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Towards Carbon Neutrality: An LCA-based Assessment and Reduction Pathways for Prefabricated Components in a Semiconductor Facility

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ABSTRACT

Within the context of global carbon neutrality initiatives, prefabricated buildings are recognized for their pivotal role in decarbonizing the construction sector. However, the manufacturing of their components remains a carbon-intensive process. This study conducts a systematic assessment of carbon emissions from prefabricated component production for a semiconductor manufacturing facility, employing Life Cycle Assessment (LCA) and emission factor methods. The results identify concrete and steel production as the dominant sources, collectively contributing 82.7% of total emissions (10,794 tons and 2,285 tons CO_2e, respectively). An integrated "technology-economy-policy" pathway is proposed. Technical innovations, including low-carbon cement substitution and photovoltaic power integration, could abate electricity-related emissions by 35%. Complementary carbon offset strategies, such as CO_2 mineralization curing and forestry carbon sinks, could yield an additional annual reduction of 17%. The implementation of this framework is projected to cumulatively reduce 600–800 million tons of CO_2e by 2030, contributing 19% to the construction sector's carbon peak target. This research provides a quantitative framework and actionable insights for the low-carbon transition of prefabricated buildings, facilitating a sectoral shift from scale expansion toward quality and efficiency.

KEYWORDS

Prefabricated buildings, Carbon emissions, Life Cycle Assessment (LCA), Low-carbon construction, Decarbonization, Carbon offset strategie

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1. INTRODUCTION

Global greenhouse gas emissions have exhibited a sustained upward trajectory over the past several decades, exacerbating the climate crisis to an increasingly urgent and critical stage, as noted by Filonchyk et al. (2024). In 2022, the International Energy Agency (2023) reported that energy-related carbon dioxide emissions rose by 0.9% (approximately 321 million tons), reaching a historic peak of more than 36.8 billion tons. According to El Sheikh (2022), the construction sector is among the primary contributors to this issue, accounting for approximately 40% of total carbon emissions in Europe, while the United Nations (2023) estimated that the sector contributes about 21% of global emissions. Throughout its entire life cycle—from material production and construction to operation and use—the building industry generates substantial emissions, making its transformation pivotal to global climate mitigation efforts. In response to this urgency, the United Nations (2023), in collaboration with the governments of France and Morocco and the United Nations Environment Programme (UNEP), launched the Buildings Breakthrough initiative at the 2023 United Nations Climate Change Conference (COP28), aiming to make "near-zero-emission, climate-resilient buildings" the new global norm by 2030. Against this backdrop, Zhou et al. (2023) identified prefabricated construction as a crucial pathway for decarbonizing the building sector. By shifting a substantial portion of on-site construction processes to controlled factory environments, this approach significantly enhances resource efficiency, reduces construction waste, and demonstrates a lower carbon footprint throughout its life cycle compared with conventional cast-in-place construction methods.

Meanwhile, the rapid growth of another high-demand, high-investment, and time-sensitive industry—the semiconductor sector—has further underscored the significance of prefabricated construction. In recent years, technological advancements have driven robust global expansion within the semiconductor industry. According to the Semiconductor Industry Association (2025), global semiconductor sales reached USD 630.5 billion in 2024, surpassing initial expectations. Furthermore, the World Semiconductor Trade Statistics (WSTS) organization projects that global semiconductor sales will rise to USD 701 billion in 2025, representing a year-on-year increase of 11.2%. Driven by the surge in demand for advanced applications, the global semiconductor industry is undergoing a simultaneous wave of capacity expansion. In such industries characterized by high precision and rapid construction requirements, prefabricated buildings not only demonstrate advantages in production and assembly efficiency but also serve as a crucial pathway for advancing green manufacturing and low-carbon construction.

However, to fully harness the carbon reduction potential of prefabricated buildings, it is essential to focus on the component manufacturing stage—still a major source of emissions, as highlighted by Jin et al. (2025). Quantitative analysis of the carbon footprint during this phase provides a scientific basis for identifying low-carbon material alternatives and clean energy pathways, thereby enabling a deeper exploration of the inherent tension between industrialized production and high carbon emissions, as discussed by Huang and Wang (2023). Through empirical measurements and data modeling, this study further explores the technological potential of prefabricated buildings within the pathway toward "life-cycle carbon neutrality," encompassing strategies such as clean energy substitution and the utilization of recycled materials. It proposes a multidimensional sustainable framework that integrates technological, economic, and policy synergies. Against the backdrop of the global transition toward carbon neutrality, reducing emissions at this stage has become a critical and urgent challenge.While existing research has predominantly centered on the overall construction phase of projects, systematic studies focusing on carbon emission quantification and pathway optimization during the production stage of prefabricated components remain limited. Addressing this gap, this study develops a carbon emission modeling framework that integrates Life Cycle Assessment (LCA) and the emission factor method to investigate the full production-cycle carbon footprint of prefabricated components. Grounded in a comprehensive literature review and empirical data from a prefabrication project for a semiconductor facility, the framework incorporates key influencing parameters — including production cycle, component dimensions, output volume, transportation distance, and energy consumption—to identify major emission sources such as concrete and reinforcing steel.Through empirical measurement and data modeling, carbon emissions are quantified by incorporating specific emission factors into the analytical structure. Furthermore, a multidimensional strategy for emission reduction is proposed, integrating technological, economic, and policy dimensions. The research aims to support a shift in the construction industry from “scale expansion” to “quality and efficiency enhancement,” providing both theoretical foundations and practical insights to advance the low-carbon development of prefabricated buildings.

2. LITERATURE REVIEW

2.1 Carbon Emission (CE) Mechanism

Carbon emissions generally refer to the release of carbon dioxide (CO_2) or other greenhouse gases (GHGs), such as methane (CH_4) and nitrous oxide (N_2O), with their quantities expressed in carbon dioxide equivalents (CO_2-eq). The primary sources include fossil fuel combustion, industrial processes, and land-use changes , while building operations, energy consumption, industrial production, and transportation represent the main emission sectors. As a critical indicator for assessing climate change, carbon emissions form the fundamental basis for achieving global carbon peaking and carbon neutrality targets. According to the International Energy Agency (2023), technological innovation serves as an effective means of reducing CO_2 emissions, and investment in renewable energy within the construction sector is equally essential. Erdoğan et al. (2020) argue that technological innovation, economic growth, and urbanization are the primary determinants of emissions; thus, achieving a balance among economic development, population growth, and environmental protection is particularly crucial. According to the World Resources Institute (2004), carbon emissions are categorized into three scopes: Scope 1 refers to direct emissions, Scope 2 to indirect emissions from purchased energy, and Scope 3 to other indirect emissions occurring across the entire value chain. For prefabricated buildings, Scope 3 emissions typically account for the largest proportion, primarily due to the high reliance on external industrial chains for component manufacturing and material supply, which generates substantial upstream indirect emissions. The breakdown is explained in the following subsections.

2.1.1 Low-Carbon Material Strategies in Prefabricated Construction

In the low-carbon transition of the construction industry, the use of green building materials is of critical importance. Contemporary international prefabricated building design increasingly emphasizes the integration of energy-efficient materials and construction techniques. Selbyville (2020) projects that the global market for prefabricated construction will reach USD 174 billion by 2026, growing at a compound annual rate of approximately 7.1%. However, there remains considerable room for improvement in overall energy efficiency (International Energy Agency, 2023).In terms of performance, innovative green materials demonstrate significant advantages. For instance, Lakatos (2022) reports that new insulation materials exhibit superior thermal resistance compared to traditional polystyrene foam boards, effectively reducing building energy consumption and enhancing comfort levels. Similarly, Lu et al. (2021) show that certain high-performance concretes possess enhanced impermeability and frost resistance, thereby extending building lifespan. Nevertheless, some emerging materials still face potential durability challenges, such as the development of microcracks (Rajczakowska et al., 2024).From an economic perspective, the initial research, development, and production costs of innovative green materials are relatively high; however, their advantages in energy efficiency and durability can reduce overall costs over the building’s life cycle (Wang & Liu, 2021). In contrast, traditional high-carbon materials, though cheaper to procure, tend to incur higher long-term costs due to elevated energy consumption and frequent maintenance requirements.Regarding carbon emissions, new materials exhibit greater mitigation potential. Recycled aggregate concrete reduces resource extraction and energy consumption by utilizing construction waste, while low-carbon concrete decreases CO_2 emissions during production through the incorporation of limestone powder (PLC) and supplementary cementitious materials (SCMs) (United Nations Environment et al., 2018). Moreover, bio-based materials, which possess carbon sequestration and storage capabilities, have emerged as a promising direction for prefabricated component production, offering a novel pathway toward achieving “negative carbon emissions” in the construction industry (Bourbia et al., 2023; Filonchyk et al., 2024):

(1) Gilmour, Ghimire, Wright, et al. (2024) report that bio-concrete has recently utilized Microbially Induced Calcium Carbonate Precipitation (MICP) technology to convert CO_2 into mineral form, demonstrating significant carbon sequestration potential. In engineering trials, they reduced CO_2 concentrations from approximately 3800 ppm to 820 ppm, highlighting the potential of such cement-based materials for carbon-negative applications.

(2) De, Yang, Lee, et al. (2025) indicate that mycelium composite panels, produced from agricultural waste substrates such as sawdust and coir, exhibit lightweight, high-strength, biodegradable properties while maintaining low energy consumption. They also note that the manufacturing process consumes considerably less energy compared with conventional synthetic foam materials.
(3) Van der Lugt, Vogtländer, Van der Vegte, et al. (2015) highlight that bamboo fiber composites offer excellent mechanical performance along with low-carbon advantages. Their life-cycle assessments indicate that bamboo fiber reinforced panels significantly reduce carbon emissions compared with traditional wood or petroleum-based composites, with one case showing a reduction of approximately 51% in CO_2 emissions.

