

REPORT FOR SCIENTIFIC AND TECHNOLOGICAL RESEARCH PROJECTS

Research on Life Cycle Carbon Emission Calculation



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Content

ABSTRACT	1		
1. Introduction	2		
1.1 Background	2		
1.2 Chinese and International Research Review	3		
1.3 Challenges	9		
2. Detailed calculation method of building carbon emission IN CHINA	11		
2.1 Confirmation of system boundary	11		
2.2 Basic calculation method	13		
3. Research on the Bee Museum Project	16		
3.1 Background and significance of the project	16		
3.2 Project Overview	17		
3.3 Purpose and tools of analysis	18		
3.4 Life cycle assessment methodology	18		
3.5 Data sources and selection principles	19		
3.6 Life cycle analysis results	20		
3.7 Process cumulative contribution analysis	27		
3.8 Bee Museum Project Summary and Recommendations	28		
4. Technical analysis of the Bee Museum	30		
4.1 Main technical measures of the project	30		
4.2 Specific technical analysis	31		
5. Analysis of carbon emission calculation methods IN Europe	40		
5.1 Current status of research on calculating carbon emissions for buildings in Europe	40		
5.2 comparative analysis	42		
6. Analysis of Improvement Potential in Building Carbon Emission Calculation Methodologies	47		
6.1 Deepening the accurate calculation analysis of carbon emission calculations for buildings at different phases of the process	47		
6.2 Expansion of digitalisation and information technology applications	47		
6.3 Integrated platform for carbon emission accounting, evaluation and optimization	48		
A1. Reference	49		
A2. Glossary	50		

ABSTRACT

In the contemporary era, global climate change has become a pressing challenge that demands a coordinated response from the international community. To impede the ongoing degradation of the climate, it is imperative that the international community promptly implements measures aimed at reducing greenhouse gas emissions. In September 2020, China proposed a "dual-carbon" strategic goal to achieve "carbon peaking" by 2030 and "carbon neutrality" by 2060 (referred to as the "30-60 dual-carbon" goal), while concurrently strengthening its efforts to reduce greenhouse gas (GHG) emissions. The "30-60 Dual Carbon" objective aims to attain "carbon peaking" by the year 2030 and "carbon neutrality" by the year 2060 (referred to as the "30-60 Dual Carbon" objective). Concurrently, the strategy emphasises the enhancement of collaborative efforts with other nations and the proactive promotion of implementing the global dual carbon strategy. This strategy aims to protect the global environment, reduce dependence on finite resources, and create favourable conditions for sustainable development in the future.

In China, the operation phase of buildings is responsible for up to 22% of the country's total carbon emissions. Consequently, the effective implementation of energy-saving and emission-reduction measures in the building sector is of paramount importance for China to achieve its dual-carbon strategy. Concurrently, given its status as a primary contributor to global carbon emissions, the investigation of carbon emissions throughout the entire life cycle of the building sector is imperative for the advancement of low-carbon buildings and the realization of the objective of green buildings.

This study will provide an exhaustive analysis of building life cycle carbon emissions in China, with a focus on policy standards, calculation methods, and

challenges, as well as an in-depth comparative study of practices in Europe and Switzerland. The study encompasses the compilation and examination of prevailing policies and standards, calculation methodologies employed in China, and a succinct overview of the prevailing challenges in the domain of calculating carbon emissions from buildings in China. The study incorporates a case study of the Shaanxi Demonstration Project, which exemplifies the implementation of the research methodology by decomposing the calculation process and encapsulating the Swiss side's recommendations for enhancing the project. The study's findings reveal an exploration of European and Swiss practices in building carbon calculations. It also engages in ongoing exchanges with the relevant Swiss team and utilizes comparative analysis to assess the carbon reduction potential of the Shaanxi demonstration project and the direction of improvement in China's carbon calculation methodology.

The primary findings of the study highlight the disparities in assessing life cycle carbon emissions from buildings between China and other regions, particularly Switzerland. The study also incorporates Switzerland's Experience and technology to improve the accuracy of carbon emissions estimation throughout the entire life cycle of buildings. Additionally, it suggests expanding the use of digital technologies. This approach aims to enhance the calculation methods for life cycle carbon emissions in China. It is expected that this study will provide valuable references for future related research efforts.

1. INTRODUCTION

1.1 Background

In light of the escalating crisis of frequent extreme weather events on a global scale, carbon neutrality has emerged as a pivotal strategy to achieve global climate objectives. These objectives, as outlined in the Paris Agreement, include the ambitious target of maintaining the increase in global average temperature to within 2°C and striving for 1.5°C, if feasible. In the context of the global effort to combat climate change, governments, international organizations, and enterprises have been instrumental in formulating relevant policies and making commitments. It is imperative to acknowledge that China's recent entry into the arena of carbon emission calculations, in comparison to the established practices in the European region. Nevertheless, it is important to acknowledge the Chinese government's ongoing commitment to promoting carbon emission reduction in China through various initiatives and directives. In the subsequent section, we will expound upon the specific measures implemented by the Chinese government to curtail carbon emissions from buildings, with a particular focus on national guidelines and standards at the national, local, and group levels.

Initially, in 2009, the Chinese government established an explicit objective of reducing greenhouse gas emissions by 2020. The introduction of this target marked the commencement of China's escalated endeavors to confront the issue of climate change and its pledge to advocate for green and low-carbon development. In 2021, the Chinese government put forward the "30-60 Dual Carbon" goal, further emphasizing the importance of reducing greenhouse gas emissions, and striving to achieve carbon peaking by 2030 and carbon neutrality by 2060. The setting of this goal provides a clear time node and task requirements for carbon reduction in building carbon emissions.

It is worth noting that in 2009, China established a target of reducing carbon dioxide emissions per unit of GDP by a minimum of 40 to 45 % by 2020 compared with 2005. In the subsequent development, the target was further elevated, with the objective being to reduce CO₂ emissions per unit of GDP by 60% to 65% by 2030 compared to 2005. This enhancement is indicative of China's commitment and initiatives to reduce carbon emissions. Furthermore, it establishes elevated standards and requirements for carbon emission reduction in the building sector. Achieving the "30-60 Dual Carbon" objective necessitates the implementation of more robust policies and measures by China to encourage the transformation of the construction industry into a green and low-carbon direction. Consequently, the calculation of carbon emissions over the entire life cycle of a building becomes imperative. This is necessary not only to facilitate a more profound comprehension and control of carbon emissions, but also to provide data support for policy development and technological innovation.

The calculation of building carbon emissions is predicated on a comprehensive analysis of the design process, encompassing the excavation of the interaction mechanism of space type, building components, and the natural environment. This analysis entails a thorough examination of the composition of the building and various facilities, facilitating the reduction of energy consumption and carbon emissions from the source. Consequently, the construction of low-carbon space enables the creation of a low-carbon building. Secondly, the calculation of carbon emissions serves as a quantitative metric for assessing the efficacy of low-carbon construction technologies. The refinement of the calculation method for building carbon emissions enables the quantitative analysis of the entire life cycle emissions of a building. Consequently, this facilitates the evaluation of the effectiveness of various low-carbon technologies in reducing carbon emissions. It is imperative to acknowledge the significance of carbon emission calculation in the context of the

construction industry's entry into the carbon trading market. The construction carbon emission, serving as the fundamental basis and constraint value in accounting, directly influences the representativeness and comparability of accounting results. Consequently, the definition of the boundary for calculating carbon emissions in the construction field and the accounting of construction carbon emissions data are the primary concerns in construction carbon trading.

Given the significance and intricacy of calculating carbon emissions from buildings, a series of policies and standards have been implemented in China to reduce carbon emissions from buildings. These include the encouragement of the construction industry to adopt new technologies, materials, and processes to reduce the intensity of carbon emissions. It has also ensured that carbon emissions from the construction industry are effectively controlled by increasing supervision and enforcement. Furthermore, it promotes synergistic development between the construction industry and other industries to collectively construct a green and low-carbon industrial system. These measures have been demonstrated to enhance the overall energy efficiency and environmental performance of the construction industry. Furthermore, these measures provide substantial support for the realisation of China's carbon peaking and carbon neutrality goals.

In summary, the Chinese government has exhibited a resolute and long-term commitment to carbon reduction. The lucidity of these objectives and aspirations not only delineates a course for the mitigation of carbon emissions from the construction sector, but also furnishes a substantial impetus to China's green and low-carbon development. In the future, it is expected that the construction industry will continue to make progress and contribute to the carbon neutrality goal under the guidance of national policies.

1.2 Chinese and International Research Review

1.2.1 Chinese and International Relevant Policies and Standards

■ International Policy Standards

In 1998, the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), in collaboration with governments, businesses, and environmental organizations worldwide, jointly initiated the Greenhouse Gas Protocol (GHG Protocol) to establish a credible and efficient framework for carbon footprint accounting. The current version of the GHG Protocol, released in 2009, consists of four independent yet interrelated standards: the Corporate Accounting and Reporting Standard, the Corporate Value Chain (Scope 3) Accounting and Reporting Standard, the Product Life Cycle Accounting and Reporting Standard, and the Project Quantification Methodology. Among them, the Product Life Cycle Accounting and Reporting Standard focuses on individual products of enterprises to account for the greenhouse gas emissions throughout the product life cycle, identifying the best mitigation opportunities in the life cycle of the selected product. Since its release in 2009, this version has been widely adopted internationally and has played an important role in promoting the development of international carbon accounting and carbon reduction.

In 2008, the Specification for the Assessment of Greenhouse Gas Emissions for Goods and Services over Their Life Cycle (PAS 2050), compiled by the British Standards Institution, was officially promulgated, marking the birth of the world's first product carbon footprint standard. Based on life cycle assessment theory, PAS 2050 provides specific and clear methods for carbon footprint calculation and offers two evaluation schemes: "cradle-to-gate" (B2B) and "cradle-to-grave" (B2C).

In 2013, using PAS2050 as a reference, the International Organization for Standardization's Products Carbon Footprint (ISO 14067) was released, aiming to provide a standardized methodology for quantifying the carbon footprint of products and services at all phases of the life cycle, and to improve the generalizability and comparability of the results of the calculations. Both ISO 14067 and ISO 14044 standards indicate that the system boundary determines which unit processes should be included in the study and affects the level of detail of the results, so the system boundary should be limited to the number of unit processes and the level of detail. ISO 14067 and ISO 14044 both point out that the system boundary determines which unit processes should be included in the study and also influences the level of detail of the quantification of the results, so the limitation of the system boundary should be limited to the number of unit processes and the level of detail.

In addition to the above standards, international standards include the ISO 21930 series of standards, of which ISO 21931 provides a generic framework for assessing the environmental, social and economic characteristics, aspects and impacts of new or existing buildings on the design of the building, the production, construction, operation, maintenance and refurbishment of building products, materials and components, and end-of-life processes. The main change in the second edition (ISO 21931-1:2022) compared to the first edition (ISO 21931-1:2010) is the broadening of the scope from a methodological framework for assessing only the environmental performance to include methods for assessing the economic and social performance of the building work as an overall basis for sustainability assessment.

Similarly, in the EU, there is EN 15978, which provides a comprehensive framework for calculating and assessing the carbon emissions of a building throughout its life cycle. This includes the use phase of the building as well as the production of building materials, the construction of the building, maintenance renewals and ultimately, the demolition and reuse of materials. By following this standard, architects and engineers can design buildings that are more energy efficient and have a lower environmental impact.

Earlier than the exploration of the EU framework system, Switzerland has established a local standard system for building energy efficiency and carbon emission management since the 1990s, providing practical references for the subsequent EU whole life cycle assessment framework. Take the Minergie standard as an example. This standard specifies advanced building energy efficiency indicators, maximizes the use of renewable energy generated by the building itself, and emphasizes the health and comfort of buildings, which has gained wide market recognition in Switzerland and surrounding countries.¹ In addition, since 1998, the Swiss Federal Office of Energy has been working with the cantons to promote the SIA building code (standard SIA 380/1) and the Minergie labelling series. The SIA 380 standard has been updated several times, most recently in 2016. In terms of calculating carbon emissions from buildings, Switzerland, as an EU country, follows both the ISO standard and its own SIA series of standards, which will be analysed in Chapter 5.

▪ Chinese policy standards

As a large developing economy, China has significant energy consumption and carbon emissions in the construction industry. Achieving energy conservation and emission reduction in construction plays a crucial role in the low-carbon development of China's economy. The main relevant standards in China are as

¹ Source: the news *Memorandum of Understanding between Switzerland and China in the Field of Building*

Energy Efficiency on the official website of the Swiss Embassy

follows.

The Assessment Standard for Greening Building (GB/T 50378-2006) was promulgated and implemented in 2006, and has been revised in 2014, 2019 and 2024. This standard was developed through extensive investigation and research, careful summation of practical experience, reference to relevant international standards, and multiple revisions following broad consultation, ultimately forming a technical index system for green building evaluation tailored to China's national conditions.

In December 2019, the Standard For Building Carbon Emission Calculation (GB/T51366-2019) was formally implemented, which was compiled by the China Academy of Building Research Ltd. and the China Academy of Building Standard Design and Research Institute Co. Ltd. as the chief editorial unit, is the first national standard for calculating carbon emissions from buildings in China. The standard compilation team conducted extensive investigation and research, carefully summarized practical experience, and compiled based on extensive consultation. The content emphasizes the composition of activity data and carbon emission calculation methods and stipulates the carbon emission calculation for three parts of the building operation phase, construction and demolition phase, and building materials production and transportation phase. For the calculation of carbon emissions from buildings, the standard carbon emission factor is defined as “a coefficient that corresponds energy and material consumption to carbon dioxide emissions and is used to quantify the emissions of relevant activities at different phases of a building”.

Considering the demand for carbon emission factors for different types of building carbon emission activities at different phases, the appendices of the Standard for

Calculation of Carbon Emission (GB/T 51366-2019) give the carbon emission factors for major energy sources building materials, and transportation of building materials, as well as the operating characteristics of buildings and the data on the energy consumption of commonly used construction machinery shifts as the main basis for the calculation of carbon emission from buildings.

