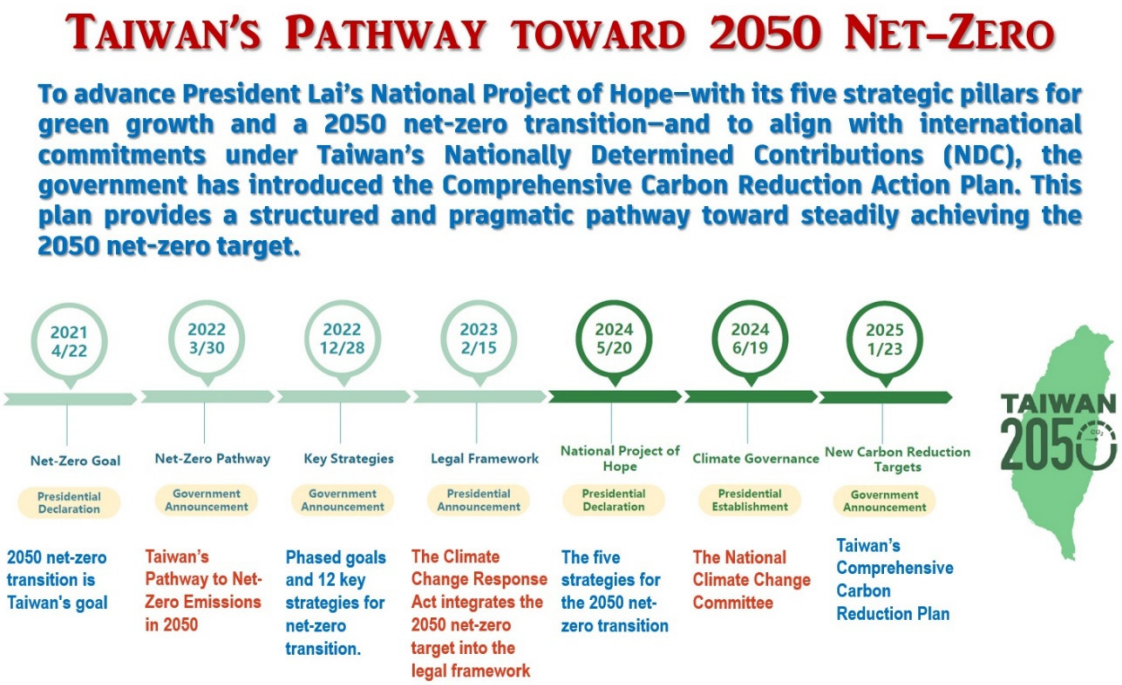

Figure 14. Progressive carbon reduction pathway integrating project-level measures with sector-wide transitions [22,31].

6. Conclusions and Recommendations

6.1. Conclusions

This study presented a detailed construction-stage carbon footprint assessment of the Anhsin Bridge, focusing on the role of construction materials in shaping embodied greenhouse gas emissions. Total emissions were estimated at 55,349 tCO_2e, confirming that material production dominates the carbon profile of long-span bridge construction. Structural steel was the largest contributor, accounting for more than half of the total emissions, while reinforcing steel, concrete, and cement together contributed approximately 39%. These findings are consistent with international observations that steel-intensive bridge systems are inherently material-driven in terms of embodied carbon.

Despite its high emission intensity during production, structural steel demonstrated substantial advantages from a construction materials perspective. Its high strength-to-weight ratio enabled efficient structural forms and reduced foundation demands, while excellent ductility and fatigue resistance supported safety and durability requirements. The extensive use of prefabricated steel components facilitated modular construction, shortened erection time, improved quality control, and reduced on-site environmental disturbance. Moreover, the high recyclability of steel provides a strong foundation for circular construction practices and future integration of low-carbon or green steel technologies.

The evaluation of mitigation strategies showed that material-oriented and construction-stage interventions can deliver meaningful emission reductions. Among the evaluated strategies, supplementary cementitious material substitution provided the largest reduction, while optimized steel erection methods and increased formwork reuse further contributed to mitigating emissions associated with temporary works and equipment use. Together, these measures demonstrate that incremental, technically feasible interventions can effectively target high-emission materials without compromising structural performance or constructability.

Comparative analysis indicates that the emission intensity of the Anhsin Bridge is within the range of comparable international steel bridge projects, though still influenced by reliance on virgin steel and conventional production routes. This highlights the importance of advancing low-carbon steel supply chains, promoting recycled steel use, and adopting performance-based material specifications in public infrastructure projects.

From the perspective of construction materials, the findings underscore that achieving substantial carbon reductions in steel-intensive infrastructure will require both project-level optimization and systemic innovation in material production, recycling, and procurement. Future research should extend the analysis to full life-cycle stages, investigate the application of recycled and green steel, and develop localized emission factors for construction materials. Such efforts will be essential to support the transition toward low-carbon, high-performance steel bridge construction aligned with long-term climate targets.

6.2. Recommendations

Policy. Implement performance-based material specifications, strengthen SCM supply chains, incentivize low-carbon steelmaking, and mandate embodied carbon disclosure for public works to enhance transparency.

Practice. Incorporate carbon metrics into design and tender evaluations, improve construction logistics through advanced erection planning, and institutionalize material reuse to foster circularity.

Research. Develop localized emission factors for higher accuracy, investigate green steel and alternative binders, and expand multi-project datasets for robust benchmarking.

6.3. Limitations and Future Research Directions

This study focuses exclusively on the construction stage and does not seek to provide a detailed cost–benefit or life-cycle cost analysis; instead, cost-related information is used solely to contextualize the practical feasibility of the proposed carbon mitigation strategies. Although the emission factor–based approach offers transparency and consistency, it remains sensitive to assumptions related to emission databases and material sourcing. Future research should extend the analysis to full life-cycle assessments, further examine the impacts of prefabrication and construction equipment electrification, and compare results across different bridge typologies and regional contexts. Such efforts would help strengthen empirical benchmarks and support Taiwan's pathway toward its 2030 and 2050 net-zero emission targets.

A qualitative sensitivity assessment indicates that the three largest excluded items—equipment manufacture, worker commuting, and site office operation—would collectively contribute less than 5% of total construction-stage emissions and would not alter the dominance of material-related emissions or the main conclusions of this study. In addition, a ±20% variation in assumed transportation distances or alternative mode shares would result in less than a 2% change in total construction-stage emissions, confirming that material transportation is a secondary contributor compared with material production.

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Conflicts of Interest: Author Chia-Cheng Lee was employed by the company New Asia Construction and Development Corporation. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

MRT	Mass Rapid Transit
AKLRM	Ankeng Light Rail Metro
BIM	Building Information Modeling
CFP	Carbon Footprint
CO_2e	Carbon Dioxide Equivalent
EPA	Environmental Protection Administration (Taiwan)
GHG	Greenhouse Gas
HDPE	High-Density Polyethylene
ISO	International Organization for Standardization
LCA	Life-Cycle Assessment
MOTC	Ministry of Transportation and Communications (Taiwan)
SCM	Supplementary Cementitious Material
TFES	Truss-Frame Erection System

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