2.1.2 Optimization of Production Processes

The production phase of prefabricated components is a major source of carbon emissions, with mitigation strategies primarily focused on process optimization and energy structure improvements. Armstrong, Kamath, Zhao, et al. (2023) indicate that conventional precast concrete production commonly suffers from low mold reuse rates, high energy consumption during curing, and insufficient equipment efficiency. To address these challenges, the International Energy Agency and OECD (2019) propose a multi-level process optimization approach. This approach includes enhancing mold standardization and reuse rates, adopting lightweight low-carbon materials, and employing digital manufacturing technologies such as 3D printing to achieve resource savings and upstream emission reductions. In addition, the International Energy Agency and OECD (2019) also emphasize introducing clean energy and waste heat recovery systems in the curing stage to gradually replace fossil fuel-based heat sources and improve energy efficiency. Furthermore, Barbhuiya, Das, Adak, et al. (2025) highlight the integration of emerging low-carbon technologies such as carbon capture and mineralization curing into the production system to embed carbon fixation processes, thereby realizing a synergistic effect of “process carbon sequestration” at the production end. Overall, these systematic improvements in equipment energy savings, thermal energy recovery, and process integration optimization can significantly reduce energy consumption and carbon emissions in the production of prefabricated components, providing sustainable technological support for the carbon-neutral transition of industrialized construction.

2.1.3 Optimization of Energy Structure and Energy Efficiency

Enhancing energy utilization efficiency in the production of prefabricated components is a key pathway toward achieving carbon neutrality. The International Energy Agency (2023) highlights that current research primarily focuses on two aspects: first, the introduction of high-efficiency energy-saving equipment, such as optimally designed mixing systems and intelligent lighting control, which can reduce energy consumption and extend equipment lifespan; second, the use of renewable energy sources, including distributed photovoltaics, wind power, and waste heat recovery, to achieve partial self-sufficiency and energy substitution, thereby reducing reliance on fossil fuels.Studies have shown that the integrated application of energy-saving technologies and renewable energy can effectively reduce production energy consumption and carbon emissions by approximately 20%–30%, providing crucial support for the green and low-carbon transformation of the prefabricated construction industry. At the same time, the actual benefits of these technologies are highly dependent on regional resource conditions: the northwest region is rich in solar and wind energy; coastal areas have advantages for offshore wind power; hydropower is mainly distributed in the southwest and central regions; and urban areas offer potential for rooftop-distributed photovoltaic applications.

2.1.4 Economic Feasibility and Life Cycle Cost Considerations

The promotion of low-carbon technologies requires consideration of both environmental benefits and economic feasibility. Based on a Life Cycle Cost (LCC) model, a cost-benefit analysis was conducted for the main emission reduction measures, as summarized in the table 1:

Table 1. Cost–Benefit Analysis of Different Technical Measures

Technical Measures	Initial Cost	Annual Emission Reduction (tCO_2e)	Annual Benefit (10,000 CNY)	Payback Period (Years)
Factory Rooftop Photovoltaic System	150	1200	800,000 CNY electricity savings	5-7

CO_2 Mineralization Curing Equipment	300	2000	400,000 CNY carbon credit revenue	8-10
Aluminum Alloy Mold Retrofit	50	300	150,000 CNY steel savings	3-4

Data Description:
Photovoltaic (PV) System: 1 MW installed capacity, annual electricity generation of 1.2 million kWh (electricity price 0.6 CNY/kWh), with emission reduction calculated at 0.59 kg CO_2e/kWh.
CO_2 Mineralization Curing: Includes capture and injection equipment; emission reduction accounts for CO_2 sequestration and energy savings from replacing conventional steam curing; carbon trading revenue is calculated at 40 CNY/t CO_2e.
Formwork Modification: Emission reductions arise from decreased transportation energy consumption and reduced steel usage.
Analysis results indicate that PV systems and aluminum formwork modifications involve low investment with quick payback, making them suitable for promotion among small and medium-sized enterprises. In contrast, CO_2 mineralization curing requires reductions in technological costs and policy support for large-scale implementation.

2.2 Carbon Neutrality Pathways

The concept of “carbon neutrality” in the building sector can be traced back to 2002, when the 2030 Challenge was launched (Architecture 2030, 2006), advocating that all new and renovated buildings should achieve net-zero emissions by 2030. Since then, both academia and industry have extensively explored pathways to carbon neutrality. For example, Costa, Amorim, and Ribeiro Silva (2020) proposed renovation guidelines for 240 office buildings in Brasília, achieving a 46% reduction in total energy consumption through the integration of passive design strategies and renewable energy systems. Moreover, projects such as Skanska’s low-carbon cement initiative in Sweden and the Circular Building project in the Netherlands have further demonstrated the feasibility of carbon-neutral buildings through the integrated application of modular design, recycled materials, and photovoltaic façade systems. These studies indicate that achieving carbon neutrality in buildings is a systemic process requiring the coordination of multidimensional technologies and management strategies, including technological innovation, renewable energy utilization, carbon capture, utilization, and storage (CCUS), as well as circular economy approaches. The breakdown is explained in the following subsections.

2.2.1 Optimization of Raw Material Selection

To achieve near-zero emission targets, in addition to reducing fossil fuel use, enhancing carbon sequestration through vegetation is essential. Different plant types exhibit significant variation in carbon uptake: Jin, Zhang, Guo, Hu, Zhang, and Yan (2023) noted that trees, with large biomass and long lifespans, serve as the primary carbon sinks, while shrubs and herbaceous plants, although lower in per-unit carbon absorption, can achieve substantial total uptake through dense planting.

Table 2. Daily Carbon Sequestration per Unit Leaf Area of Different Plant Life Forms （g/(m2・d)）

Life Form	Number of Species	Average Value	Maximum Value	Minimum Value
Minimum Value	77	7.81	20.09(Picea asperata)	1.03(Dracaena sanderiana)
Deciduous Trees	118	9.75	34.10(Populus alba var. pyramidalis)	0.68(Ceiba speciosa)
Evergreen Shrubs	80	7.99	21.72(Rhodomyrtus tomentosa)	0.90(Vinca major 'Variegata')
Deciduous Shrubs	56	10.05	36.21(Clematis grandiflora)	1. 50(Rosa multiflora)
Vines	33	3.70	11. 90(Euonymus fortunei var. radicans)	0.02(Polygonum multiflorum)
Herbaceous Flowers	81	12.16	88.64(Potentilla anserina)	0.41(Convolvulus arvensis)

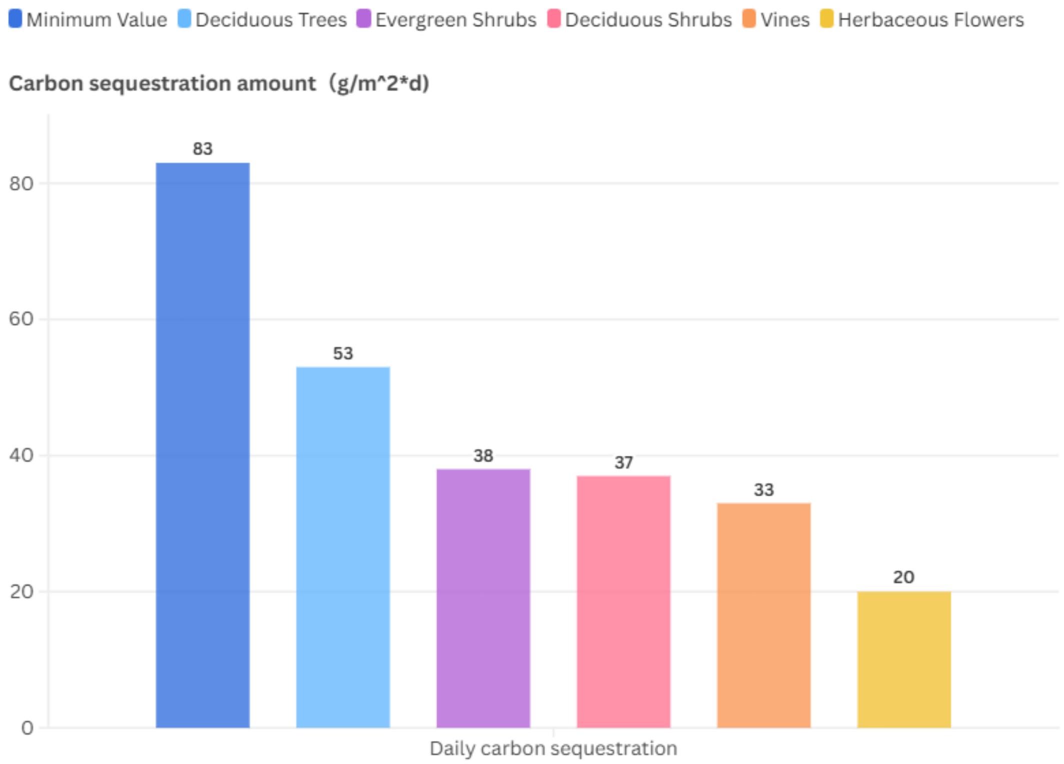


Figure 1. Daily carbon sequestration per unit canopy area of different life-form landscape plants.

As shown in Table 2 and Figure 1, different plant life forms display considerable differences in daily carbon sequestration per unit leaf area. Herbaceous flowers exhibit the highest maximum sequestration rate (88.64 g/(m^2 • d)), represented by Potentilla anserina, while vines show the lowest (0.02 g/(m^2 • d)). On average, deciduous shrubs (10.05 g/(m^2 • d)) and deciduous trees (9.75 g/(m^2 • d)) perform better than evergreen shrubs. These findings suggest that a balanced combination of trees, shrubs, and herbaceous plants can effectively enhance the overall carbon sequestration efficiency of green systems. In practice, priority should be given to native tree species with strong carbon sequestration capacity and high pollution resistance, combined with vertical greening and rooftop gardens to expand green coverage. At the same time, Wei et al. (2023) emphasized that remote sensing and intelligent monitoring technologies should be employed to track vegetation growth, with regular maintenance and replanting, thereby establishing a stable and efficient carbon sink system within prefabricated building industrial parks.

2.2.2 Application of Carbon Trading Market Mechanisms

Currently, carbon trading markets are one of the key instruments for controlling emissions. Based on the “cap-and-trade” principle, governments or relevant authorities set a regional carbon emission cap and allocate emission allowances to enterprises. During production and operation, if a company’s actual emissions exceed its allocated quota, it must purchase additional allowances from the market; conversely, if emissions are below the quota, the surplus can be sold for profit. Jiang, Wang, Xu, et al. (2024) highlighted that this mechanism incentivizes enterprises to proactively implement emission reduction measures to lower their allowance requirements, thereby generating economic benefits and promoting the efficient allocation of market resources. As shown in Figure 2, China’s national carbon trading system consists of a key institutional framework, an operation supporting system, and a multi-level supervision mechanism. Together, these elements ensure accurate emissions monitoring, transparent trading, and effective policy enforcement across different administrative levels.