The General Specification for Building Energy Efficiency and Renewable Energy Utilization (GB 55015-2021), which came into effect on April 1, 2022, is mandatory in the field of building energy efficiency and renewable energy utilization. The standard emphasizes that projects should do carbon emission analysis and that new, expanded and reconstructed buildings, as well as energy-saving renovation of existing buildings, should be designed for building energy efficiency.

As for the level of local and group standards, various regions are now actively exploring and working to build a building carbon emission standard system that meets their characteristics. The purpose of this initiative is not only to refine and improve the effectiveness of the implementation of national standards but also to take into full consideration regional differences, such as climatic conditions, the supply of building materials, the level of economic development and other factors, to formulate carbon emission control requirements that are more in line with the actual situation of the local community. Through the establishment of local standards, the local construction industry can be more effectively guided to transform into a low-carbon, environmentally friendly direction, promote the popularization and development of green buildings, and contribute to the regional efforts to achieve the goal of carbon neutrality. The following table shows the work of some regions.

Regions	Standards
Beijing	《Design Standard for Ultra-Low Energy Residential Buildings》 (DB11/T 1665-2019)
Shandong Province	《Guide for design and construction of prefabricated steel structure residence》 (JD37-002-2023)
Guangdong Province	《Guidelines for Calculating Building Carbon Emissions (Trial)》
Sichuan Province	《 Chengdu City Green Building Construction Drawing Design and Review Technical Essentials (2021 Edition)》
Jiangsu Province	《Guidelines for Calculating Carbon Emissions from Civil Buildings in Jiangsu Province》
Shaanxi Province	《Residential Building Life Cycle Carbon Emission Calculation Standard》 (DB61/T 5008-2021)
Hong Kong	《Guidelines for Calculating and Reporting Greenhouse Gas Emissions and Reductions for Buildings in Hong Kong (Commercial, Residential, or Public Use)》

Table 1-1 Carbon emission standards for buildings in some regions. Source: Xi'an University of Architecture and Technology

In addition to the support and coordination of local governments at all levels in calculating carbon emissions, many groups and organizations are also actively developing standards for calculating carbon emissions in buildings. These organizations include industry associations, environmental protection organizations, scientific research institutes, etc., which play an important role in promoting the standardization of carbon emission calculation. Industry associations provide specific implementation standards for building carbon emission calculations through the formulation of industry regulations and

guidelines. Through advocacy and publicity, environmental organizations have raised public awareness of building carbon emissions issues and promoted the development and implementation of relevant standards. Through in-depth research, scientific research organizations have provided scientific evidence and technical support to ensure the accuracy and reliability of building carbon emission calculations. The combined efforts of these groups and organizations have resulted in better standards for building carbon emission calculations, providing strong support for achieving carbon emission reduction targets.

For example, the China Association of Construction Supervisors has developed the Code for Quality Acceptance of Construction of Building Energy Conservation Projects (JGJ/T 246-2011), which specifies the quality acceptance standards for the construction of building energy conservation projects and addresses the impact of the construction process on carbon emissions. In addition, the Technical Guidelines for Low-Carbon Buildings (JGJ/Z 73-2012) elaborates on the technical aspects of low-carbon building design and implementation, with a special focus on strategies to reduce carbon emissions from buildings. The China Engineering Construction Standardization Association promulgated the Standard for Statistics and Analysis of Building Carbon Emission Data (CECS 374:2014), which provides specific methods and requirements for statistics and analysis of building carbon emission data. The Evaluation Standard for Carbon Neutral Buildings (CECS 550:2023), on the other hand, covers the calculation of building carbon emissions, including the calculation methods for building implicit carbon and building operational carbon.2022 In September 2022, the China Urban Science Research Association issued the Quality Requirements for Building Carbon Emission Analysis Reports, a document that provides a detailed exposition of the accounting boundaries and methodologies for building carbon emissions.

1.2.2 Overview of common calculation methods in China and abroad

A review of the current state of research on the calculation of carbon dioxide emissions from buildings in China and foreign countries shows that there is some consensus on the logic and methods of calculating carbon dioxide emissions from buildings in China and other countries. In terms of calculation methods, the carbon emission factor method is more widely used. However, due to the complexity of the construction industry and buildings, the practice of building carbon emission calculation and the technological and management innovation of building carbon emissions reduction also face many problems and shortcomings, which need to be further explored and solved.

According to different research objects and research purposes, the main methods of building carbon emission calculation in buildings and construction industry are: carbon emission factor method, mass balance method and actual measurement method, etc., which are described as follows.

- Carbon emission factor method

The carbon emission factor method calculates the amount of carbon emissions produced by an activity using a defined factor, which in this case is the amount of carbon emissions produced per unit of that activity. The basic principle of the carbon emission factor method is to identify the number of activities that produce carbon emissions and determine the carbon emissions produced by that portion of the activity according to the carbon emission factor. With the complex composition and long duration of the activities of the whole building carbon emission, the carbon emission factor method is highly feasible for calculating the carbon emission of the whole life cycle of the building in the calculation time of

the building carbon emission, combined with the analysis of the volume of works and the monitoring data of the use of energy consumption, and it is also the calculation method commonly adopted by various Chinese and international LCA evaluation standards at present. Based on the estimated value of the building design or the measured value of the actual construction operation, we can obtain the values of each activity, including the input of building materials, the volume of work in the construction phase, the heating energy consumption in the use phase, etc., and multiply them by the corresponding carbon emission factors, such as the carbon emission per unit of material, the carbon emission per unit of machinery and equipment, the carbon emission per unit of energy, etc., and calculate the carbon emissions generated by the various activities in the life cycle of the building and the total carbon emission from the input materials. The carbon emissions of each activity and the total input material in the life cycle of the building are calculated separately.

- Mass balance method

The mass balance method is a specialized method for accurate calculation of carbon emissions from buildings, which relies heavily on the layout of equipment and processes in a building and can capture the actual sources and quantities of carbon emissions from buildings in detail. However, this method has a number of limitations, the most important of which are its high workload and data requirements.

In the construction sector, the material balance approach is particularly suitable for building types that involve complex equipment and processes, such as large public buildings and industrial plants. It provides accurate data on the carbon emissions of buildings by analyzing in detail the energy consumption of the building, the use of building materials and the emissions during the operation of the building. For example, in the desulfurization Process in a building, the mass

balance method can accurately calculate the carbon emissions of the chemicals consumed by the desulfurization equipment and the emissions gases produced. This requires detailed recording and analysis of the operating data of the desulfurization equipment, the consumption of chemical substances and the composition of the emitted gases, which is a relatively large amount of work and a demanding data requirement.

In addition, the material balance approach needs to take into account new chemical substances and equipment introduced into the building each year when calculating the building's carbon emissions. This requires detailed recording and analysis of the performance parameters, operating data and chemical consumption of the new equipment by the relevant staff to accurately calculate the carbon emissions generated by the new equipment in the course of its operation. This process is also time-consuming, and the data requirements are relatively high. Despite the shortcomings of the mass balance method in terms of workload and data requirements, its accuracy and applicability still make it an important application in the building sector. By analysing the layout, process flow and energy consumption of a building in detail, the mass balance method can provide strong data support for the accounting and reduction of carbon emissions from buildings. At the same time, this method can also provide useful references for energy saving and emission reduction in the process of building design and operation and help the building industry achieve greener and more sustainable development.

- Actual measurement method

In the field of pollution monitoring, the actual measurement method has become more widely used. This method is used to estimate carbon emissions by obtaining pollutant concentration and flow data through direct measurements at the site of a specific pollution source. In practice, however, the feasibility of this method faces

certain challenges, as it is susceptible to significant influence from environmental factors and is, therefore, mainly suitable for monitoring pollution sources in operation. In addition, it is important to ensure that sampling is representative, as using measured data to count emissions from sources will introduce large errors if samples are not taken correctly. The table below summarizes the advantages and disadvantages of these methods.

Method	Advantages	Disadvantages
Carbon emission factor method	Easy to calculate without large deviations	Wide variation in carbon emission factors, with greater requirements for locality and timeliness
Mass balance method	More accurate data on carbon emissions are available	Comprehensive analytical studies of inputs and outputs, heavy workload and complex process
Actual measurement method	Accurate calculation of CO ₂ emissions during the use phase, reflecting the real situation	Experiments are harder to manipulate and more likely to become contaminated

Table 1-2 Advantages and Disadvantages of Three Methods. Source: Xi'an University of Architecture and Technology

Overall, the carbon emission factor method is the most authoritative and widely used carbon emission calculation method in the building sector. It is worth noting that in China, the building carbon emission calculation method is relatively mature and mainly adopts the concept of full life cycle assessment (LCA), which comprehensively considers the carbon emission of each phase of production, transportation, construction, use and final disposal of building materials. Within this framework, the emission factor method is widely used to provide a scientific and accurate quantitative result for the carbon emission of building projects, thus

providing strong technical support for the green transformation and low-carbon development of the building industry.

1.3 Challenges

Although China has made significant progress in the area of building carbon emission, such as through promoting green building materials, optimizing architectural design and construction processes, and implementing stricter environmental standards, it still faces many challenges, which will be discussed in detail below.

1.3.1 Difficulty in obtaining and accounting for data

According to the "2023 China Building and Urban Infrastructure Carbon Emission Research Report", the total national carbon emission of the whole building process will be 4.07 billion tonnes of CO₂ in 2021, accounting for 38.2% of the national energy-related carbon emission. Of this, 1.70 billion tonnes of CO₂ will be emitted during the building material production phase, 0.07 billion tonnes of CO₂ during the building construction phase, and 2.30 billion tonnes of CO₂ during the building operation phase, which indicates that the carbon emission varies significantly between phases, and the accounting work is complicated and data is difficult to obtain.

In addition, the traditional method of calculating the carbon emissions of buildings is based on the design information of the construction drawings, which include a variety of materials and equipment, usually more than 60 types, and the number of independent products can be more than 2,000 pieces. Using this method to calculate the carbon emissions of buildings requires a huge database of carbon

emission factors and consumes a lot of time and human resources. This method is not only inefficient, but also contradicts the original purpose of quickly assessing the environmental impact of buildings, especially after the completion of building construction, and then the practical significance of environmental impact accounting is limited.

Therefore, it is necessary to develop fast and efficient methods for calculating physical carbon emissions according to the different phases and contents of building design. Such a method can provide timely feedback to help optimise the design, improve the efficiency of the assessment and better achieve rapid assessment of the environmental impact of buildings. This approach not only reduces the use of resources, but also considers environmental impacts at the design phase, leading to more sustainable building design.

1.3.2 Technological innovation and policy standards

Technological progress plays a key role in reducing carbon emissions from the building sector, but currently, the impact of technological progress has a negative driving effect on carbon emissions from China's building sector, suggesting that there is still much room for technological improvement. At the same time, there may be inconsistencies in building energy efficiency and carbon reduction policies and standards across regions, which affects the accuracy and comparability of carbon emission calculations.

It has been reported that carbon emissions from buildings peaked in 2016, then declined in 2020 due to the epidemic, before recovering in 2021². This may reflect

² Source: China Association for Building Energy Efficiency, Research Institute for Urban and Rural Construction and Development, Chongqing University. *Research Report on Building Energy Consumption*

and Carbon Emissions in China (2023) [J]. *Architecture*, 2024(2): 46-59.

a decline in building activity during the epidemic and a lack of subsequent technological advances and policy adjustments.

The work profile of the China Building Energy Efficiency Association's Specialized Committee on Building Energy Consumption and Building Carbon Emission Data states that the committee aims to integrate industry strengths, collaborate on specialized research on building energy consumption and building carbon emission, and consolidate the building energy efficiency database. This implies that there are certain challenges and needs in the current accounting, research and application of building energy consumption and carbon emission data.

1.3.3 Detailedness and Operability of Building Carbon Emission Calculation Methods

China issued the Standard For Building Carbon Emission Calculation (GB/T 51366-2019) in 2019, which regulates the calculation of carbon emission of each component from the level of carbon emission composition of the whole life cycle of a building, and provides the corresponding calculation formula, which has a certain universality. However, due to the complexity of the building composition, the long life cycle, and the lack of detail in the standard, it only serves as a basic guideline for the calculation of carbon emissions of buildings, and the specific implementation of the operational process is not very instructive. There is no academic monograph on the detailed methodology of building carbon emission calculation, so building practitioners lack technical support and application guidance in the process of carbon emission management.

As for the lack of operability, it is more reflected in the lack of calculation methods for the pre-construction feasibility study and program design phase without detailed data, and the existing calculation software is mostly based on the basic requirements of "Standard For Building Carbon Emission Calculation " (GB/T

51366-2019), which is divided into phases according to the whole life cycle, and the analysis of calculation results is not precise enough. There is a lack of classification and refinement of the composition of carbon emission in various phases of the building, and it is insufficient to cope with carbon emission management. These challenges and dilemmas point to the need for a more sophisticated approach to the analysis of the carbon footprint of buildings.

These challenges and dilemmas indicate that China needs to further strengthen its data collection and accounting capacity in building carbon emission calculation, promote technological innovation, and harmonize policy standards. These measures should make it possible to more effectively address the challenges of reducing carbon emissions in the construction sector.

2. DETAILED CALCULATION METHOD OF BUILDING CARBON EMISSION IN CHINA

At present, the current Chinese calculation of carbon emissions from buildings is based on the Standard for Building Carbon Emission Calculation (GB/T51366-2019), which details the specific calculation methods and steps for calculating carbon emissions from buildings.

In this standard, taking into account the long life cycle of buildings, the industrial chain involved is also more complex; from the extraction of raw materials to the end of the building, the entire cycle spans a long period. In order to ensure that the calculation of carbon emissions from buildings does not overlap with the calculation of carbon emissions from the building materials industry, transport, and other sectors, the standard provides a detailed breakdown of the different phases in the life cycle of a building. These phases include:

- Production and transportation of building materials
- Construction and demolition of building
- Operation of building

By clearly defining the phases, the carbon emissions of a building's whole life cycle can be calculated more scientifically and accurately. This avoids duplication of calculations between different industries and provides data to support the building industry's low-carbon development.