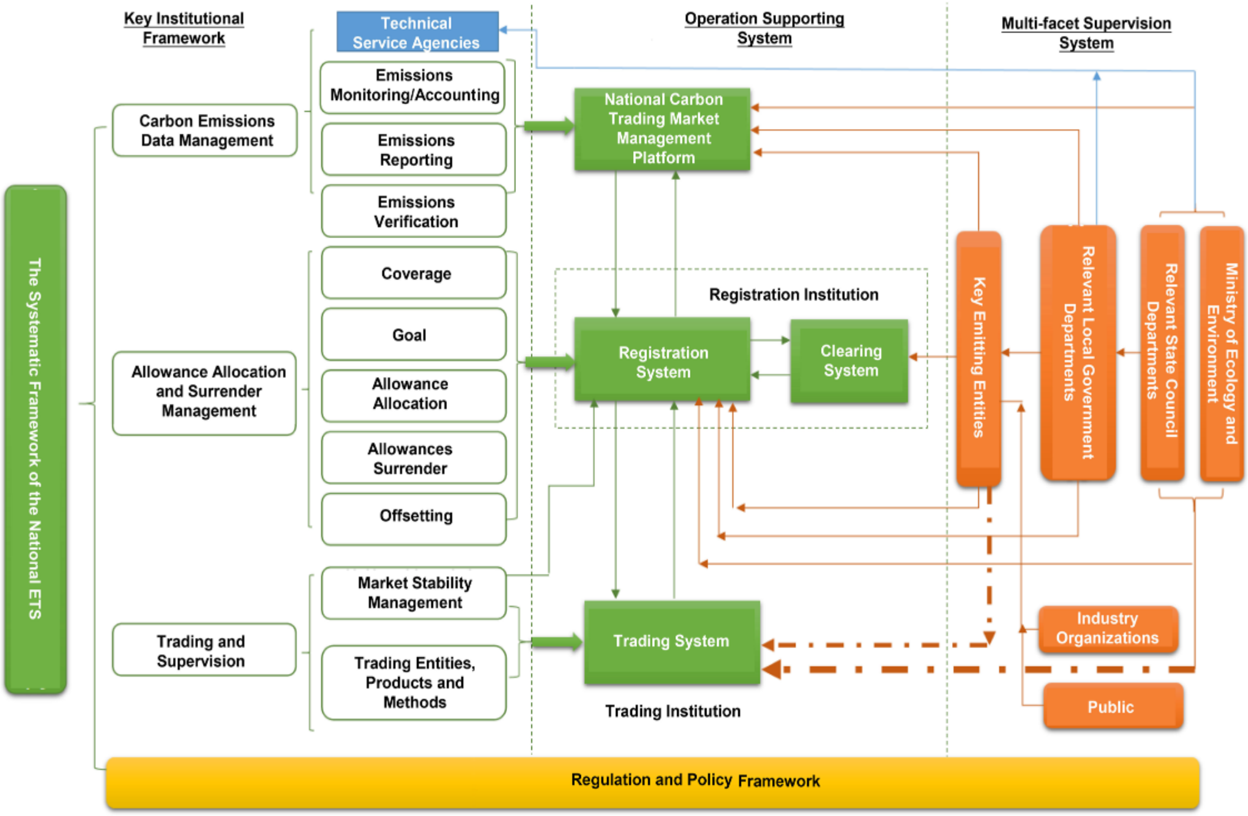


Figure 2. National Carbon Emission Trading Market System Structure

(Source: Ministry of Ecology and Environment of the People's Republic of China. (2024). National Carbon Market Development Report)

Carbon trading markets primarily operate under two models: allowance trading and project-based trading. In allowance trading, enterprises exchange emission rights allocated by the government; for example, the European Union Emissions Trading System (EU ETS) falls into this category, where market price signals are established through auctions and allocation of allowances. Project-based trading, on the other hand, focuses on specific emission reduction projects, such as the Clean Development Mechanism (CDM), where Certified Emission Reductions (CERs) generated by approved and verified energy-saving or emission reduction projects can be traded in the market.Prefabricated component manufacturing enterprises can participate in carbon trading by purchasing emission allowances or selling surplus quotas. During China’s second compliance period of the carbon market, the comprehensive closing price ranged between 50 and 82 CNY per ton, according to the Ministry of Ecology and Environment of China (2024). As shown in Figure 3, the operation of China’s national carbon market demonstrates a gradual stabilization and price increase trend across the first and second compliance cycles. The daily trading volume (blue bars) remained relatively low in early stages but increased significantly during key compliance periods, while the composite market closing price (red line) rose steadily, reflecting growing market maturity and enterprise participation.

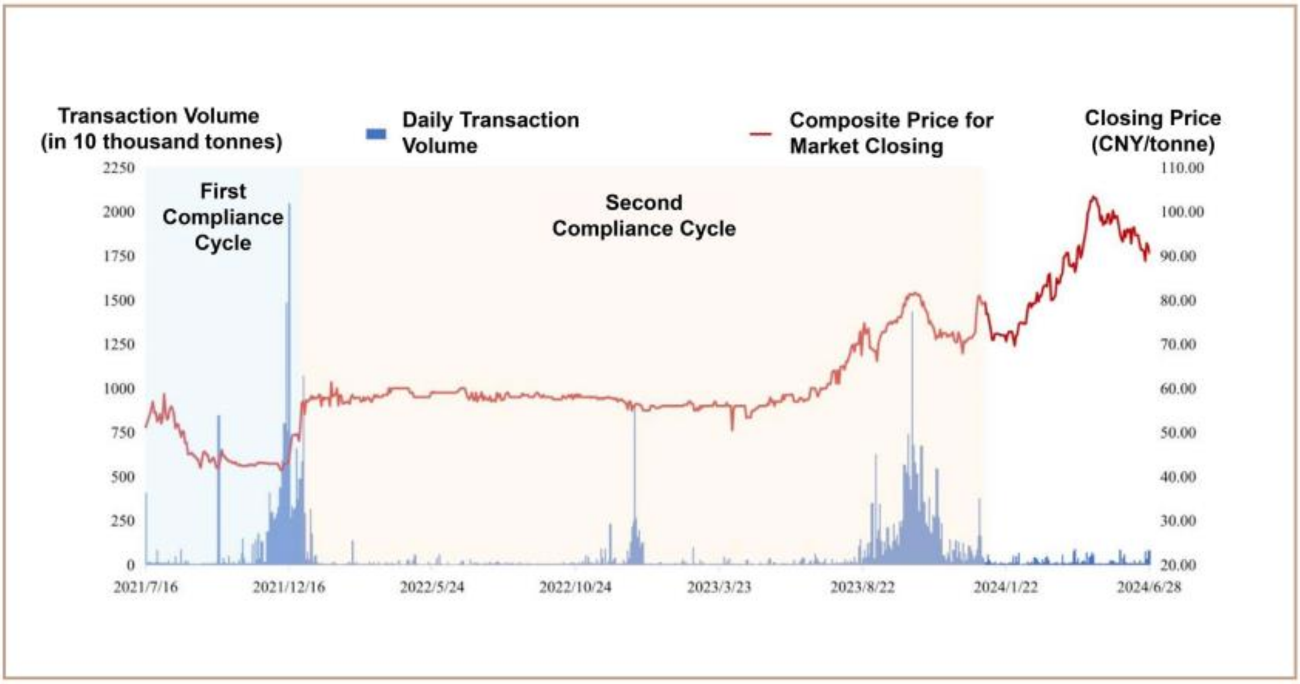


Figure 3. Operation Status of the National Carbon Emission Trading Market

(Source:Ministry of Ecology and Environment of the People's Republic of China. (2024). National Carbon Market Development Report)

Enterprises should assess their carbon emissions in advance; if there is a risk of exceeding their allowances, they must purchase additional quotas to avoid penalties. Similarly, if capacity expansion leads to increased emissions, corresponding allowances should be acquired. Conversely, if enterprises reduce emissions through energy-saving technologies, process optimization, or other measures, they can sell surplus quotas to generate revenue.

2.2.3 Carbon Capture Technologies

In the carbon-neutral pathway for prefabricated component production, Carbon Capture, Utilization, and Storage (CCUS) technologies have emerged as a frontier emission reduction approach and an important area of research and application. The core mechanism involves directly capturing CO_2 at the emission source and achieving reduction through conversion or storage.Common methods include chemical absorption, physical adsorption, membrane separation, and low-temperature condensation, which enable efficient capture from high-emission processes. Do, You, and Kim (2022) indicated that the captured CO_2 can be utilized for concrete mineralization curing, chemical synthesis, or geological storage, thereby balancing environmental benefits with economic value.

However, the widespread adoption of CCUS remains constrained by high costs and insufficient infrastructure. To address this, coordinated efforts between government policy support and corporate technological innovation are needed: the government can provide financial and tax incentives, while enterprises focus on improving capture and conversion efficiency and accelerating the development of transportation and storage systems.In the future, this technology can be integrated with renewable energy and smart manufacturing systems to establish a comprehensive low-carbon production model. Wang, Liu, Li, et al. (2023) suggested that prefabricated component enterprises can achieve phased offsets through measures such as forestry carbon sinks, distributed photovoltaics, and carbon allowance trading, enabling a multi-level, incremental carbon neutrality strategy.

2.2.4 Carbon Labeling System for Prefabricated Components

Carbon labels and Environmental Product Declarations (EPDs) are important tools for promoting the greening of the prefabricated component supply chain. Carbon labels quantify the greenhouse gas emissions across a product’s entire life cycle, enhancing information transparency, encouraging enterprises to optimize production processes, and guiding consumers toward low-carbon products. EPDs, on the other hand, assess a product's environmental performance according to internationally recognized standards, thereby improving an enterprise's competitiveness in the global market . In the context of the Carbon Border Adjustment Mechanism (CBAM), component manufacturers can establish a dual-indicator system of "carbon footprint + proportion of recycled materials" to comprehensively demonstrate environmental advantages and enhance brand and market recognition. Overall, the combination of carbon labels and EPDs not only helps improve carbon management across the supply chain but also provides an international pathway for the green transformation of the prefabricated construction industry.