2.1 Confirmation of system boundary

2.1.1 system boundary

- Production and transportation of building materials

A 'cradle-to-gate' LCA model should be used to calculate carbon emissions during the production phase of building materials. The boundary of the model starts from the upstream production of raw materials and energy and extends to the point where the building materials leave the factory. The transport distance of key building materials at this phase must be determined by consulting design drawings, purchasing lists, and other technical information related to the construction of the project. Factors for carbon emissions include:

- Carbon emissions from extraction and processing of raw materials.
- Carbon emissions from the extraction and production of building materials.
- Carbon emissions from the transport of raw materials and energy.
- The production process of building materials directly generates carbon emissions.

If some emission data are missing or not considered in the calculation process, this should be clearly stated in the report.

The theoretical boundary should cover the following links to calculate carbon emissions from the transport phase of building materials.

- The transport process from the production site of the building materials to the building site.
- The energy consumed in the transport process and its carbon emissions in the extraction and processing phases.
- Carbon emissions from the production process of the means of transport.
- Carbon emissions from the construction of infrastructure such as roads.

These calculations ensure that the carbon emissions from the extraction of raw materials to the final use of building materials can be fully assessed, providing accurate data to support a construction project's carbon footprint analysis.

- Construction and demolition of building

The building construction phase is the process of transforming the various resources invested in the construction of the project into a building unit through a series of activities that are rationally organized in time and space in accordance with the relevant standards based on the architectural design documents, the design of the construction organization or the construction program. The main components include:

- Energy consumption of the subcomponent works that make up the construction unit;
- Energy consumption for various non-engineering entity measures in technical, living, safety and other aspects that occur before and during the construction of the project to complete the construction.

The corresponding construction phase carbon emissions are divided into two parts:

- Carbon emissions from fuel and electricity consumed during the construction of the project sub-components;
- Carbon emissions from fuel and electricity consumed during the implementation of the project.
- Carbon emissions from buildings during the demolition phase include all types of energy and power consumed by the mechanical equipment used for manual demolition and demolition using small machines and equipment.

- Operation of building

In order to assess the carbon emissions of a building during its operational life, it is necessary to take a comprehensive view of the emissions from the following key links: the HVAC system, the provision of hot water in China, the operation of lighting and lifts, the use of renewable energy and the sequestration of carbon by the building's carbon sink system. By carefully considering these key aspects, the environmental impact of the building during its actual use can be more accurately assessed.

2.1.2 Types of greenhouse gases

Greenhouse gases (GHGs) include carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and other gases. Among them, CO₂ is the most common greenhouse gas produced by human activities, and in order to standardise the results of the measurement of the total greenhouse effect, it is established that kgCO₂e is the basic unit for measuring the greenhouse effect. Carbon dioxide equivalent (kgCO₂e) refers to the mass of CO₂ that has the same greenhouse effect as a given mass of a given GHG, and is a unit of measurement that can be used to compare the greenhouse effects of different GHGs.

The GHG produced during the construction, operation, and decommissioning of buildings is mainly CO₂, and its calculation result is usually expressed in kg CO₂; the GHG emitted during the production and transport of building materials and refrigerants includes various GHGs, and its carbon intensity is usually expressed in carbon dioxide equivalent (kgCO₂e).

Carbon emissions per unit area of a building are usually used to compare the carbon emissions of different building design options and different buildings, and the carbon emissions per unit area of a building are obtained by dividing the

carbon emissions of the building by the floor area.

2.2 Basic calculation method

Commonly used calculation formulae vary according to the categorisation of the phases of the whole life cycle of a building.

2.2.1 Operation phases

For the calculation of the carbon emissions in the operational phase, the carbon emissions of the building shall be determined on the basis of the different types of energy consumption of each system and the carbon emission factors of the different types of energy, and in accordance with the general provisions, the total carbon emissions per unit of floor area in the operational phase of the building (C_M) shall be calculated according to the following formula:

$$C_M = \frac{[\sum_{i=1}^n (E_i EF_i) - C_p]y}{A} \quad (2.2-1)$$

$$E_i = \sum_{j=1}^n (E_{i,j} - ER_{i,j}) \quad (2.2-2)$$

In the formula:

C_M — Carbon emission per unit building area during the operation phase (kgCO_2/m^2)

E_i — Annual energy consumption of the i type of buildings (Unit /a)

EF_i — The carbon emission factor of the i type of energy

$E_{i,j}$ — Type i energy consumption for type j systems (Unit/a)

$ER_{i,j}$ — Amount of Class I energy supplied by renewable energy systems for Class J systems (Unit/a)

C_p — Annual carbon reductions from built green space carbon sink systems (kgCO_2/a)

i — Type of end-use energy consumed by the building, including electricity, gas, oil, municipal heat, etc.

J — Types of building energy systems, including heating and air conditioning, lighting, Chinese hot water systems, etc.

y — Building design Lifetime (a)

A — Building area (m^2)

2.2.2 Construction and demolition phases

There are some differences in the calculation formula between the construction and demolition phases.

■ Construction phases

Carbon emissions during the construction phase of buildings should be calculated using the following formula:

$$C_{JZ} = \frac{\sum_{i=1}^n E_{JZ,i} EF_i}{A} \quad (2.2-3)$$

In the formula:

C_{JZ} — Carbon emissions per unit of floor area during the building construction phase (kgCO_2/m^2)

$E_{jz,i}$ —— Total energy consumption in category I during the construction phase of the building (kgCO₂/kWh or kgCO₂/kg)

EF_i —— Carbon emission factors for energy type i (kWh or kg)

A —— Building area (m²)

■ Demolition phases

The carbon emissions per unit area for this phase should be calculated using the following formulae:

$$C_{cc} = \frac{\sum_{i=1}^n E_{cc,i} EF_i}{A} \quad (2.2 - 4)$$

In the formula:

C_{cc} —— Carbon emissions per unit of floor area during the building construction phase (kgCO₂/m²)

$E_{cc,i}$ —— Total energy consumption in category I during the construction phase of the building (kWh or kg)

EF_i —— Carbon emission factors for energy type i (kgCO₂/ kWh)

A —— Building area (m²)

The amount of energy used in the manual and mechanical demolition phases of a building shall be calculated according to the following formulae:

$$E_{cc} = \sum_{i=1}^n Q_{cc,i} f_{cc,i} \quad (2.2 - 5)$$

$$f_{cc} = \sum_{j=1}^m T_{B-i,j} R_j + E_{jj,i} \quad (2.2 - 6)$$

In the formula:

E_{cc} —— Energy consumption during the demolition phase of the building (kg or kWh) ;

$Q_{cc,i}$ —— Scope of work for the type i demolition project;

$f_{cc,i}$ —— Energy consumption factor per unit of measure for the ith dismantling project (kWh/unit of measure or kg/unit of measure);

$T_{B-i,j}$ —— Unit volume of work for the type i demolition project j type of construction machinery Unit consumption;

R_j —— Energy use for the j type of construction machinery unit for the i demolition project;

i —— Project serial number in demolition works;

j —— Construction machinery serial number。

2.2.3 Building materials production and transportation phase

When calculating the production and transportation phases of building materials, it should be calculated in accordance with the current national standards "Principles and Framework for Life Cycle Assessment of Environmental Management" (GB/T 24040) and "Requirements and Guidelines for Life Cycle Assessment of Environmental Management" (GB/T24044). The calculation is made according to the following formula:

$$C_{jc} = \frac{C_{sc} + C_{ys}}{A} \quad (2.2 - 7)$$

In the formula:

C_{jc} — Carbon emissions per unit of floor area in the production and transport phases of construction (kgCO₂e/m²)

C_{sc} — Building carbon emission at production phase (kgCO₂e)

C_{ys} — Building carbon emission at transportation phase (kgCO₂e)

A — Building area (m²)

- production phase

The formula for the production phase of building materials shall be calculated in accordance with the following formula.:

$$C_{sc} = \sum_{i=1}^n M_i F_i \quad (2.2 - 8)$$

In the formula:

C_{sc} — Carbon emissions from the production phase of building materials (kgCO₂e)

M_i — Consumption of major building material type i

F_i — Carbon emission factor for major building materials in category i (kgCO₂e/unit of building materials)

- transportation phase

The formula for the transportation phase of building materials is as follows:

$$C_{ys} = \sum_{i=1}^n M_i D_i T_i \quad (2.2 - 9)$$

In the formula:

C_{ys} — Carbon emissions during the transportation phase of building materials (kgCO₂e)

M_i — Consumption of major building material type i (t)

D_i — Average transport distance for building materials in category i

T_i — Carbon emission factor per unit weight of transport distance for transport mode of building materials of type i [kgCO₂e/(t·km)]

3. RESEARCH ON THE BEE MUSEUM PROJECT

3.1 Background and significance of the project

3.1.1 Background

Liuba County, Shaanxi Province, is located at the southern foot of the Qinling Mountains(a mountain range in central China), with a beautiful ecological environment, abundant honey plants, and a long history of beekeeping. However, for a long time, the local bee industry has been mainly based on the traditional breeding and sales mode, and the added value of the industry needs to be improved. In order to give full play to the resource advantages of Liuba, promote the development of the honeybee industry, and create a special eco-tourism brand, the Shaanxi Province Liuba Bee Museum project came into being. The location of project is shown in Figure 3-1.

In March 2023, the ‘Bee Research and Rural Revitalisation Tourism Base in Huoshaodian Township, Liuba County, Hanzhong City, Shaanxi Province’ project was selected as one of the second batch of demonstration projects of the Sino-Swiss Zero Carbon Building Project. The project is a ministerial-level international cooperation project initiated by the Chinese Ministry of Housing and Urban-Rural Development and the Swiss Agency for Development and Co-operation (SDC). The project was launched in May 2023 and is expected to be officially completed in 2024 with the joint efforts of the Chinese and Swiss teams for about a year.



Fig. 3-1 The project is located in a rural natural setting, Source: Sino-Swiss ZEB Project, Shaanxi Liuba Demonstration Project Team

3.1.2 Significance

■ Industry Promotion

Deeply excavate the connotation of honeybee culture, inject cultural elements into the honeybee industry, and enhance the added value of the industry. Promote the industry to diversify from single production and sales to diversified development, including science education and tourism experience, by displaying bee breeding technology and bee product processing process. Providing a platform for local beekeepers to learn and exchange, ideas will help promote advanced breeding techniques and management experience and improve the efficiency and quality of bee breeding, thus increasing the income of beekeepers and promoting the large-scale and standardized development of the local bee industry.

■ Cultural Heritage

Honeybee culture is an important part of human agricultural culture. The

construction of the museum can systematically collect, organize, and display the history, culture, and folklore related to honeybees to protect and pass on this unique cultural heritage. Let more people understand the important role of bees in the ecosystem and the long-term symbiotic relationship between human beings and bees, and enhance people's awareness of the protection of natural ecology.

■ Tourism Development

Enrich the tourism resources of Liuba County and provide tourists with a novel and interesting tourist attraction. It attracts more tourists to visit and prolongs their stay in Liuba and promotes the development of local tourism. At the same time, it forms a linkage with the neighbouring natural landscapes and rural tourism projects to create a comprehensive tourism route and enhance the overall attractiveness and competitiveness of tourism in Liuba.

3.2 Project Overview

3.2.1 Basic information of the building

Name	Bee Museum
Type of architecture	public building
site area(m ²)	4674.10m ²
building area(m ²)	1404.3m ²
storey	2 floors above ground
building density	16.30%
plot ratio	0.29
green area ratio	37%
parking space for motor vehicles	15 vehicles

Table 3-1 Basic Information Table. Source: Xi'an University of Architecture and Technology

3.2.2 Exhibition content

As a comprehensive building, it integrates scientific research, interactive experience, bee culture exhibition and bee product sale, and has several exhibition halls, including the Honey Bee Culture and History Exhibition Hall, the Bee Breeding Technology Exhibition Hall and the Bee Product Exhibition Hall.

- Honeybee Culture and History Exhibition Hall: Through pictures, texts, objects and other forms, it displays the development and evolution of honeybees in the long history of mankind, as well as myths and legends, lyrics and songs, and folk culture related to honeybees.
- Honeybee Breeding Technology Exhibition Hall: It introduces in detail the characteristics of the ancient round barrel beekeeping technology, the reproduction and feeding management of honey bees, and the prevention and treatment of diseases and pests. An interactive experience area is set up so that visitors can personally operate beekeeping tools and simulate some aspects of beekeeping to increase their sense of participation and interest.
- Bee Products Exhibition Hall: displays various types of bee products and introduces their nutritional value, efficacy and processing technology. Visitors can taste authentic Liuba honey and other bee products and buy related souvenirs.

The museum also has a science education area and a multimedia screening room. The science education area regularly organizes bee science lectures and training activities for primary and secondary school students and the general public to popularise the knowledge of bees and the concept of ecological protection. The multimedia screening room shows bee-related documentaries, allowing visitors to gain a more intuitive understanding of the habits and ecological value of bees.

3.3 Purpose and tools of analysis

The purpose of the analysis in this section is to carry out building life cycle carbon emission calculations aimed at quantitatively analyzing building carbon emission hotspots, further proposing carbon emission reduction measures and achieving a reduction in carbon intensity. The project is designed in accordance with the requirements of the General Specification for Building Energy Efficiency and Renewable Energy Utilization (GB55015-2021) and the Technical Standard for Near-Zero Energy Consumption Buildings (GB/T 51350-2019), and with reference to the national standards of the Standard for Building Carbon Emission

Calculation(GB/T51366-2019) and the Energy Efficiency Design Standard for Public Buildings (GB/50189-2015) for the production of building materials and the calculation of carbon emission in buildings. The carbon emission calculation of the building life cycle is carried out with reference to the requirements of the national standard 'Standard For Building Carbon Emission Calculation ' (GB/T51366-2019) and the 'Energy Efficiency Design Standard for Public Buildings ' (GB/50189-2015), which stipulate in detail the calculation of carbon emission in the building materials production and transportation phase, building construction phase, building operation phase and building demolition phase.

The analyzing tools are Microsoft Excel, Swire Ultra Low Energy Calculation Software PHES 2022.

3.4 Life cycle assessment methodology

3.4.1 Life Cycle Assessment

The Life Cycle Assessment (LCA) process enables both systematic and quantitative analyses of evaluation objectives. The results of LCA can help production units identify key environmental issues and the main processes that cause environmental impacts, thus avoiding the transfer of environmental issues from one life cycle phase to another, or from one type of environmental impact to another.

3.4.2 system boundary

One of the key aspects of building life cycle assessment is the definition of the building life cycle system boundary, including the detailed description of the building system boundary and the mapping of the boundary between the building and the environment, as well as the identification of the relevant individual

processes throughout the life cycle of the building. Within the framework of this system, the system boundary of a building is defined as a collection of intermediate products and unit process flows that form the building entity and functions within the building site, including the production and transport phase of building materials, the construction phase of the building, the operation phase (HVAC, Chinese hot water system, lighting and lift system, renewable energy and building carbon sinks) and the end of life phase of the building in terms of both direct and indirect GHG emissions. and indirect GHG emissions during the end of life phase of the building. This is illustrated in Figure 3-2.

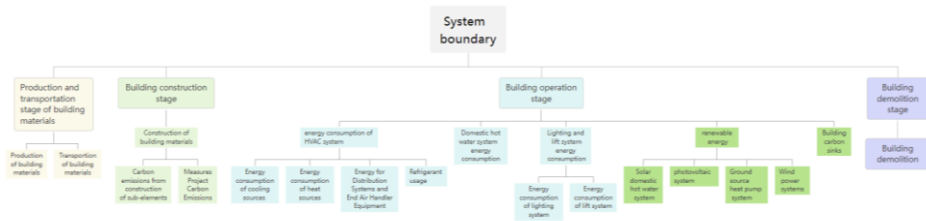


Fig. 3-2 Boundaries of system accounting in the framework. Source: Xi'an University of Architecture and Technology

The framework divides the life cycle of a building into the production and transport of building materials, the construction of the building, the operation of the building and the demolition of the building. The building operation phase includes the accounting of the HVAC system, Chinese hot water system, lighting and lift system, renewable energy and green space carbon sink.

3.5 Data sources and selection principles

3.5.1 Source of usage (activity) data

- Building material use: Construction works quantity list.
- Building material transport: Construction works bill of quantities and national standard

"Standard For Building carbon emission calculation " (GB/T51366-2019).

- Construction energy consumption: bill of quantities.
- Building operation: simulation using Swire Ultra Low Energy Calculator PHES 2022.
- Building demolition: calculation of building carbon emissions during the demolition phase according to the Building Demolition Budget Quota SH00-31-2019.
- Green space carbon sink: Calculated using the planting type-area method proposed by Taiwanese scholar Lin Xiande in his book Green Building Interpretation and Evaluation Manual, combined with the actual situation of the project.

3.5.2 Emission data sources

- Building materials production phase: relevant carbon emission factor data from Standard For Building Carbon Emission Calculation (GB/T51366-2019); CBCED database, DH 2.0 database, CPCFFD 2022 database;
- Building materials transport phase: relevant carbon emission factor data from the Standard for Building Carbon Emission Calculation (GB/T51366- 2019), CBCED database;
- Building Construction Phase: relevant carbon emission factor data from the Standard For Building Carbon Emission Calculation (GB/T51366-2019), CBCED database;
- Building Operation Phase: relevant carbon emission factor data from the Standard For Building Carbon Emission Calculation (GB/T51366-2019);
- Building demolition phase: relevant carbon emission factor data from the Standard For Building Carbon Emission Calculation (GB/T51366-2019), CBCED database;

3.5.3 The principle of selectivity

The rounding rules used in this report are based on the weight ratio of each material input to the weight of the product or total process input. The specific rules are

- If the weight of common materials is <0.05% of the product weight, and if the weight of

materials containing rare or high purity ingredients is <0.01% of the product weight, the upstream production data of the material can be ignored; the total ignored material weight does not exceed 3%;

- low-value waste materials, such as fly ash, slag, straw, waste, etc., can be ignored for their upstream production data;
- In most cases, production facilities, plants, facilities, etc. can be ignored;
- Known emission data within the selected environmental impact type should not be ignored.

3.6 Life cycle analysis results

3.6.1 Building materials production and transport phase

- The principle of selectivity

According to the principle of rounding and the weight proportion of each building material (as shown in Figure 3-3), the weight and percentage of each building material are calculated and the building materials with a weight proportion of <0.05% are discarded and their upstream production data are ignored. Following the principle of rounding, the carbon emissions from the production and transport of steel, concrete, cement mortar, sand and gravel, wall materials, bricks, insulation materials, paints and coatings, waterproofing materials, etc. are now mainly calculated after screening.

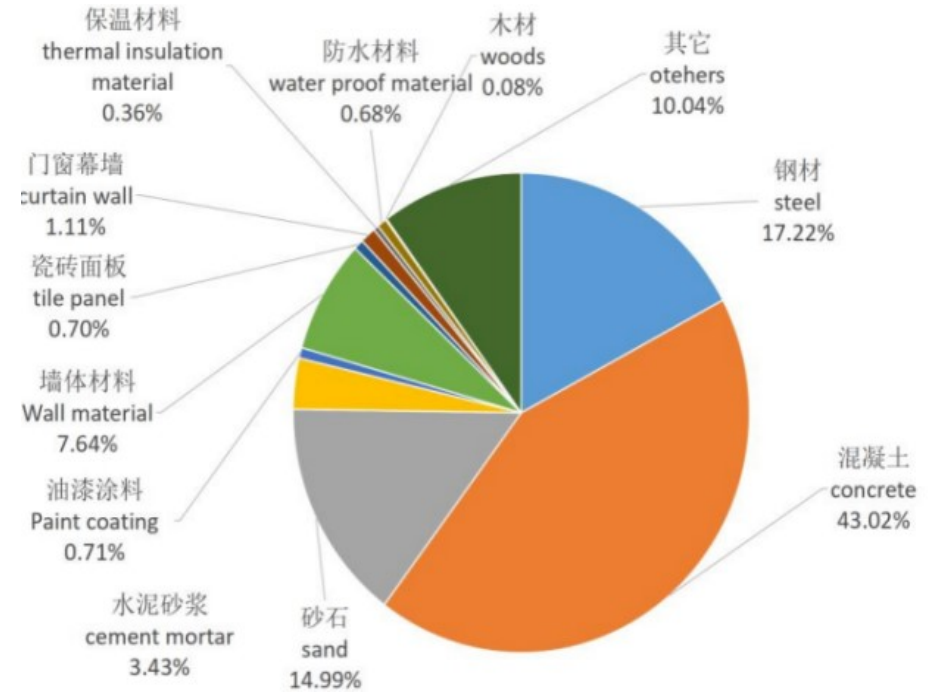


Fig. 3-3 Weight share of each building material. Source: Sino-Swiss ZEB Project, Shaanxi Liuba Demonstration Project Team

- Building materials production phase

The carbon emission of the building material production phase of this building classifies the building material types into steel, concrete, sand and gravel, cement mortar and so on. Based on the project bill of quantities, the carbon emission factors corresponding to the building materials were found in the national standard "Standard For Building Carbon Emission Calculation" (GB/T51366- 2019), DH2.0, CBCED, CPCFFD 2022 and other databases by summarizing the number of building materials of each type, and the calculations were carried out according to Equations 2.2.2 - 6 in Chapter II.

The carbon emissions in the building material production stage were calculated according to both the types of building materials and the sub-projects and sub-divisional works. The calculations show that steel accounts for 53.96% of the carbon emissions in the production stage, while concrete accounts for 15.49%. Among the sub-projects and sub-divisional works, the production stage of metal steel structures has the highest proportion of carbon emissions, reaching 32.07%, followed by concrete steel structure projects, accounting for 25.15%. The specific data are shown in figures 3-4 and 3-5.

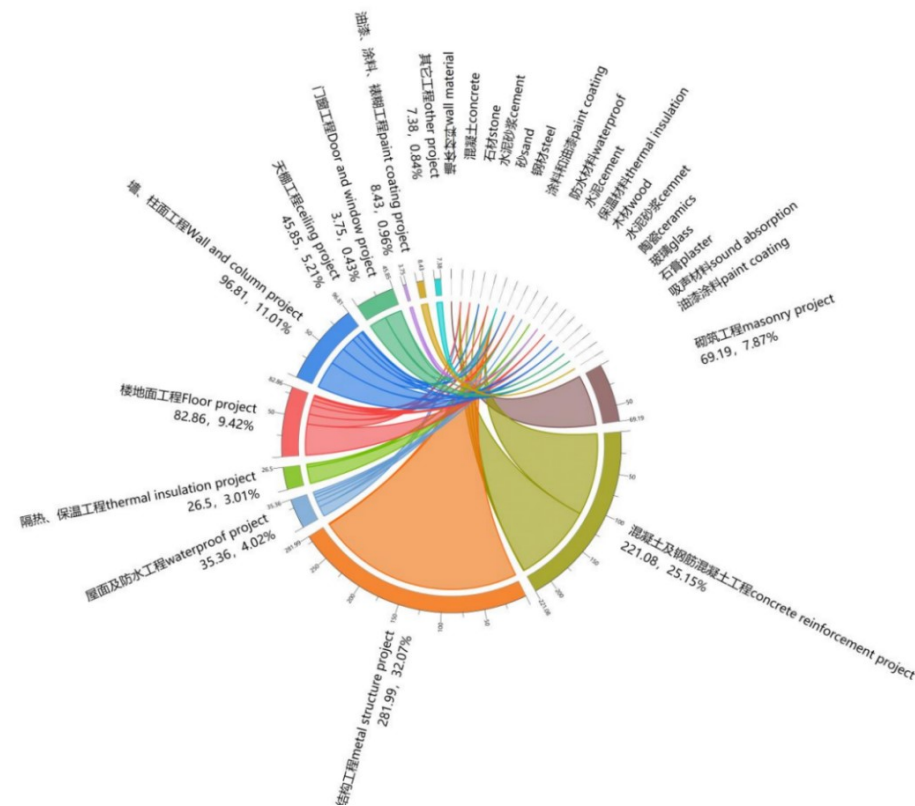


Fig. 3-4 Carbon Emission Proportion Chord Diagram for Sub-Parts of the Project (Units: kgCO₂e/m². Source: Sino-Swiss ZEB Project, Shaanxi Liuba Demonstration Project Team

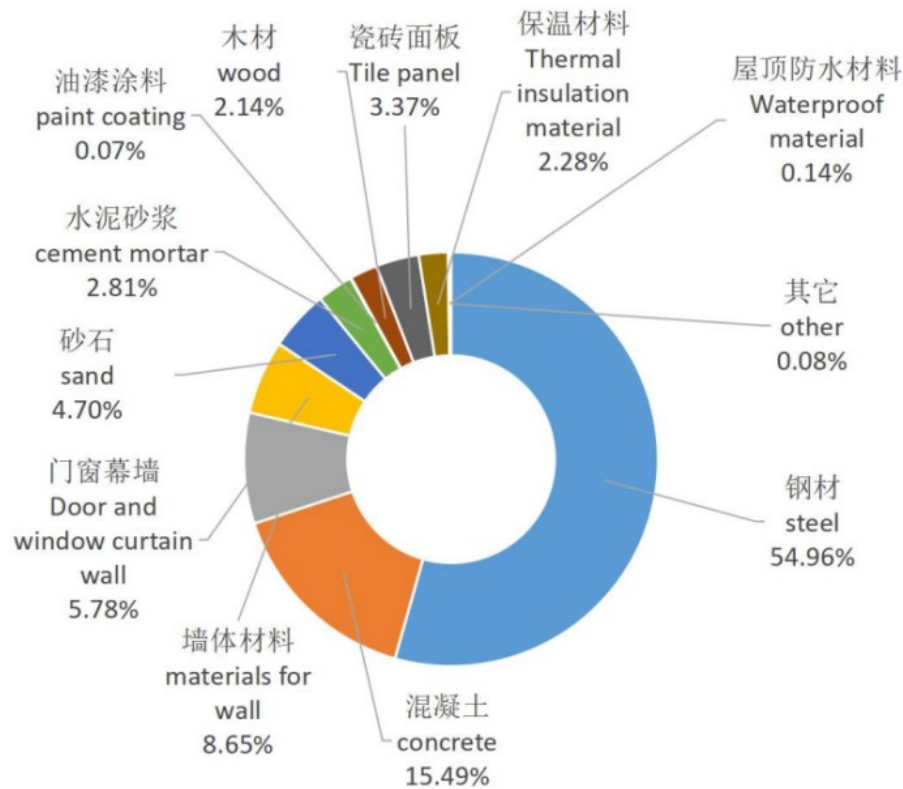


Fig. 3-5 Carbon emission share of each building material in the building material production phase. Source: Sino-Swiss ZEB Project, Shaanxi Liuba Demonstration Project Team

According to the calculation, the carbon emission of the building in the production phase of building materials is 1234.66tCO₂e, and the carbon emission per unit building area is 879.20kgCO₂e/m², and the average annual carbon emission per unit building area is 17.58kgCO₂e/(m²·a).