2.2.5 Industrial Symbiosis and Cross-Sector Carbon Loop

In the production of prefabricated components, industrial symbiosis and cross-sector carbon loops enhance emission reduction and efficiency through the sharing of energy and resources. The main strategies include:

(1) Jouhara, Khordehgah, Almahmoud, et al. (2018) indicated that high-temperature waste heat from steel plants can be redirected to steam curing of prefabricated components, replacing fossil fuels and reducing energy consumption and carbon emissions.;

(2) Cement Plant Carbon Capture and Mineralization: CO_2 emissions from cement production are captured and used for concrete mineralization curing, achieving cross-sector emission reduction synergy;

(3) Ma (2025) highlighted that large-scale use of fly ash or slag in concrete can reduce cement consumption and CO_2 emissions.;

(4) Ma (2025) also noted that establishing a closed-loop recycling system to process construction waste into recycled aggregates for component production can reduce overall carbon emissions by approximately 12%.

This model, through multi-industry resource integration, provides a systematic pathway for the low-carbon development of the prefabricated construction industry.

2.3 Low-Carbon Performance and Life-Cycle Characteristics of Prefabricated Buildings

2.3.1 Low-Carbon Characteristics of Prefabricated Buildings

Prefabricated buildings are characterized by factory-produced components and rapid on-site assembly, representing a key manifestation of construction industrialization. Their core advantages include a high degree of standardization, shorter construction cycles, and efficient resource utilization, all of which effectively reduce environmental impact. Studies have shown that, compared with traditional cast-in-place construction methods, prefabricated buildings offer significant benefits in controlling construction waste and reducing carbon emissions. Jaillon, Poon, and Chiang (2009) found that prefabricated construction can substantially reduce the generation of construction waste, highlighting its potential in green building development. From a transportation perspective, Wang, Zhang, Hou, et al. (2021) developed a carbon emission assessment model, demonstrating that shorter transportation distances are a key factor for carbon reduction in prefabricated buildings. Dodoo, Gustavsson, and Sathre (2009) compared concrete and timber structures during demolition and recycling phases, showing that timber structures, due to their higher recyclability, perform better in terms of carbon mitigation. Overall, existing studies generally agree that prefabricated buildings demonstrate significant low-carbon potential in material conservation, transportation optimization, and recycling, providing an important pathway for the green transformation and sustainable development of the construction industry.

2.3.2 Carbon emission structure in the life cycle of prefabricated buildings

The life cycle of a prefabricated building—comprising the embodied, operational, and demolition and disposal phases—involves distinct activities and corresponding sources of carbon emissions at each stage, the overall characteristics of which are summarized in Table 3.

Table 3. Life-Cycle Carbon Emission Characteristics of Prefabricated Buildings

Life Cycle Stage	Main Activities	Typical Carbon Emission Sources	Impacts of Prefabrication Characteristics
Embodied stage	Raw material extraction and transportation;	Material production processes (cement, steel); production	Core stage. Industrialized production improves efficiency, but manufacturing

	component production; component transportation; on-site construction and installation	energy consumption (electricity, heat); fuel consumption for transportation; energy use of construction machinery	processes themselves are carbon-intensive (as analyzed in Chapter 4). Prefabrication enables standardization and reduces material waste from on-site wet operations.
Operation stage	Daily building operation (heating, cooling, lighting, equipment, etc.)	Energy consumption during building operation (electricity, natural gas, etc.)	Relatively less associated with structural form (prefabricated vs. cast-in-place). Primarily depends on envelope performance and equipment efficiency.
Demolition and disposal	Building demolition; waste transportation; waste treatment (landfilling, incineration, recycling)	Energy consumption of demolition machinery; fuel consumption for transportation; emissions from waste treatment processes; carbon offsets from recycling and reuse	Potential stage. Component-based design facilitates disassembly and material sorting/recycling (e.g., steel structures, large concrete components), improving resource recovery rates and reducing disposal-related emissions.

2.4 Life Cycle Assessment (LCA) Method

Against the backdrop of global climate change mitigation and the decarbonization of the construction industry, Life Cycle Assessment (LCA) has gradually become a core method in international building environmental research, used to systematically evaluate the overall environmental impact of prefabricated buildings at different stages. Early international studies primarily focused on comparing the environmental performance of building materials and structural systems. Guggemos and Horvath (2005) were among the first to apply life cycle assessment (LCA) to the quantitative analysis of the construction phase, highlighting that prefabricated construction can effectively reduce on-site energy consumption and waste generation. Khasreen, Banfill, and Menzies (2009) argued that focusing solely on greenhouse gas emissions is overly narrow and emphasized the need for a comprehensive assessment of buildings from the perspective of overall environmental impact. With the standardization of LCA methodologies (ISO 14040/14044), researchers have begun adopting full-process perspectives, such as "cradle to grave" or "cradle to cradle," to establish life cycle models with clearly defined system boundaries and traceable data. Monahan and Powell (2011) used LCA methods to find that modular buildings exhibit significantly lower carbon emissions during the production phase compared to conventional structures, while energy consumption during the operational phase depends on the thermal performance and airtightness of the building envelope.Nordic countries such as Sweden, Finland, and Norway emphasize the systematic assessment of material recycling and reuse in LCA practice. For instance, Andersson et al. (2019) employed scenario-based analysis to reveal the sensitivity of overall carbon reduction potential to the reuse rate of building components.

Overall, international studies consistently indicate that prefabricated buildings offer clear advantages over traditional cast-in-place structures in terms of material utilization, construction energy consumption, and waste management. However, current research faces key challenges, including regional differences in database applicability, inconsistencies in system boundary definitions, and a lack of data for the recycling phase.Future trends indicate that LCA is evolving from static assessment toward design-oriented, real-time decision-support systems. By integrating with Digital Twin technology, Building Information Modeling (BIM), and Life Cycle Cost (LCC) analysis, it enables sustainable optimization and carbon management across the entire building life cycle. In summary, from an international perspective, life cycle assessment is not only a core method for evaluating the environmental performance of prefabricated buildings but also a crucial scientific tool for advancing the global construction industry toward low-carbon, circular, and intelligent transformation.

2.5 Literature Summary

In summary, carbon emissions from prefabricated buildings are primarily concentrated in the embodied phase, while the demolition and recycling stages hold significant potential for future carbon reduction. Existing studies largely focus on technological innovation and circular economy models, relying on market-based mechanisms and emphasizing the role of corporate initiative and market incentives in emission reduction.However, quantitative research on cross-sector collaboration remains relatively limited, and a systematic understanding of carbon emissions and carbon neutrality across the full life cycle of buildings is still incomplete. In response to the lack of comprehensive studies on carbon neutrality, this paper innovatively employs the LCA method to discuss carbon emissions and carbon neutrality measures and outcomes for prefabricated buildings in a more full-cycle and systematic manner.

Therefore, based on a full life cycle perspective, this paper systematically analyzes and validates data on the carbon emission characteristics and technological innovation pathways of prefabricated buildings across production, transportation, construction, and demolition stages, aiming to establish a comprehensive and quantifiable assessment framework to provide a scientific basis for achieving carbon neutrality in the construction industry.

3. RESEARCH METHODOLOGY

3.1 Carbon Emission Source Identification

With the rapid development of prefabricated buildings, their anticipated low-carbon potential has not yet been fully realized. Huang and Wang (2023) noted that the primary reason lies in the persistence of high-carbon processes across multiple production stages during the materialization phase, as illustrated in Figure 4. The major sources of carbon emissions include:

(1) Material Production Phase: Large amounts of CO_2 are released during cement calcination and steel smelting, while auxiliary materials (e.g., additives) also consume energy and generate emissions;

(2) Component Manufacturing Phase: Operation of mechanical equipment (e.g., mixers, vibrators) consumes electricity, and the hydration reaction during concrete curing further produces CO_2;

(3) Wang, Zhang, Hou, et al. (2021) indicated that heavy trucks, flatbed vehicles, and other transport equipment rely on fossil fuels, with their combustion constituting indirect carbon sources during the transportation phase.

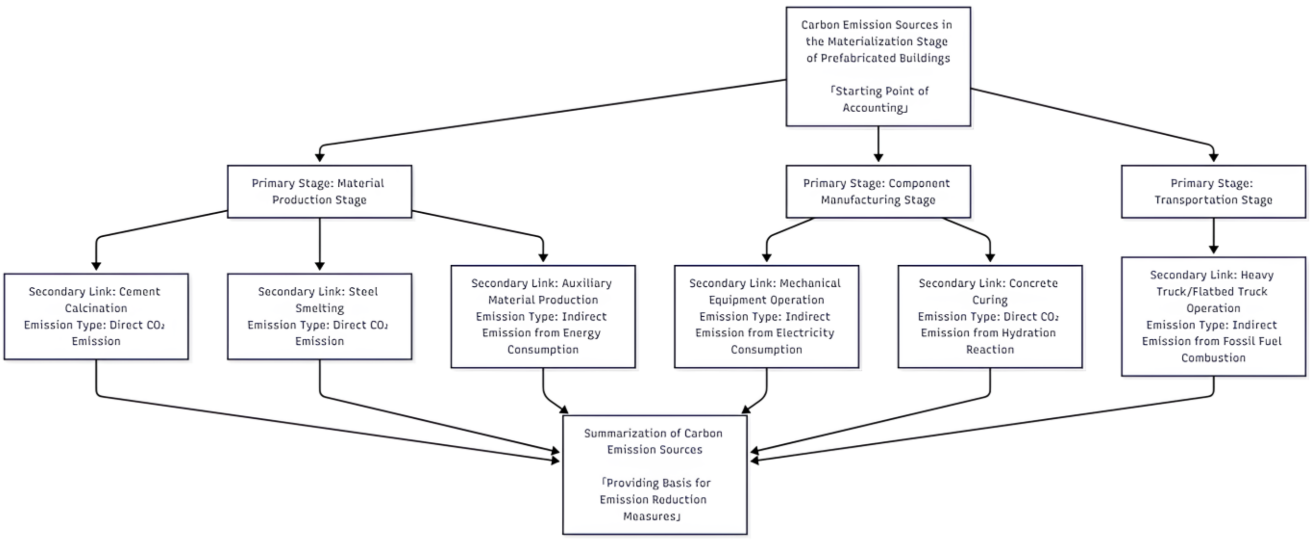


Figure 4. Flowchart for Identifying Carbon Emission Sources in the Materialization Stage of Prefabricated Buildings

Accurate identification of carbon emission sources serves as the fundamental prerequisite for formulating targeted mitigation measures. The identification process is illustrated in the following figure 5.