Materials transportation phase

In the calculation of the carbon emission of the transportation of building materials, the default mode of transportation is heavy-duty diesel truck transportation (load 18t), and its carbon emission factor is 0.129kgCO₂e/(t·km) as specified in the national standard "Standard For Building Carbon Emission Calculation" (GB/T51366-2019); according to the national standard "Standard For Building Carbon Emission Calculation" (GB/T51366-2019), the default value of the transportation distance is 40km for concrete and 500km for other building materials. According to the national standard "Standard For Building Carbon Emission Calculation" (GB/T51366-2019), the carbon emission of building materials in the transportation phase is calculated according to formula 2.2.2-9 in Chapter 2 as follows.

$$C_{ys} = \sum_{i=1}^n M_i D_i T_i$$

Total

The Standard For Building Carbon Emission Calculation (GB/T51366-2019) stipulates that the carbon emission of building materials shall be calculated by combining the production and transportation phases according to the calculation formula 2.2.2 - 7, as follows.

$$C_{jc} = \frac{C_{sc} + C_{ys}}{A}$$

Based on the project bill of quantities, the carbon emission of the production and transportation phase of the building materials is calculated to be 1329.76tCO₂e, the carbon emission per unit building area is about 946.93kgCO₂e/m², and the average annual carbon emission per unit building area is 18.94kgCO₂e/(m²·a).

Among them, steel and concrete contribute most of the carbon emissions due to the large amount of engineering use, with values of 693.85 and 196.64tCO₂e respectively, accounting for 52.18% and 14.79%, and the rest of the building materials such as cement, mortar, wall materials, and sand and gravel also contribute part of the carbon emissions, as shown in Figure 3-6.

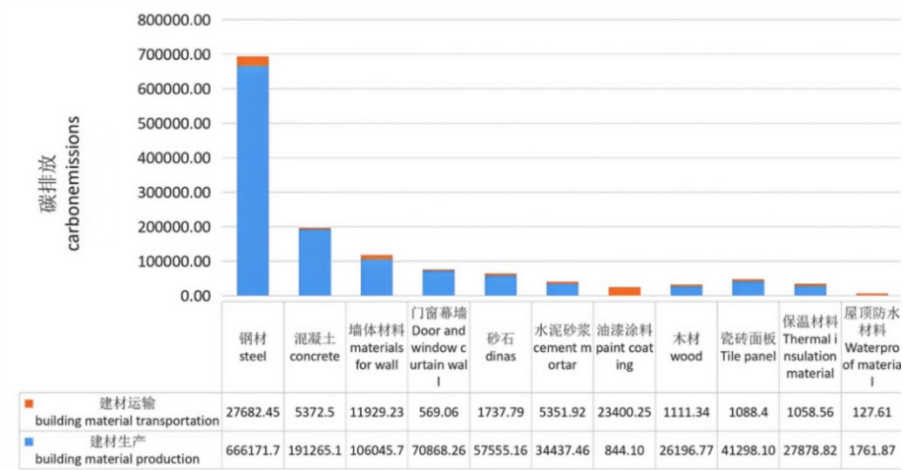


Fig. 3-6 Carbon emissions from building materials production and transportation phase, Source: Sino-Swiss ZEB Project, Shaanxi Liuba Demonstration Project Team

3.6.2 Building construction phase

Carbon emissions from the construction phase mainly come from the energy consumption of machinery and equipment used in construction. Based on the bill of quantities of construction works, the carbon emissions from the construction phase are calculated in accordance with equation 2.2.2-3 in Chapter 2, as follows.

C_{Jz} = (Σ_{i=1}ⁿ E_{jz,i} EF_i) / A

The carbon emission caused by the building construction phase is 61.81tCO₂e, and the carbon emission per unit of floor area is 44.01 kgCO₂e/m², and the annual average carbon emission per unit of floor area is 0.88kgCO₂e/ (m²·a), see Table 3-2 for details.

Type of energy	Unit.	Consumption	EF	Carbon Emission	Total
diesel	kg	1557.29	3.760	5855.39	
electricity	kWh	95857.99	0.581	55693.49	61809.59
petrol	kg	67.72	3.850	260.71	

Table. 3-2 Energy consumption and building carbon emission during the construction phase of the building. Source: Xi'an University of Architecture and Technology

3.6.3 Building operation phase

- Energy consumption in building material operation phase

The calculation and analysis software used in this report is the Swire ultra-low energy consumption calculation software PHES2023. The Green Building Swire ultra-low energy consumption software PHES runs on the CAD platform and is developed based on the ‘Near-Zero Energy Consumption Building Technical Standards’ and the ultra-low energy consumption standards of each province, which supports energy-saving design and simulation calculation and evaluation of the ultra-low energy consumption phase of residential buildings across the country, and it can calculate the yearly cooling of the building, heating demand, lighting power consumption, total primary energy of the building and other

indicators are calculated, as shown in Table 3-3.

Type	Average annual electricity consumption per unit of floor area[kWh/(m ² ·a)]	Annual electricity consumption (kWh)	50-year electricity consumption per unit of floor area (kWh/m ²)	50-year electricity consumption (10 ⁴ kWh)
cooling	7.76	10897.368	388.00	54.49
heat	1.42	1994.106	71.00	9.97
light	14.91	20938.113	745.50	104.69
sockets	23.07	32397.201	1153.50	161.99
elevator	0.71	997.053	35.50	4.99
photovoltaic	-90.86	-127594.698	-4543.00	-637.97
Total	-42.99	-60370.857	-2149.50	-301.84

Table 3-3 Energy Consumption in the Operation Phase of the Building, Source: Xi'an University of Architecture and Technology

This report establishes the passive ultra-low energy consumption analysis model of Liuba Bee Study Tourism Complex based on the architectural design drawings and other relevant information provided by the client and using the energy consumption calculation software PHES2022, with the building life span of 50 years, calculates the energy consumption of the building throughout the whole life cycle and combines it with the energy and carbon emission factors given in the "Standard For Building Carbon Emission Calculation" (GB/T51366 -2019). Factors are given in the GB/T51366-2019 to calculate the carbon emission in the

operation phase of the building.The carbon emission in the operation phase of the building is calculated according to the following formula :

$$C_M = \frac{[\sum_{i=1}^n (E_i EF_i) - C_p]y}{A}$$
$$E_i = \sum_{j=1}^n (E_{i,j} - ER_{i,j})$$

On request, the carbon emission factor for electricity is taken as 0.5810kgCO₂e/kWh, so the carbon emission from energy consumption during the building's operational phase is:
E_iEF_i= (-3018400×0.5810) /1000=-1753.69tCO₂e

- greenfield carbon sink

The green area carbon sink is calculated based on the planting type area method of Taiwan's Lin Hsien-Te and the 50-year life cycle. The project's green area type is shrub and grassland, and since the project is located in the warm temperature zone, the climate change factor is taken as 0.7. Therefore, the carbon sink of the green area is calculated according to the following formula:

$$C_s = \sum_{i=1}^n A_i \times C_{pi} \times \varepsilon \tag{3.6-1}$$

In the formula:

C_s —— 50-year total carbon sequestration by greenery within the planning horizon, kgCO₂e

A_i —— Planted area of different greening types, m^2

C_{Pi} —— Carbon sequestration per unit area in 50 years, $kgCO_2/m^2$

P_i —— Green planting methods, ε is the climate correction factor

Therefore, the carbon sink of green space is: $C_s = 325 \times 1729 \times 0.7 = 453.86 tCO_2$, the life cycle carbon sink is $393.35 tCO_2e$, the carbon sink per unit of building area is $280.10 kgCO_2e/m^2$, and the annual average carbon sink per unit of building area is $5.60 kgCO_2e/(m^2 \cdot a)$.

To sum up, the operational carbon emission of the building mainly comes from the electricity consumed by the building in order to meet people's daily demand for heating, cooling and lighting, etc. as well as the carbon reduction from photovoltaic power generation and the carbon sink of the green space, and the carbon emission of the building in the operational phase is calculated to be $-2147.18 tCO_2e$, the carbon emission per unit of building area is $-1529.00 kgCO_2e/m^2$, and the annual average carbon emission per unit of building area is $-30.58 kgCO_2e/(m^2 \cdot a)$, as shown in Table 3-4.

electricity	type	Average annual carbon emissions [$kgCO_2e/ (m^2 \cdot a)$]	Carbon emissions per unit of floor area over 50 years (kWh/m^2)	Carbon emissions over 50-year life cycle (tCO_2e)
cooling		4.49	224.5	315.265
heat		0.85	42.5	59.683

light		8.65	432.5	607.36
sockets		13.39	669.5	940.179
other	elevator	0.43	21.5	30.192
renewable	type	Average annual carbon emissions [$kgCO_2e/ (m^2 \cdot a)$]	Carbon emissions per unit of floor area over 50 years (kWh/m^2)	Carbon emissions over 50-year life cycle (tCO_2e)
renewable resource	photovoltaic (E_p)	-52.79	-2639.5	-3706.65
carbon sink	[$kgCO_2e/ (m^2 \cdot a)$]	-5.6	-280	-393.348
Total		-30.58	-1529.00	-2147.175

Table 3-4 Carbon Emissions in Operation Phase. Source: Xi'an University of Architecture and Technology

3.6.4 Building demolition phase

The building demolition phase consists of the dismantling of the building and the disposal of the waste, and most of the carbon emissions generated in this phase come from the energy consumed during the demolition work and the fuel consumed during the transport of the building waste.

Demolition phase

The carbon emission from the demolition phase mainly comes from the energy

consumption of mechanical equipment used in the construction, and the project calculates the carbon emission from the demolition phase according to the national standard GB/T51366-2019 and the ‘Budgetary Quotas for Demolition of Buildings’ (SH00-31-2019).

$$C_{cc} = \frac{\sum_{i=1}^n E_{cc,i} EF_i}{A} \tag{2.2.2 - 4}$$

After calculation, the carbon emission of the demolition phase is 22.64tCO₂e, the carbon emission per unit of floor area is 16.12kgCO₂e/m², and the annual average carbon emission per unit of floor area is 0.32 kgCO₂e/(m²·a).

▪ Disposal of Waste

The carbon emission at this phase is mainly divided into two parts: the recycling of some building materials and the transport of building waste to the treatment plant.

According to the national standard ‘Standard For Building Carbon Emission Calculation’ (GB/T51366-2019), the calculation of the energy consumption generated by the transport of waste after the demolition of the building is consistent with the transport of building materials. Therefore, the carbon emission generated by the outward transport of rubbish is 95.107 tCO₂e, the carbon emission per unit of building area in 50-year life cycle is 67.73 kgCO₂e/m², and the average annual carbon emission per unit of building area is 1.35 kgCO₂e/(m²·a). For steel, aluminium alloy and other building materials with high recycling rate to be reused, according to the carbon emission calculation results of building materials production phase in the previous section, it can be seen that

the carbon reduction generated by recycling is 361.953 tCO₂e, the carbon reduction per unit of building area is 257.75 kgCO₂e/m², and the average carbon reduction per unit of building area per year is 5.16 kgCO₂e/(m²·a), see Table 3-4 for details. 3-5.

Type	Recovery rate	Weight of recovered parts(t)	Recovery of partial carbon reductions (tCO ₂ e)	Total carbon reduction (tCO ₂ e)
Steel	0.5	208.39	333.086	
timber	0.5	0.99	0.881	
Glass and aluminium alloys	0.5	13.47	27.806	361.95
plaster cast (for a broken bone)	0.5	3.86	0.181	

Table 3-5 Material Recycling Data. Source: Xi'an University of Architecture and Technology

In summary, adding the building demolition phase and the waste disposal phase together, the life cycle carbon emission of this phase is -244.20tCO₂e , and the carbon reduction per unit of building area is -173.90kgCO₂e/m², with an average annual carbon reduction per unit of building area of -3.48 kgCO₂e/(m²·a).

3.6.5 Summary of results

Through the calculation of carbon emission in each phase of building life cycle in the previous section, it can be concluded that the total carbon emission of building life cycle of this project is -999.81 tCO₂e, and the carbon emission per unit of building area is -711.96 kgCO₂e/m², and the annual average carbon emission per unit of building area is -14.24 kgCO₂e/(m²·a).The specific carbon emissions of

each sub-phase of the building are shown in Tables 3-6 below.

Phase	subphase	carbon footprint (tCO ₂ e)	Carbon emissions per unit of floor area (kgCO ₂ e/m ²)	Average annual carbon emissions per unit of floor area [kgCO ₂ e/ (m ² ·a)]
Production and transportation	Production Phase	1234.66	879.20	17.58
Phase of building materials	Transportation Phase	95.11	67.73	1.35
Building construction	Building construction Phase	61.81	44.01	0.88
Operation Phase	Building Operation Phase	-2147.18	-1529.00	-30.58
Building demolition	Building demolition Phase	22.64	16.12	0.32
Waste disposal	Recycling	-361.95	-257.75	-5.16
	Waste export	95.11	67.73	1.35
Total		-999.81	-711.96	-14.24

Table.3-6 Carbon Emissions from the Life Cycle of the Project's Buildings, Source: Xi'an University of Architecture and Technology

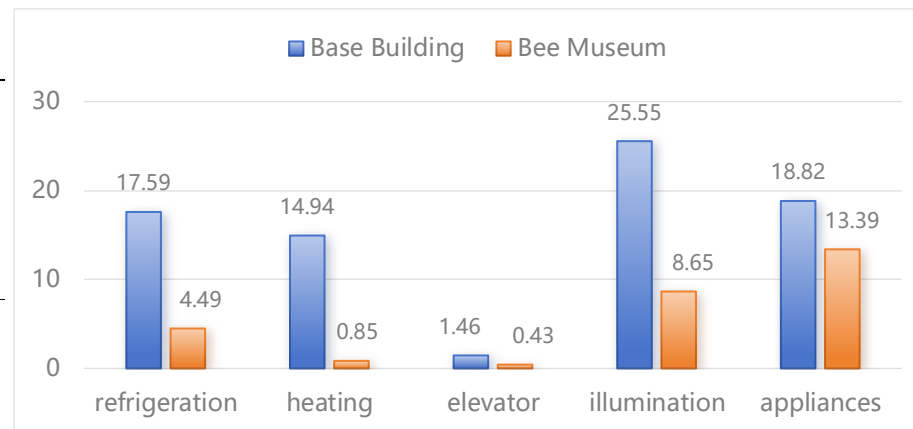


Fig. 3-7 Carbon emissions of the Bee Museum compared to the baseline building, Source: Sino-Swiss ZEB Project, Shaanxi Liuba Demonstration Project Team

As shown in Figure 3-7, removing the carbon emission reduction from photovoltaic power generation as well as greenfield carbon sinks, the carbon emission from the operation of the building body of the project is calculated to be 27.81tCO₂/a, which is 64% of the carbon emission reduction rate compared with that of the baseline building.