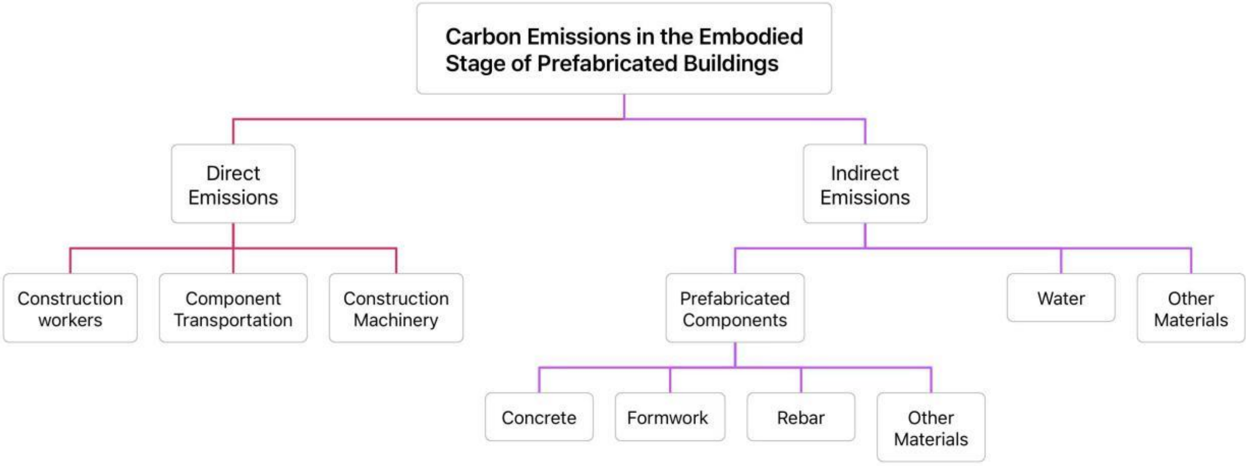


Figure 5. Identification of Carbon Emission Sources in Prefabricated Buildings

3.2 Carbon Emission Calculation Methods

After identifying the three major sources of carbon emissions during the materialization stage of prefabricated buildings—material production , component manufacturing, and transportation —as well as their specific emission nodes, it is necessary to quantify the carbon emission intensity of each source through scientific calculation methods. This quantification provides accurate data support for the formulation of subsequent mitigation measures. The calculation of building carbon emissions primarily involves the following two approaches:

(1) Model Estimation Method involves using mathematical models or simulation methods to comprehensively consider process flows, energy consumption, and material usage, reflecting the interactions among various factors. This method requires extensive process data and assumptions, as demonstrated by Guo, Zhang, Zhao, et al. (2024);

(2) The Emission Factor Method calculates carbon emissions per unit of product or service by multiplying activity data of emission sources by corresponding emission factors. This approach is more practical and widely applicable, as illustrated by Bertolini, Duttilo, and Lisi (2025) and supported by the Greenhouse Gas Institute (2022).

Given the limited availability of measured data from prefabricated component factories, this study ultimately adopts the emission factor method for carbon accounting. To clearly illustrate the application process and data flow of this method, Figure 6 presents the carbon emission calculation framework developed for this research, detailing the decision logic, core data sources, and key computational steps.

The acquisition of core data integrates multiple approaches: on the one hand, through interviews with 14 experts in the field of prefabrication engineering (see Table 4); on the other hand, through long-term field investigations, extended observations, and comprehensive literature review of prefabricated building factories. These combined efforts yielded the key carbon emission factors required for calculation. It should be noted that all emission factors used in this study were obtained from the Carbon Footprint Information Platform in Taiwan, ensuring the consistency and reliability of the data.

Table 4. Overview of Interviewed Experts in Prefabrication Engineering

No.	Department	Position	Expertise	Years of Experience in Prefabrication Engineering
1	General Manager's Office	Senior General Manager	Prefabrication planning, production, and construction management	30

2	Prefabrication Project Department	Senior Deputy General Manager	Prefabrication design planning, production, and construction management	28
3	Prefabrication Project Department	Production Manager	Prefabrication production and construction management	12
4	Prefabrication Production Department	Senior Deputy General Manager	Prefabrication planning and production management	27
5	Prefabrication Production Department	Senior Associate Manager	Prefabrication production planning, manufacturing, and management	25
6	Prefabrication Production Department	Senior Associate Manager	Prefabrication planning and production management	24
7	Prefabrication Production Department	Senior Associate Manager	Prefabrication planning and production management	24
8	Prefabrication R&D Department	Deputy General Manager	Prefabrication system design planning, technological innovation, R&D, and improvement	17
9	Prefabrication R&D Department	Associate Manager	Technological innovation, R&D, and improvement of prefabrication systems	11
10	Prefabrication R&D Department	Assistant Manager	Innovation and R&D in prefabrication system design planning	7
11	Prefabrication Design Department	Senior Associate Manager	Prefabrication design planning	27
12	Prefabrication Design Department	Senior Manager	Prefabrication design planning	24
13	Prefabrication Design Department	Deputy General Manager	Prefabrication design planning, production, and construction management	17
14	Prefabrication Design Department	Deputy General Manager	Prefabrication design planning and production management	17

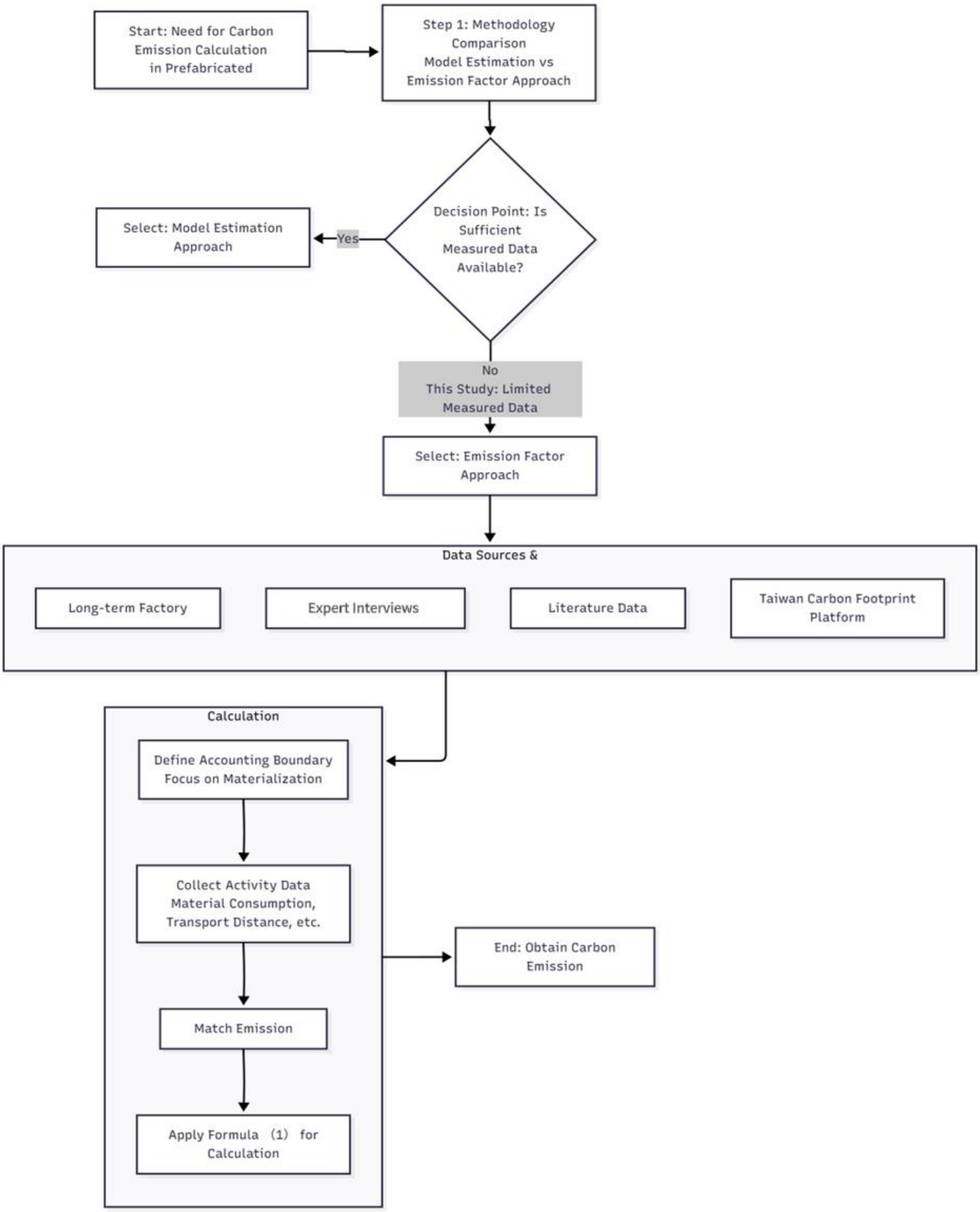


Figure 6. Flowchart for Selection and Execution of Carbon Emission Calculation Methods

3.3 Classification of Emission Types and Formulas

Life Cycle Assessment (LCA) serves as a fundamental methodology for evaluating the environmental impacts of buildings throughout their entire life cycle, spanning from raw material extraction, production, and transportation to operation and demolition. The general LCA calculation formula is given as follows:

$$GHG = AD \times EF \tag{1}$$

Where GHG represents greenhouse gases, AD denotes activity data, and EF refers to the emission factor.
Based on this methodological framework and relevant data sources, it is essential to clarify the specific classification of emission types and the corresponding computational logic. To enable systematic quantification, this study further refines the emission boundaries within the embodied phase of prefabricated buildings and develops detailed calculation formulas for each sub-stage.
The building life cycle is generally divided into three main phases: the embodied phase, operational phase, and demolition phase. As this study focuses on the production of prefabricated components, only carbon emissions associated with the embodied phase are considered. Within this phase, LCA is employed to validate emission results and identify key high-emission processes—notably cement and steel production, as noted by Xu, Zhu, and Wang (2024). Early applications, including Swedish residential case studies (Jönsson, Tillman, & Svensson, 1997) and the WRI hybrid input–output model (Onat, Kucukvar, & Tatari, 2014), have demonstrated the feasibility and robustness of LCA in carbon accounting.
The integration of the LCA framework with the emission factor method not only improves the accuracy and comparability of results but also provides a solid scientific basis for formulating targeted carbon reduction strategies. The embodied phase emissions are further subdivided into three sub-stages, as shown in Formula (2):

$$C_z = C_{y1} + C_{y2} + C_{y3} \tag{2}$$

Where:

Cy1 represents emissions from the component production phase;

Cy2 represents emissions from the transportation and storage phase;

Cy3 represents emissions from the on-site hoisting phase.