3.7 Process cumulative contribution analysis

Combined with the carbon emission calculation results in the previous section, it can be seen that the project generates -999.81tCO₂e of carbon emissions, the life cycle carbon emissions per unit of building area are -711.96 kgCO₂e/m², and the annual carbon emissions per unit of building area are -14.24kgCO₂e/ (m²·a) . The carbon reduction generated by the photovoltaic power generation and the carbon sinks in the green areas not only offsets the carbon emissions from energy consumption generated by heating and air conditioning, lighting, etc. in the building operation phase but also offsets the implied carbon emissions in other

phases; in addition, 393.35 tCO₂e of carbon sinks are generated due to the absorption of carbon dioxide by photosynthesis of landscaping plants. The next phase is the production and transport of building materials, which generates 1329.76 tCO₂e or 946.93 kgCO₂e/m² of carbon emissions. The remaining processes, such as construction and demolition, contributed to the rest of the carbon emissions. It can be seen that building production and transportation are the main contributors to building carbon emissions in the whole life cycle, which can be considered for optimisation and improvement.

In addition, for the building waste management phase, the reuse of a large number of recyclable building materials such as steel and glass reduces the carbon emissions of the building by 257.75 kgCO₂e/m² and improves the environmental performance of the building (Figure 3-8).

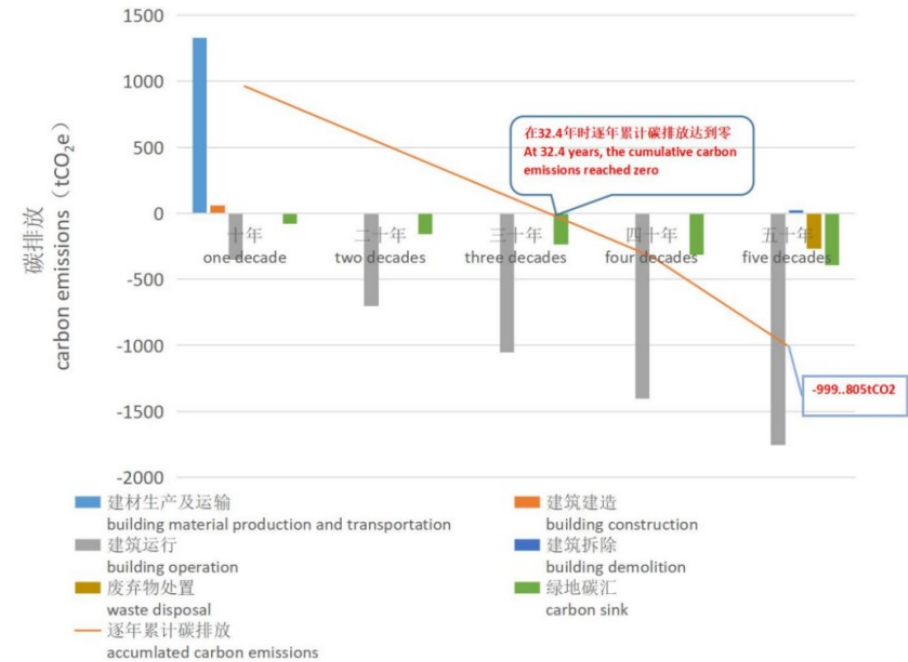


Fig. 3-8 Life Cycle Carbon Emission Changes of the Project, Source: Sino-Swiss ZEB Project, Shaanxi Liuba Demonstration Project Team

3.8 Bee Museum Project Summary and Recommendations

3.8.1 Summary and Interpretation of Analytical Results

- Note on completeness: Building carbon emissions in the demolition phase are calculated according to the 'Building Demolition Budget Quota' SH00-31-2019; data collection and modelling for the remaining phases is complete.
- Data quality assessment: The relevant activity data of this report are taken from the actual bill of quantities of the building project and the relevant carbon emission factors are taken from the validated standard GB/T51366-

2019. The CBCED database, the DH 2.0 database and the CPCFFD 2022 database therefore ensure the quality of the data.

3.8.2 Recommendations for project improvements

- Selecting building materials with good weathering performance can effectively extend the service life of building materials, thereby reducing energy consumption and carbon emissions;
- It is critical to choose high-performance building materials with low environmental impact, such as natural materials like wood. First of all, as a carbon-negative material, wood has a significant potential to reduce emissions. It not only reduces the environmental impact per unit of building material, but also reduces the amount of building material used, thereby reducing economic costs. Secondly, the superior thermal insulation properties of materials such as wood can effectively reduce the internal temperature of a building from changes in the external environment, thus helping to reduce the energy consumption of the building during its use.
- Increase the proportion of recyclable building materials used, this method can reduce the resources and energy consumption generated by the processing of new materials, for the sustainability of the building is very important, with good economic and social benefits. For example, steel, aluminium alloys and glass with high recycling rates;
- Increasing the proportion of green roofs and landscaped areas in buildings can reduce land carbon sinks, which are reduced by land use. At the same time as improving the space utilization rate and increasing the amount of green space, it can also improve the ecological environment around the base and provide good conditions for shade and recreation for nearby residents;
- Renewable energy is energy from nature, including solar energy, hydroelectric energy, wind energy, tidal energy, geothermal energy, biomass energy and so on. Renewable energy is an inexhaustible energy source. It has the advantages of wide distribution of resources and is suitable for local development. According to the characteristics and

economic performance of different types of renewable resources, currently widely used in construction is mainly solar energy, followed by and geothermal energy, biomass energy and wind energy; for urban buildings, the more widely used is solar energy. The combination of renewable energy and buildings has become an inevitable trend to promote energy saving and emission reduction in buildings.

4. TECHNICAL ANALYSIS OF THE BEE MUSEUM

4.1 Main technical measures of the project

The project is a full life cycle zero carbon building, and a variety of measures have been adopted to reduce the building's implied and operational carbon, the main technical measures are as follows.

4.1.1 Embodied carbon reduction measures

- Reduction design: the equipment pipes of the ground floor and first floor share the bridge and space in the ceiling of the ground floor, and the first floor does not have a ceiling. Reasonable design of floor height, the height of the ground floor is controlled at 4.5m.
- Lightweight design: Optimize column spacing in architectural design to reduce the dimensions of beams and columns, thereby minimizing steel consumption. Utilize refined steel for the steel frame of the second-floor terrace roof to reduce cross-sectional dimensions and lower steel usage.
- Green design: The structural system adopts low-carbon steel structure, and the use of green building materials exceeds 50%. The carbon reduction of recyclable materials is 361.95tCO₂e.
- Designed for longevity: The building plan adopts a frame structure to form a large open space with sufficient spatial flexibility and adaptability. The steel structure is treated with anti-corrosion and fire protection, which ensures a long structural life.
- Synergistic design: The design of the project upholds the concept of integrating design and technology to form an integrated team. Calculations of building energy consumption and carbon emissions are carried out throughout the design process to guide project optimization.

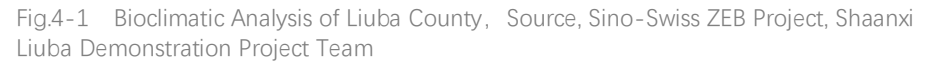
4.1.2 Operational carbon reduction measures

- Thermal insulation: Design appropriate thermal insulation performance of the building envelope, taking into account winter thermal insulation and summer thermal insulation.
- The building envelope selects a structure with a heat transfer coefficient of $K=0.21\text{W}/(\text{m}^2\cdot\text{K})$ for the roof, $K=0.30\text{W}/(\text{m}^2\cdot\text{K})$ for the external walls and $K=1.5\text{W}/(\text{m}^2\cdot\text{K})$ for the external windows (including the translucent curtain wall).
- Solar control: Select architectural glass curtain walling with a low solar heat gain coefficient (SHGC) and install external solar shading devices;
- Natural Ventilation: Increase the natural ventilation effect of the building by reasonably designing the opening fan of the glass curtain wall, controlling the building depth and other measures;
- Low-carbon space: based on meeting the needs of building use, exhibition and other needs, reasonably control the building height, and reduce the overall cooling and heating load of the building.
- Air-conditioning system: choose the first-class energy-efficient multi-connected air-conditioning system, suitable for energy saving part of the building load;
- Fresh air system: the fresh air system is equipped with a high-efficiency heat recovery module;
- Lighting system: select high-efficiency lighting fixtures, reasonably locate lamps and lanterns, and reduce the power density of building lighting;
- Monitoring system: set up a high-level building environment and energy consumption monitoring and control system, carry out sub-metering of electricity, water and renewable energy in the building, and continuously

Water Conservation: Selection of premium water-efficient plumbing fixtures to reduce building water consumption;

Sponge Park: Establishing rainwater recycling and reuse systems and wastewater treatment and reuse systems to eliminate the impact of rainwater and wastewater on Han River tributaries.

4.2.1 Feasibility analysis of passive technology



- The outdoor dry bulb temperature $T > 26^{\circ}\text{C}$ and the total solar radiation $I > 500 \text{ Wh/m}^2$ on the horizontal surface are taken as the conditions, and the moment of shading is selected. The time when the outdoor dry-bulb temperature is more than 26°C and the total solar radiation on the horizontal surface is more than 500 Wh/m^2 is 248 hours in total, accounting for 2.83% of the whole year, and concentrating in the months of June to August; when designing, effective building shading should be considered in these periods.

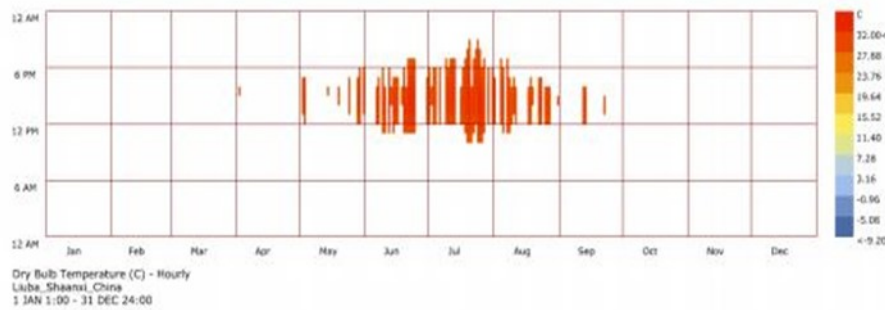


Fig 4-2 Outdoor Dry Bulb Temperature $>26^{\circ}\text{C}$, Source, Sino-Swiss ZEB Project, Shaanxi Liuba Demonstration Project Team

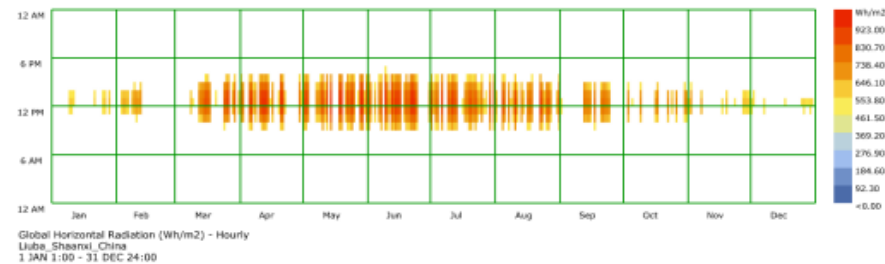


Fig. 4-3 Horizontal total solar radiation $>500 \text{ Wh/m}^2$, Source: Sino-Swiss ZEB Project, Shaanxi Liuba Demonstration Project Team

To sum up, the project finally through the curtain wall external sunshade design, the solar radiation of the curtain wall in the south direction in summer is effectively controlled, and the external sunshade can effectively block the direct sun, preventing the indoor temperature from being too high and glare; in winter, it can also satisfy the sunshine requirements, as shown in the following schematic diagram.

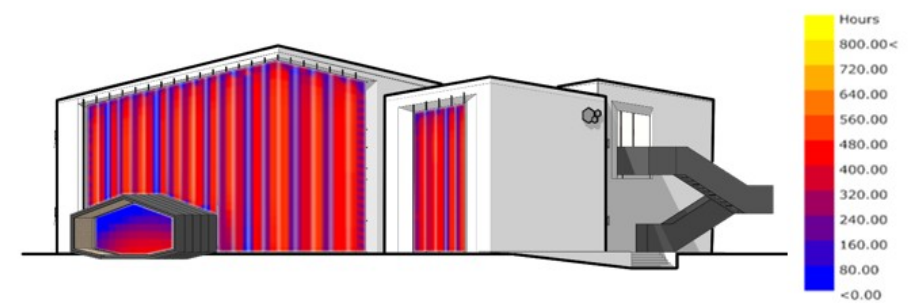


Fig. 4-4 (a) Schematic of solar radiation outside the summer months, Source: Sino-Swiss ZEB Project, Shaanxi Liuba Demonstration Project Team

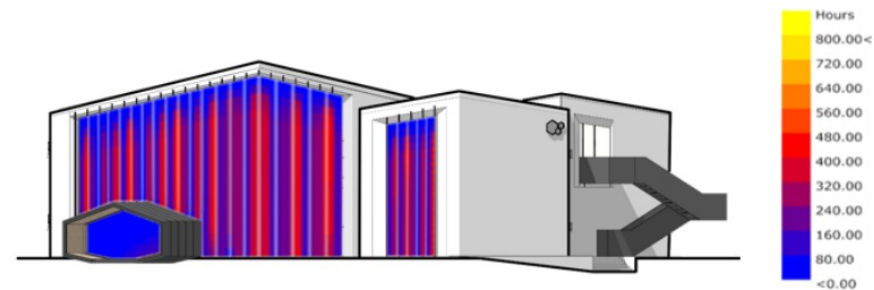


Fig. 4-4(b) Schematic of solar radiation in winter, Source: Sino-Swiss ZEB Project, Shaanxi Liuba Demonstration Project Team

■ Natural ventilation

The dominant wind direction in summer is south-east, and the dominant wind direction in winter is north-west; the overall layout of the project should be designed to facilitate natural ventilation in summer and over-season and to avoid

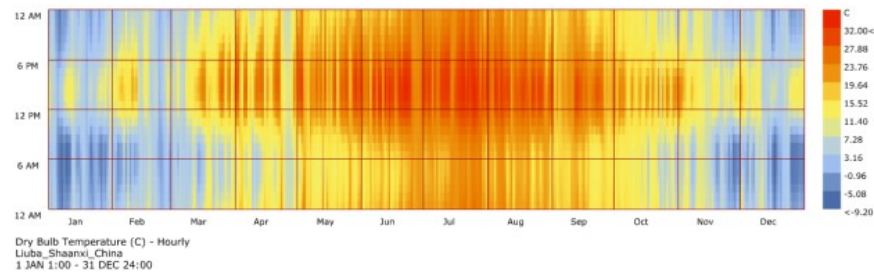


Fig. 4-5(a) Outdoor Dry Bulb Temperature 20~28°C, Source: Sino-Swiss ZEB Project, Shaanxi Liuba Demonstration Project Team

the main direction being perpendicular to the dominant wind direction in winter.