The detailed calculation of carbon emissions for each stage follows Formulas (3–5), encompassing materials, energy, transportation, and labor activities, ensuring that both process-related and activity-related emissions are included.

$$\mathbf{C_{y1}} = \sum_{i=0}^{n} (\mathbf{Mi} \times \mathbf{Fi}) \tag{3}$$

Where Mi represents the consumption of material i, and Fi denotes the carbon emission factor of material i (kg CO_2 per unit of material consumed).

$$C_{y2} = (D_h \times E_t \times EF_t \times T) + (E_{ml} \times t_1 \times EF_t) \tag{4}$$

Where Dh represents the transportation distance (km); EFt is the diesel consumption of the truck per unit distance (L/km); (EF_t) is the carbon emission factor of diesel (kg CO_2/L); Em_1 is the diesel consumption of the crane per unit time (L/h); and t1 is the hoisting time (h).

$$C_{y3} = (E_{m2} \times t_2 \times EF_e) + (E_{m3} \times t_3 \times EF_t) + \sum_{i=0}^{n} (Q_r \times F_r) \tag{5}$$

Where r represents the labor-related carbon emissions during the construction phase; Qr denotes the number of labor workdays; Fr is the labor carbon emission factor (kg CO_2/workday); Em_2 and Em_3 represent the electricity consumption of the tower crane and the diesel consumption of the crane per unit time, respectively; t_2 and t_3 refer to their corresponding operating times (h); EFe is the carbon emission factor of electricity; and EFt is the carbon emission factor of diesel.

To ensure transparency and consistency in the carbon emission estimation process, this study divides the materialization phase into three sub-stages: component production (Cy1), transportation and storage (Cy2), and on-site hoisting (Cy3). Accordingly, Figure 7 illustrates the detailed computational logic and data flow of these sub-stages, clarifying how material consumption, transportation distance, equipment energy use, and labor input collectively contribute to the total embodied carbon emissions.

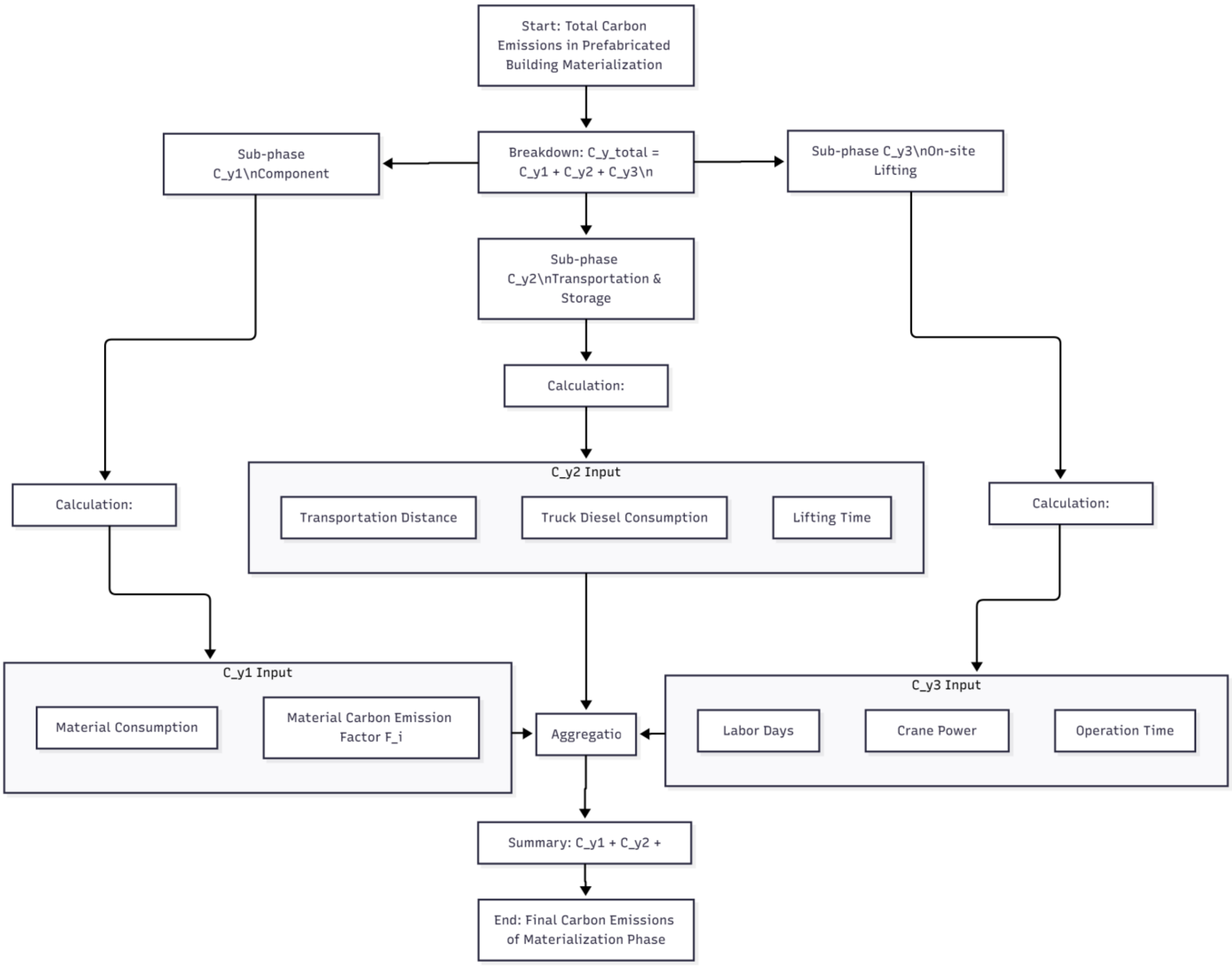


Figure 7. Flowchart for Splitting and Calculation Logic of Carbon Emissions in the Materialization Stage

4. PROJECT ANALYSIS

By adhering to the formatting and content guidelines outlined in the previous sections, contributors can ensure clarity, consistency, and alignment with the journal's editorial standards. The use of defined heading levels, standardized text styles, and appropriate formatting for figures, tables, and equations helps facilitate the peer-review and publication process. Authors are encouraged to consult this template throughout the preparation of their manuscripts to streamline submission and maintain professional presentation.

4.1 Project Information

This study takes the prefabricated component production of a semiconductor factory building in Taiwan as a case study. The project consists of an above-ground structure with a site area of 24,026 m² and a total floor area of 41,411.72 m². The structural system comprises 461 prefabricated columns, 302 wall panels, 725 large beams, and 842 small beams, achieving a prefabrication rate of 83%. The primary material used for the components is reinforced concrete.The total construction period lasted 215 days, with the hoisting stage accounting for approximately 148 days. The total number of worker attendances was 52,807, while engineer attendances reached 7,686. The transportation distance from the prefabrication plant to the construction site was 242 km. Based on data collection and analysis, the activity data for the prefabricated components are summarized in Table 5.

Table 5. Production Activity Data of Prefabricated Structural Components

Component Unit	Column	Large Beam	Small Beam	Wall Pane
Quantity (pieces)	461	725	842	302
Number of Steel Molds (sets)	11	16	18	5
Production Attendances (person-times)	1126	1198	977	1002
Total Production Hours (h)	17927	19520	16407	17915
Construction Period (days)	92	92	102	106

4.2 Basic Emission Data of the Case Study

This study applied the Life Cycle Assessment (LCA) approach and used formulas (1) to (5) to calculate the carbon emissions associated with the prefabricated components throughout the life cycle of a semiconductor plant located in Tainan.

(1) Prefabricated Component Production Stage

At this stage, formula 3 was applied to process the relevant data, and the results are shown in Table 6.

Table 6. Carbon Emission Data during the Production Stage of Prefabricated Components

Material	Consumption	Emission Factor	Carbon Emissions
Concrete	7709786kg	1.40 kgCO2e/kg	10793700
Rebar	275349.5kg	0.83 kgCO2e/kg	2285400
Electricity	2500000kwh	0.59 kgCO2e/kWh	1475000
Formwork Steel	1000kg	0.83 kgCO2e/kg	41500
Labor	4303person-times	6.61 kgCO2/person-times	28443

Note:

Consumption units —kg for materials,kWh for electricity, person-times for labor.

Emission Factor unit — $kgCO_2e$ per corresponding unit.

Carbon Emissions expressed in $kgCO_2e$.

The total carbon emissions at this stage :14,624,043 $kgCO_2e$。At this stage, the production phase accounts for the largest share among the three stages. Specifically, as shown in Figure 8, the production of concrete and steel together contributes approximately 90% of the total carbon emissions, with concrete production alone accounting for about 73.8%. These emissions include both the direct carbon emissions generated during cement production (such as the release of CO_2 from limestone calcination) and the embodied carbon emissions arising from the extraction and transportation of raw materials (e.g., limestone and clay). In addition, the energy consumption throughout the entire production chain of steel reinforcement contributes about 15.6% of the total carbon emissions.

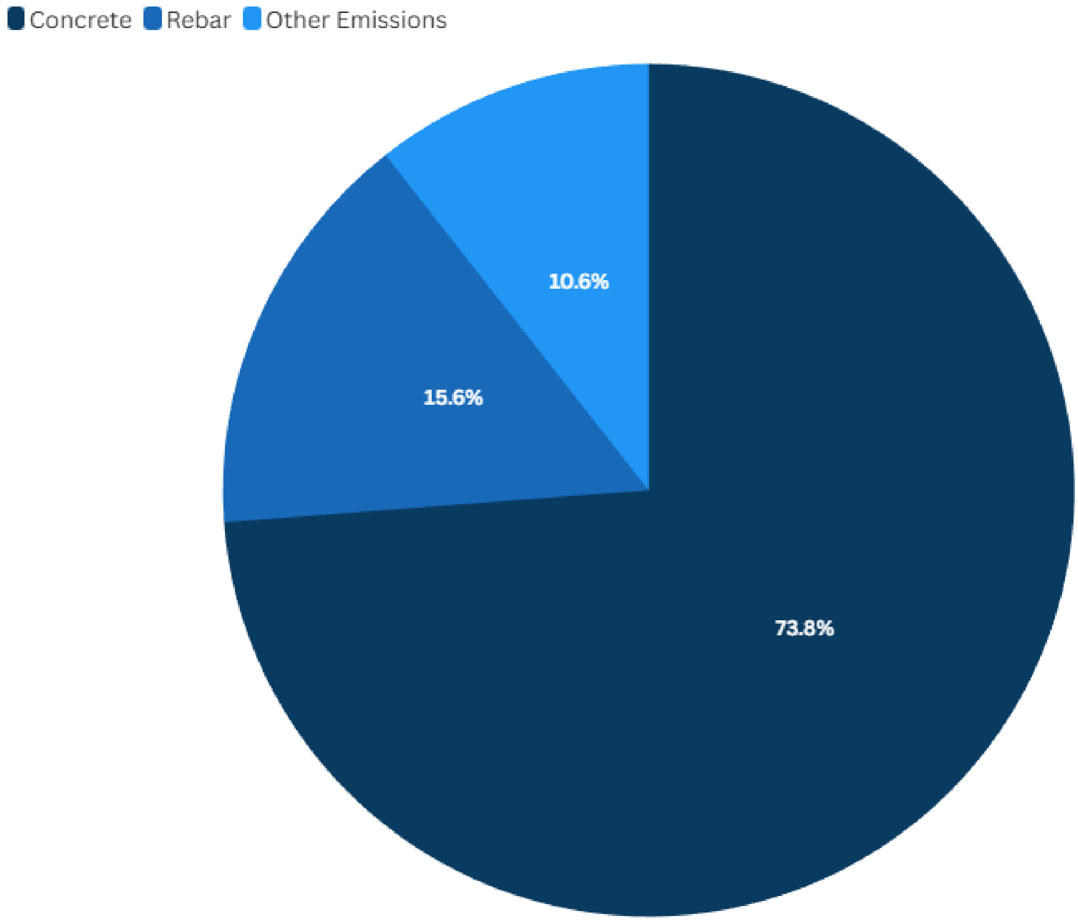


Figure 8. Percentage of the main components of carbon emissions in the prefabricated component production stage

(2) Prefabricated Component Storage and Transportation Stage

In this stage, the corresponding data were processed using Formula (4), and the results are presented in Table 7.

Table 7. Carbon Emission Data during the Storage and Transportation Stage of Prefabricated Components

Material	Consumption (L)	Emission Factor (kgCO2e/L)	Carbon Emissions ($kgCO_2e$)
Diesel for Trucks	162043.2	3.38	547706
Diesel for Cranes	23300	3.38	78754

The total carbon emissions at this stage are:626,460 $kgCO_2e$。

(3) Construction and Hoisting Stage

In this stage, the corresponding data were processed using Formula (5), and the results are presented in Table 8.

Table 8. Carbon Emission Data during the Construction and Installation Stage of Prefabricated Components

Material/Source	Consumption	Emission Factor	Carbon Emissions ($kgCO_2e$)
Tower Crane Electricity	37000	0.59	21830
Crane Diesel	39960	3.38	135065
Labor	60493	6.61	399859

Note:

Consumption units — kWh for electricity, L for diesel, and person-times for labor.

Emission Factor — in $kgCO_2e$ per corresponding unit.

Carbon Emissions — expressed in $kgCO_2e$.

The total carbon emissions at this stage are:556,754 $kgCO_2e$。

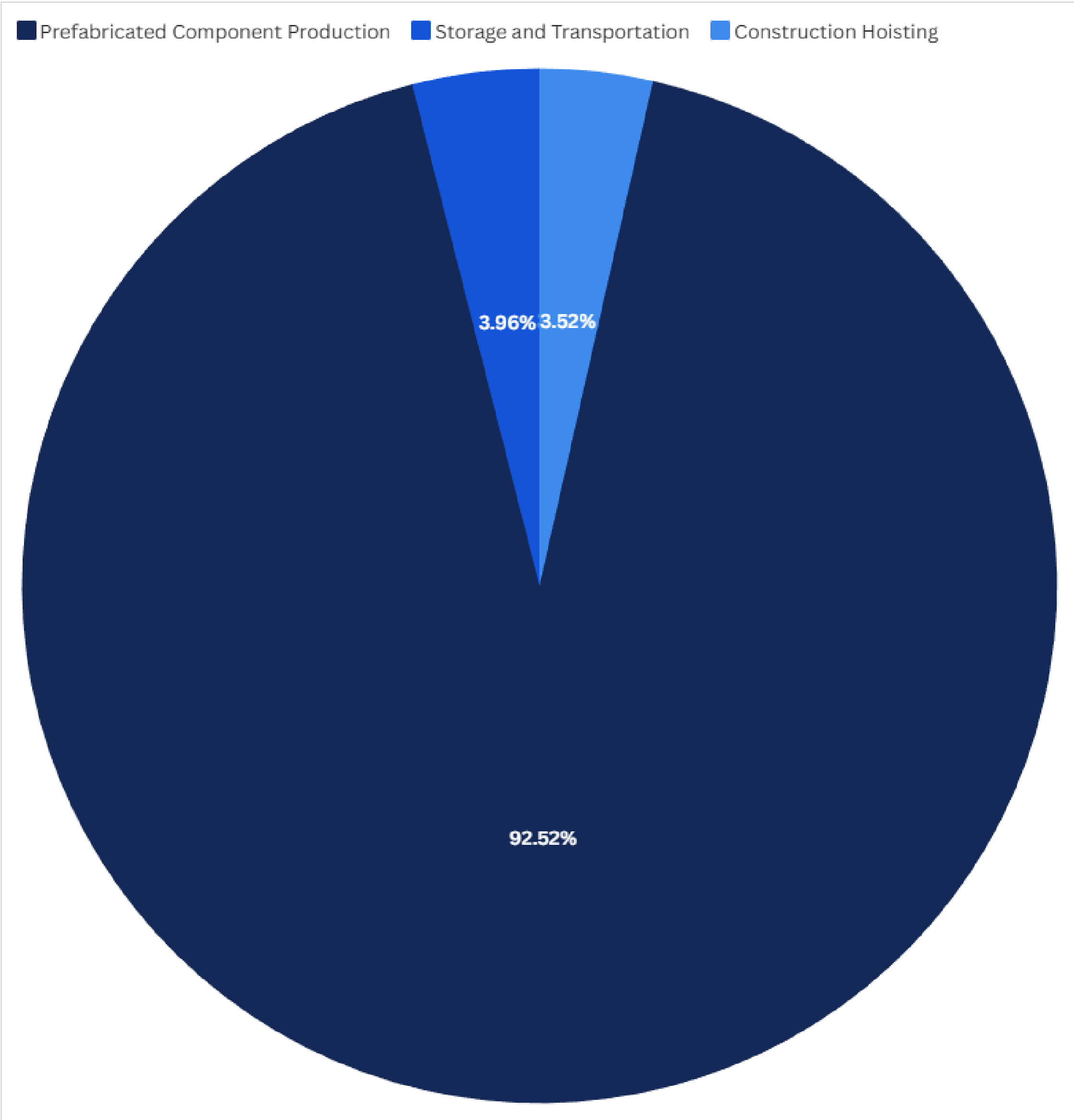
1. 

Figure 9. Percentage of carbon emissions in each construction stage

As shown in the figure 9, the carbon emissions of this project are primarily concentrated in the prefabricated component production stage, which accounts for 92.51% of the total emissions. The transportation and storage stage contributes 3.96%, while the construction and hoisting stage accounts for approximately 3.52%. In summary, the production stage of prefabricated components is identified as the dominant source of overall carbon emissions, representing about 90% of the total. Therefore, this stage will be the core focus of subsequent analysis, where multi-path strategies toward carbon neutrality will be explored in depth.

4.3 Study on Carbon Reduction Outcomes in Prefabricated Building Component Production

Given that the production stage constitutes the largest share of total life-cycle carbon emissions, optimizing production processes is considered a pivotal strategy for carbon reduction. In the production of prefabricated components, key processes—besides steel reinforcement binding—include mold fabrication, concrete casting, steam curing, demolding, and equipment operation. According to carbon emission coefficient data from one project, the production stage contributes approximately 92.58% of total emissions. Among these processes, mold fabrication (involving steel processing) generates about 100,000 kg CO_2e, steam curing of concrete accounts for roughly 25% of total electricity consumption, and the prolonged operation of equipment such as overhead cranes and bending machines leads to electricity-related emissions of approximately 1,272,500 kg CO_2e. Further analysis indicates that traditional prefabricated concrete production faces several challenges, including low mold utilization rates, dependence on fossil fuels for curing heat, and limited energy efficiency of production equipment.

From the perspective of mold fabrication, increasing the mold reuse rate can significantly reduce carbon emissions during production. In addition to reuse strategies, material substitution offers another viable pathway for emission reduction. As illustrated in Figure 10, replacing conventional steel molds (density = 7.8 g/cm^3) with aluminum alloy molds (density = 2.7 g/cm^3) can substantially lower the embodied carbon. The implementation of such lightweight aluminum molds—which are 65% lighter and have an emission factor of 0.8 kg CO_2e/kg—reduces the unit carbon emissions to about 14,000 kg CO_2e, compared to 100,000 kg CO_2e for steel formwork. For non-standard components, the use of 3D-printed custom connectors further curtails steel consumption by 18%. These findings are consistent with previous research by Armstrong et al. (2023).