By analysing the temperature humidity and outdoor wind speed of the project site throughout the year, and taking the outdoor dry bulb temperature of 20 °C <T<28°C, 40%<relative humidity<90%, and 0.1 m/s<wind speed<3 m/s as the conditions, the project is screened out to find out the corresponding natural ventilation periods. A total of 990 h are suitable for natural ventilation design, accounting for 11.30% of the annual time; 454 h are suitable for natural ventilation during the daytime, and 536 h are suitable for natural ventilation at night.

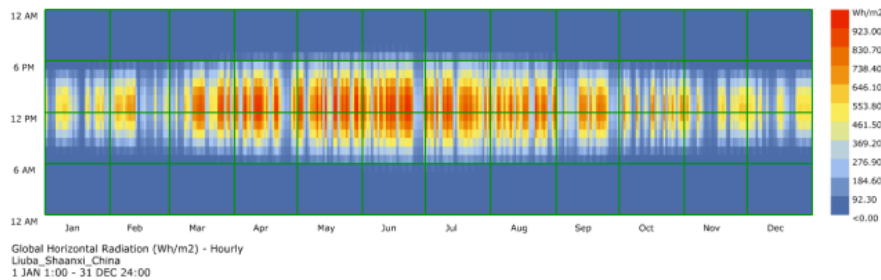


Fig. 4-5 (b) Relative humidity 40% to 90%, Source: Sino-Swiss ZEB Project, Shaanxi Liuba Demonstration Project Team

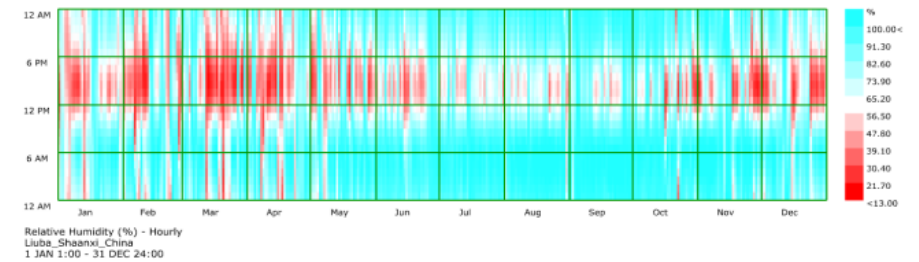


Fig.4-5 (c) Wind speed 0.1-3 m/s, Source: Sino-Swiss ZEB Project, Shaanxi Liuba Demonstration Project Team

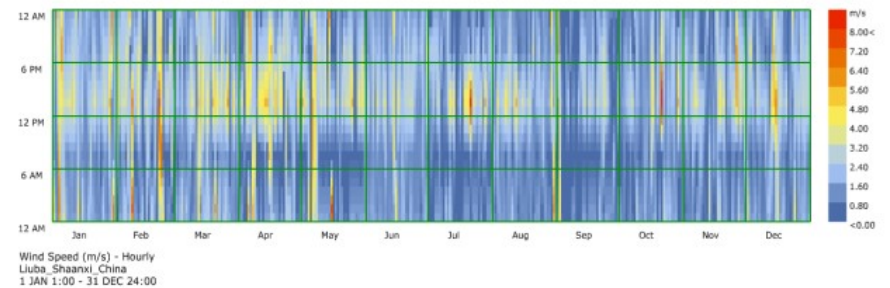


Fig. 4-5 (d) Total hourly radiation in the horizontal plane,source, ZEB Shaanxi Liuba Demonstration Project Team

Driven by the goal of maximising energy efficiency and reducing carbon emissions, the building design incorporates passive design concepts from the conception and planning phases, with a particular focus on the use of natural ventilation. Through careful planning of the building layout, window configurations and opening directions, the design team aims to maximise the use of natural forces to promote indoor air circulation and renewal. In particular, the wind characteristics

of the region in which the building is located have been thoroughly analysed, and the natural phenomenon of wind pressure differential has been skilfully exploited to create a series of highly efficient and sustainable natural ventilation systems through the rational layout of the building's air intakes and outlets, as shown in the diagram.

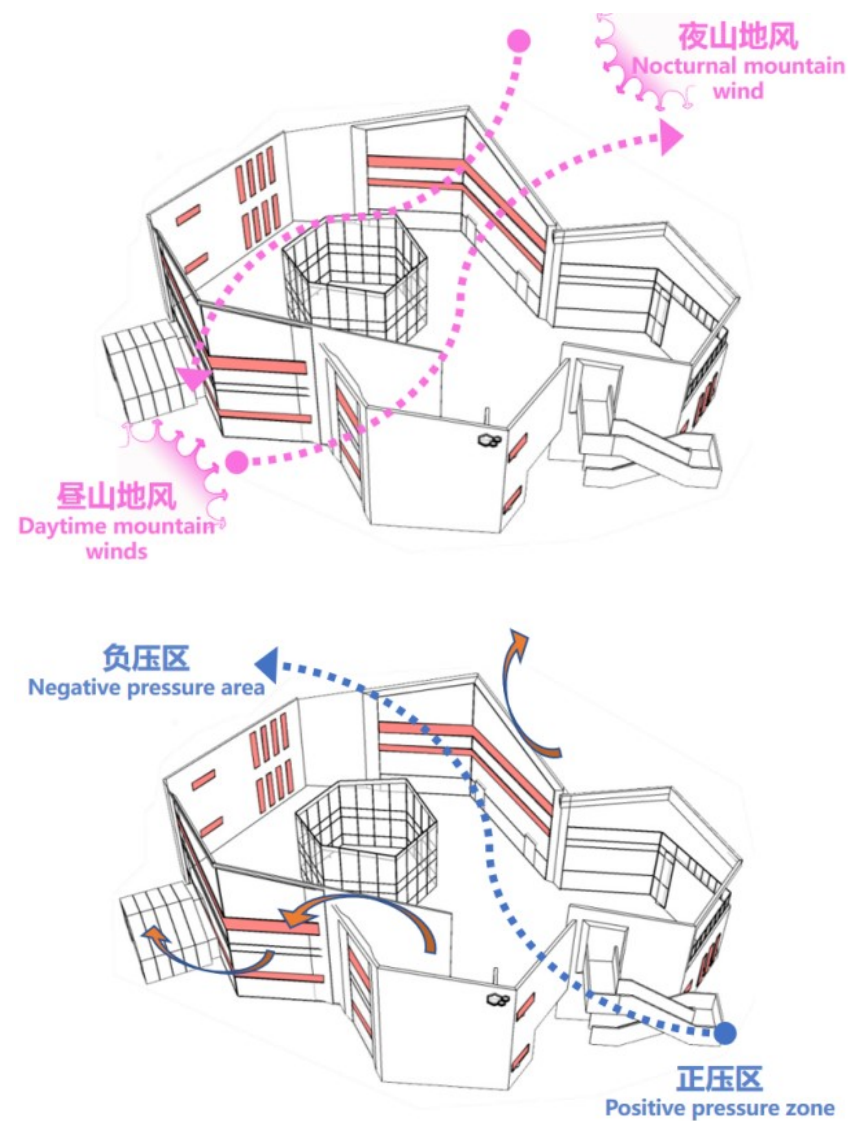


Fig. 4-6 Schematic diagram of natural ventilation, source, ZEB Shaanxi Liuba Demonstration Project Team

This design strategy not only reduces the reliance on traditional mechanical ventilation systems, thereby significantly reducing the building's energy consumption and carbon emissions during operation, but also significantly improves the comfort and health of the occupants, as the natural ventilation provides a fresher, more oxygen-rich indoor environment. In addition, the design team used precise calculations and simulations to ensure that the ventilation efficiency of the building would be maintained even in poor wind conditions, and where necessary, intelligent control mechanisms were used to seamlessly integrate the natural and supplemental ventilation systems, further enhancing the overall energy efficiency and environmental resilience of the building.

4.2.2 Renewable energy application technologies

■ Photovoltaic technology

Under the constraints of fossil fuel peaks and emissions reductions, new sources of energy are being actively sought, with solar energy being the hottest area. One hour of sunlight hitting the Earth produces enough energy to meet the world's energy needs for an entire year. Compared to fossil, nuclear and wind energy, solar photovoltaic (PV) technology applied to hydropower and biomass power generation is green, clean, safe and reliable. It is not subject to geographical constraints, does not damage the ecological environment, does not occupy land and food resources, and is a hope for sustainable development.

The average annual sunshine hours of the local area is 1804 hours; the total annual radiation is 4607.95 MJ/m², which provides an environment for the use of solar energy. Based on the solar energy resources of the geographical location of the project, it is recommended to install the PV on the roof, or to use ground-mounted PV or roof skylights with PV glass, and to use high-efficiency

monocrystalline silicon PV panels. According to the electricity demand of the project, the area of PV panels is calculated and the PV power generation system is reasonably designed.

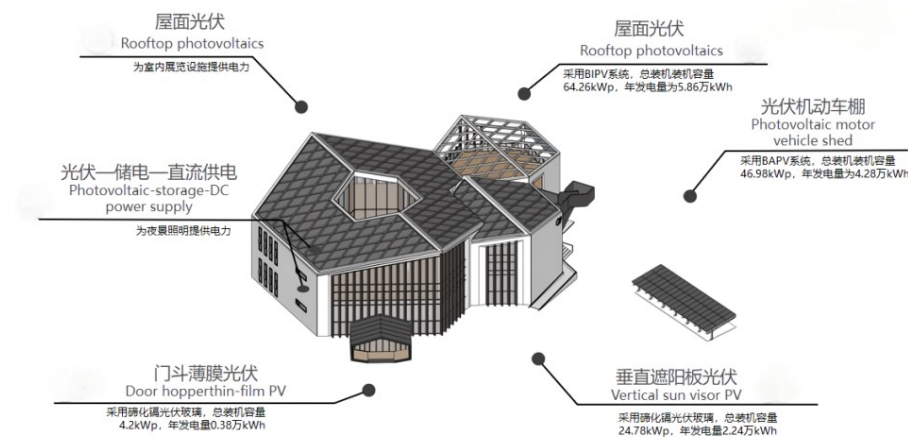


Fig.4-7 National Distribution of Solar Energy Resources, Source: Sino-Swiss ZEB Project, Shaanxi Liuba Demonstration Project Team

According to the measurement, the roof area where PV panels can be placed for this project is about 1300m² and the area where PV panels can be laid is about 240m², 120 PV panels can be laid, and the installed capacity is 63KW, and the annual power generation of this project is estimated to be about 74,000 degrees. The following is the location of the PV installation for this project.

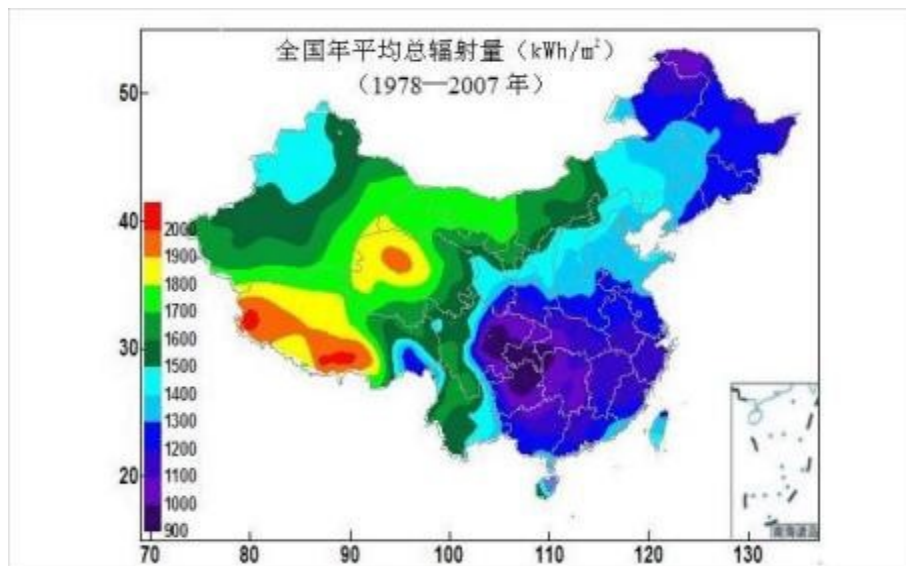


Fig. 4-8 Distribution of Photovoltaic Technology Applications, Source: Sino-Swiss ZEB Project, Shaanxi Liuba Demonstration Project Team

4.2.3 HVAC design

According to the survey report on the municipal conditions of the project, the project does not have municipal heating conditions, and the heat source programme has been demonstrated, resulting in the use of a VRF air-conditioning system (multi-unit).