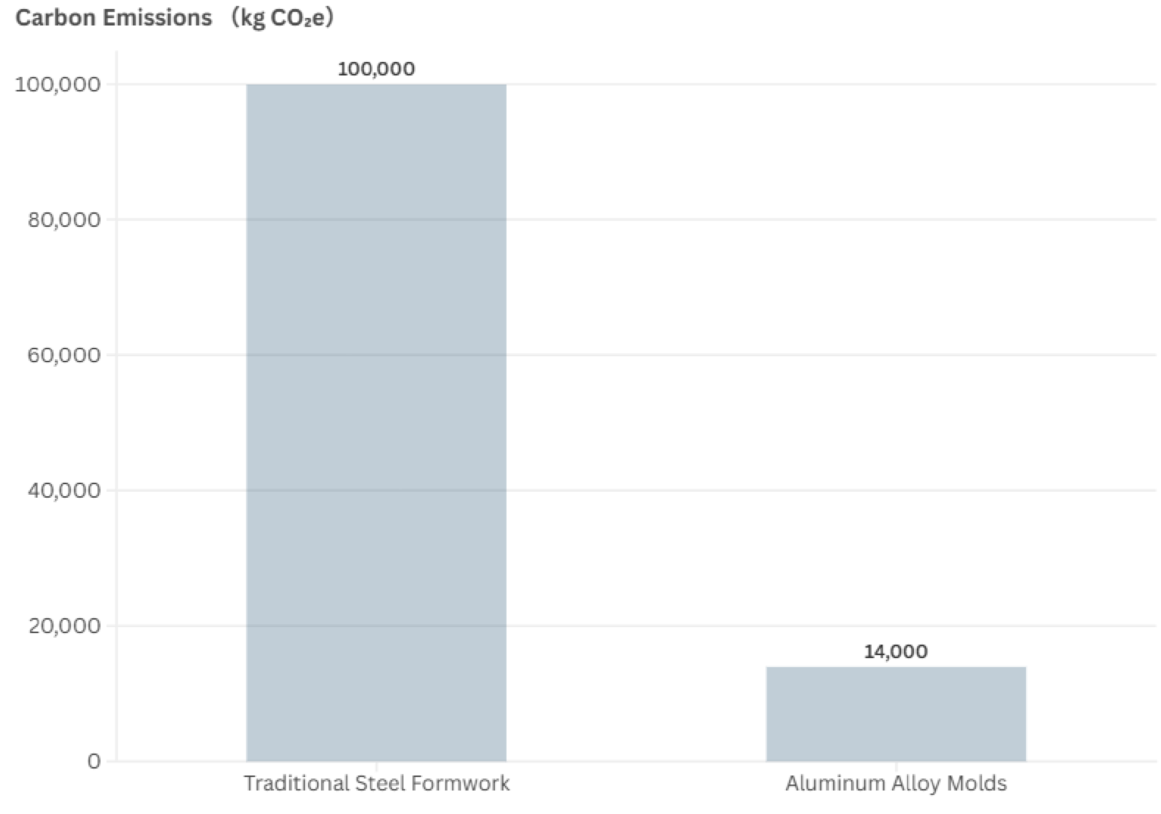


Figure 10. Carbon Emissions per Unit of Different Molds

In addition, the application of CO_2 mineralization curing technology, which injects captured CO_2 to react with cement hydration products and form calcium carbonate, can shorten the curing cycle by approximately 20% and sequester about 50 kg CO_2 per cubic meter of concrete.Through the integration of these optimization measures, the overall energy performance of prefabricated component production is markedly improved. Specifically, insulated formworks reduce heat loss by over

30%; standardized mold design decreases idle equipment energy use by 20%; photovoltaic-assisted curing replaces up to 80% of conventional energy inputs; and waste heat recovery systems can recover and reuse nearly 50% of waste heat.
According to calculations, these combined measures lead to a 26% reduction in total energy consumption and a corresponding 22% decline in carbon emissions. This gap between energy and carbon reduction reflects the current carbon intensity of the regional electricity mix. Collectively, these improvements lay the groundwork for subsequent carbon-neutral strategies in prefabricated construction.

4.4 Carbon Neutrality Outcomes

After implementing the above measures, full-process carbon accounting for prefabricated component production indicates that concrete and steel remain the dominant carbon sources, together accounting for 82.7% of total emissions. Specifically, the C35 concrete used in this project produced 10,794 tCO_2e, while steel contributed 2,285 tCO_2e.To address these high-impact sources, low-carbon cement substitution can reduce concrete-related emissions by 67%; lightweight and recyclable mold design can cut mold-related emissions by 72%; and photovoltaic direct-supply systems combined with smart variable-frequency equipment can lower production electricity emissions by 35%.When further supplemented by forestry carbon sinks (30–50 CNY/t CO_2) and distributed photovoltaic projects (annual reduction of about 305 t CO_2 per plant), the total corporate emission reduction can reach 19%, achieving an integrated low-carbon goal that combines production-phase mitigation with broader carbon neutrality objectives.

5.CONCLUSIONS AND RECOMMENDATIONS

This study examines the carbon emission characteristics of prefabricated construction methods, with analysis based on actual project data from a semiconductor facility in Taiwan. By applying the Life Cycle Assessment (LCA) methodology and carbon emission factor approach, a comprehensive carbon footprint evaluation was conducted for the prefabricated building system. The study further proposes targeted carbon neutrality measures and quantifies their potential effects. The key findings and recommendations are summarized as follows:

5.1 Research Conclusions

This study conducted a comprehensive assessment of carbon emissions generated during the production of prefabricated components for a semiconductor facility. The results reveal that concrete and steel are the dominant contributors, together accounting for approximately 82.7% of total emissions—specifically, 10,794 tCO_2e from C35 concrete and 2,285 tCO_2e from steel. Through the implementation of integrated optimization measures, significant emission reductions were achieved. The substitution of low-carbon cement reduced concrete-related emissions by up to 67%, while the adoption of lightweight recyclable molds lowered mold-associated emissions by 72%. Furthermore, the combination of photovoltaic direct-supply systems and smart variable-frequency equipment decreased electricity-related emissions by 35%.
In addition to emission mitigation, CO_2 mineralization curing demonstrated the potential to sequester 20–50 kg CO_2 per m^3 of concrete. When coupled with forestry carbon sinks (30–50 CNY/t CO_2) and distributed photovoltaic projects achieving annual reductions of about 305 t CO_2 per plant, the overall corporate emission reduction potential reached approximately 19%. Collectively, these results highlight a clear and practical pathway toward low-carbon and carbon-neutral prefabricated construction, providing both technical evidence and methodological guidance for the green transformation of the building industry. Methodologically, this study extends the application of LCA from comparative assessment toward actionable, production-oriented carbon neutrality pathways.

5.2 Practical Recommendations

(1) Focus on carbon reduction in the production stage and optimize factory-level carbon management systems
The study shows that carbon emissions in prefabricated buildings are mainly concentrated in the production phase of prefabricated components, accounting for the vast majority of total emissions. This characteristic indicates that future carbon reduction efforts should prioritize energy management and material substitution at the factory level.It is recommended to establish a comprehensive carbon emission monitoring and management system in prefabrication factories, implement sub-metering of energy consumption and emission tracing, and promote the adoption of clean energy and energy recovery systems. At the same time, digital manufacturing and intelligent scheduling technologies can be used to optimize energy efficiency in production processes and enable dynamic carbon control, achieving structural emission reductions at the source.
(2) Strengthen the comprehensive implementation of carbon neutrality measures and build a multi-level emission reduction system. The strategies proposed in this study—optimization of raw material selection, production process optimization, and carbon sink compensation mechanisms—have all demonstrated significant emission reduction potential in practice. In the future, these technologies should be systematically integrated to establish a multi-level reduction framework, spanning technical emission reduction, energy substitution, and carbon compensation. For example, within factories, energy linkage between photovoltaic power generation and curing systems can be implemented, while at the regional level, building carbon sink projects and industrial symbiosis mechanisms can be introduced, forming a carbon circulation loop from local to overall scales, potentially achieving negative emissions.
(3) Deepen the application of Life Cycle Assessment (LCA) and expand a multidimensional research framework. Future studies should further extend the depth and breadth of LCA, moving from single-project evaluations to multi-scale, cross-phase comprehensive analyses. The production, construction, operation, and demolition stages of building components should be incorporated into a unified carbon accounting framework, establishing a dynamically updated building lifecycle database to achieve quantitative and traceable carbon footprint management. Moreover, the introduction of LCA helps build a highly comparable and traceable carbon accounting system, providing data support for establishing carbon emission benchmarks, evaluating low-carbon technologies, and informing policy decisions. Promoting this approach will drive the construction industry from isolated emission reduction efforts toward systematic reduction, enabling prefabricated buildings to achieve higher levels of low-carbon transformation and sustainable development from a lifecycle perspective.

5.3 Future Research Directions

This study focuses solely on the full-lifecycle carbon emissions and carbon neutrality of a single case. Future research can be deepened in the following directions:
Firstly, more innovative strategies should be implemented at the production level to facilitate emission reduction and achieve carbon neutrality. Concurrently, given that carbon capture technologies are still in the exploratory stage and currently incur high costs (approximately USD 50 – 100 per ton), it is imperative to strengthen techno-economic assessments. In addition, as this study is based solely on a single semiconductor manufacturing project, future research should extend to other industrial sectors and incorporate a wider variety of project types and scales. The methodology for conducting detailed full life cycle assessments also requires further refinement. From a global perspective, the integration of cast-in-place and prefabricated construction methods—tailored to diverse on-site conditions—holds significant potential to broaden the application and advance the development of low-carbon building practices.

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APPENDIX A. SAMPLE APPENDIX

Authors may include supplementary material in an appendix following the references section. Each appendix should be labeled sequentially using capital letters (Appendix A, Appendix B, etc.). The formatting and font styles should remain consistent with the rest of the manuscript.

A.1 Example of a Subsection Heading

Authors may include subsections in the appendix to organize supporting tables, methods, or background content.