Variable frequency multi-unit consists of three parts: an indoor unit, copper pipe and outdoor unit, the system is simple with few failure points and a stable system, each indoor unit can be opened and controlled separately, and the host frequency conversion operation and the unit has strong adjustment ability. The refrigerant flowing in the pipe of the system will not condense above minus 40 degrees

Celsius, and there is no need for anti-freezing treatment for the pipe in winter; at the same time, the refrigerant in the pipe is non-corrosive. A rough layout is shown below.

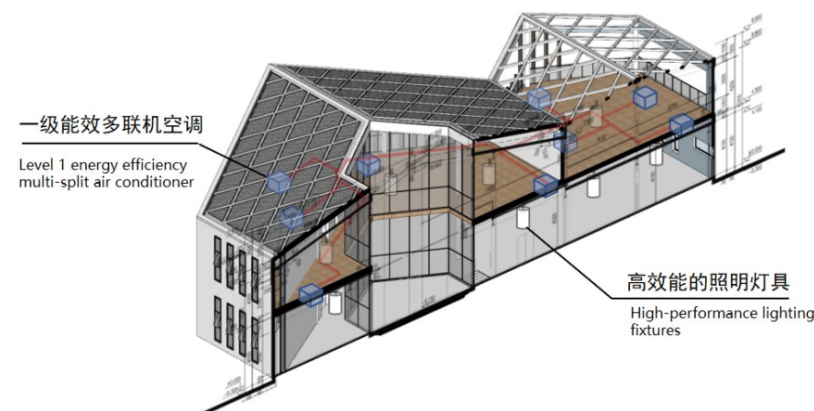


Fig.4-9 Schematic diagram of multi-unit air-conditioning arrangement, Source: Sino-Swiss ZEB Project, Shaanxi Liuba Demonstration Project Team

▪ Summer Fresh Air

Fresh air systems in the indoor staff to provide the minimum required fresh air volume at the same time, should also provide the indoor cooling and heating required to maintain the indoor environmental index requirements while meeting the passive house on the demand for cooling, and heating energy consumption.

According to the international standard "Design Code for Heating, Ventilation and Air Conditioning of Civil Buildings" GB50736-2012 Article 3.0.6, public buildings with fresh air systems, the minimum required fresh air volume per person in the main rooms should be in accordance with the provisions of the following table.

Type	Fresh air volume m ³ /(h · person)
offices	30
room	30
Lobby, Four Seasons Hall	10

Table 4-1 Minimum Fresh Air Requirements per Person in Main Rooms of Public Buildings, Source: Sino-Swiss ZEB Project, Shaanxi Liuba Demonstration Project Team

▪ Heating in winter

The high pressure chamber scroll compressor is used to improve the overall heating performance of the unit, while the heat exchanger adopts a new type of corrugated fins to improve the heat exchange area. By applying sub-temperature control, operating time and combining current, power and part load operating conditions, variable parameter defrost and optimized defrost control can be performed to maximize the unit's heating capacity and indoor thermal comfort.

Increased installation of fresh air heat recovery: The air conditioning system adopts the fresh air heat recovery air conditioning unit, and the heat recovery efficiency is more than 70%. After the cold and dry outdoor air in winter is warmed up by the apparent heat exchanger, the humidity in the fresh air is further reduced. According to the requirements of the Technical Standards for Near-Zero Energy Buildings (GB/T 51350-2019), the apparent heat efficiency of the heat exchange capacity of the new air heat recovery unit is not less than 75%, and the total heat efficiency is not less than 70%.

4.2.4 Requirements for landscape design

The building green ratio shall be calculated according to the following formula:

$$GPR = \frac{\sum(LA_i \times PA_i \times N_i) + S_f \times 3 + S_g}{S} \times 100\%$$

In the formula:

- GPR —— green ratio, %
- LA_i —— Leaf area index of trees in category i;
- PA_i —— Projected area of trees in category i, m²;
- N_i —— Number of trees in category i;
- S_f —— Shrub footprint on site, m²;
- S_g —— Grassed area on the site, m²;
- S —— Site area, m²;

The leaf area index of trees with sparse crowns can be taken as 2; the leaf area index of trees with dense crowns can be taken as 4; the projected area of trees should be calculated according to the data in the seedling table; the three-dimensional greening within the site can be included in the calculation.

The site area of the project is about 4300m², and the green area rate is calculated at 36%, with an area of about 1553m², in which trees, shrubs and grasses are combined, with a ratio of 4:4:2, and the greening rate is calculated to be about 0.94, which can reach the level of gold-grade buildings in the Carbon Neutrality Building Evaluation Guidelines.

4.2.5 Lighting Design

Energy-saving electrical equipment is used, and the electrical installations meet the energy-saving evaluation value requirements of the relevant current

international standards, and the distribution room and the electric well are located in the load centre. The transformer is energy-saving and environmentally friendly, low-loss and low-noise, and the wiring group is a dry-type transformer of Dyn11. The transformer comes with a thermostat and a forced ventilation device.

Lighting system adopts energy-saving light source, lamps and accessories, lighting design LPD value in accordance with and lower than the "General Specification for Building Energy Conservation and Renewable Energy Utilisation" (GB 55015-2021) limit value of the provisions of the building and reasonable design of the lighting control method of large space and other public areas to take zoning, timing, sensing and other energy-saving control measures, corridors, stairwells with energy-saving self-extinguishing switch.

Name	Designing building lighting power density (W/m ²)	Current value of lighting power density (W/m ²)
lobby	8	10
exhibition room	8	10
pedagogical interaction	8	9
equipment room	5	6
toilets	5	6

Table 4.2 Lighting power density for each functional room, Source: Xi'an University of Architecture and Technology

4.2.6 Intelligent monitoring systems

Environmental monitoring systems

Monitoring function:

- Monitor, display and record real-time indoor dry bulb temperature, humidity, CO₂ and PM2.5 levels.
- Monitor and display the trend of indoor meteorological parameters, key turning points and anomalies.
- Provide meteorological data statistics of each functional area, and transmit monitoring data and equipment operation status to the background server at regular intervals according to the back-end service instructions, and perform statistical analysis and processing of the collected monitoring data.
- Monitor the temperature of the air outlet of the indoor unit of the multi-connected air conditioner and communicate with the system to adjust the supply air temperature.

Alarm function:

- Pollutant exceeding alarm: timely alarm when indoor pollutants exceed the limit.
- Indoor unit air outlet temperature alarm: indoor environment monitoring temperature and humidity and air conditioning system refrigerant matching shunt and heat exchanger variable capacity to regulate the indoor heat and humidity environment.

Energy consumption monitoring

Monitoring function:

- Monitor and display the daily, weekly and monthly energy consumption data of each branch or piece of equipment, and produce year-on-year and year-to-year analysis charts.
- Monitor and display the trend, key turning points and anomalies of the energy consumption of each energy-consuming branch and equipment.
- Obtain summary statistics of energy consumption data for each energy-consuming item and area.
- Monitor and display the current, voltage, active power, reactive power, power factor, harmonic rate (not required for bus couplers), electric energy, and switch status of

the main incoming lines and bus couplers in the low-voltage switchgear of the substation.

- Monitors and displays the current, voltage, rated installed power, real time active power, reactive power (capacitor bank), power factor, kWh, long delay current protection setpoint and switching status of the outgoing line of the substation low-voltage cabinet.
- Monitoring and display of transformer load ratio, three-phase winding temperature and fan start/stop status.

Alarm function:

- Transformer: Transformer overheat alarm;
- Low-voltage cabinet inlet and outlet lines: abnormal voltage and overload alarm.

5. ANALYSIS OF CARBON EMISSION CALCULATION METHODS IN EUROPE

5.1 Current status of research on calculating carbon emissions for buildings in Europe

Firstly, with regard to the sources of carbon emissions from buildings, there are many different ways of assessing them around the world, the most widely used in Europe currently being the European Carbon Emission Agreement (ECA), which divides the sources of greenhouse gas emissions into three areas: direct emissions, indirect emissions and other indirect emissions. The ISO series of standards, such as the ISO 14000 series of environmental management standards, of which the ISO 14064(1-3) standard is an LCA. The ISO 14040 standard is a quantitative standard related to carbon footprint, based on the ISO 14040 standard. The ISO 14064 series of standards, published in 2006 and revised in 2018 and 2019, specifies an international model for the management, reporting and validation of GHG information and data. As a practical tool, ISO 14064 enables governments and businesses to account for GHG emissions to a harmonized standard while supporting carbon trading. There is also EN 15978, which provides a comprehensive framework for calculating and assessing the carbon emissions of buildings throughout their life cycle.

In terms of specific calculation methods, the following are examples from a few representative countries.

5.1.1 Switzerland

As a member of the International Organizations for standardization (ISO), Switzerland adheres strictly to the international standards issued by the ISO. In

addition to ISO standards, Switzerland, as a member of the European Economic Area (EEA), has also adopted European standards, which are often in line with ISO standards. In the case of EN 15978, for example, the standard first defines its scope, lists normative references, clarifies terminology and definitions, sets out the basic principles for assessing the environmental performance of buildings and describes in detail the calculation methods for the assessment. It also recommends the use of calculation tools and software, provides examples to aid understanding and application of the standard, and provides additional reference information and data.

EN 15978 places particular emphasis on the assessment of the whole life cycle of a building, including all phases of design, construction, use, maintenance, refurbishment and demolition. It covers a wide range of environmental performance indicators such as primary energy demand, energy efficiency, operational energy, water consumption, global warming potential, ozone depletion potential, etc. The standard provides detailed calculations of the environmental performance of buildings. The standard provides detailed calculation methods and procedures for assessing the environmental impact of buildings at different phases of their life cycle. At the same time, it recommends the use of validated calculation tools and software to perform the environmental performance assessment in order to improve the accuracy and efficiency of the assessment.

Switzerland also has its own standard for calculating CO₂ emissions, SIA 2040, which guides the calculation of energy consumption and carbon emissions in buildings. The standard specifies Abgrenzung (boundaries), Normative Verweisungen (normative references) and Standard- Berechnungsverfahren (standard calculation methods). There is also SIA 380/1, although this standard is primarily concerned with the calculation of energy consumption in buildings

rather than directly addressing the calculation of carbon emissions from buildings. However, because energy consumption is directly linked to energy consumption and associated carbon emissions, building energy consumption calculations are an important part of assessing carbon emissions from buildings.

In addition, the official website of the Swiss Federal Office for the Environment provides a CO₂ calculator to estimate the CO₂ emissions of all buildings under standard conditions. The calculator is based on data from the Swiss Federal Statistical Office's Register of Buildings and Dwellings (RBD) and includes information on the building's use, heated area, year of construction, altitude and topographical location.

5.1.2 United Kingdom

In the UK, as an active implementer of the EU Energy Performance of Building Directive (EPBD), the government has adopted the Standard Assessment Procedure for Energy Rating of Dwellings (SAP) to assess the energy consumption and carbon emissions of residential buildings. Of Dwellings (SAP) to assess the energy consumption and carbon emission of residential buildings. The assessment procedure takes into account factors such as the size and shape of the dwelling, heat transfer coefficient of the envelope, hot water usage, lighting, appliance indoor design temperature, etc., to calculate the energy consumption and annual carbon emission per unit of floor area.

For non-residential buildings, the Communities and Local Government Authority (CLGA) has developed the National Calculation Methodology Modelling Guide (NCM) for Buildings other than Residential Buildings in England and Wales and A Technical Manual for Simplified Building Energy Model (A Technical Manual for Simplified Building Energy Model). The NCM provides the information and

technical requirements needed to calculate carbon emission targets and actual building carbon emissions and provides detailed technical guidance on the government's use of SBEM and other approved software.

Based on the requirements of the NCM, different software companies have developed a variety of software for calculating and analysing building carbon emission, such as SBEM developed by The British Research Establishment (BRE), TAS series developed by Clifffield Centre for Technical Research, 'Carbon Checker' developed by South Facing Services. SBEM was developed by The British Research Establishment (BRE), TAS was developed by Clayfield Technology Research Centre, Carbon Checker was developed by South Facing Services and Hevacomp Interface was developed by Hcvacomp. This software can simulate the building environment and equipment systems and calculate building carbon emissions, among which SBEM is the most widely used in the UK.

SBEM calculates the carbon emission of the designed building according to the relevant building regulations in the UK and determines whether the new building meets the regulations based on the Target Emission Rate (TER) calculated by NCM based on the reference building. SBEM uses data from 20 building types and 68 building functional zones in the database to calculate the carbon emissions from the energy consumption of the building, as well as the carbon emissions reduction from renewable energy and clean energy systems, to arrive at the carbon emissions of the designed building.

5.1.3 German

In 2008, The German Sustainable Building Council (DGNB) launched the DGNB Sustainable Building Assessment Technology System, which takes the annual carbon emission per unit of building area as the unit of calculation, proposes a

complete and clear calculation method for building carbon emission, and establishes a database for carbon emission of building materials and building equipment. The database of carbon emissions from building materials and construction equipment has been established. The assessment technology system divides the whole life cycle of a building into four phases: production of building materials and construction, use of the building, maintenance and renewal of the building, and demolition and reuse of the building. The calculation methods for each phase are as follows:

Production of building materials and construction: Taking into account the carbon emissions from the extraction of raw materials, the production of materials, the transport of materials and the construction of the building, the building is disassembled according to the German building system, sorted according to structural and decorative parts and configurations, the volume of all building materials and building equipment used in the building is calculated, the loss of materials during construction and transport of materials is taken into account, and a comparison is made with relevant databases to derive the CO₂ equivalents of the different materials and equipment used in the production process. Carbon emissions from materials are calculated over 100 years.

Usage of building: This mainly includes the energy used for heating, cooling, ventilation, lighting and other functions to maintain the normal use of the building. According to the energy consumption of the building in the process of use, different types of energy are distinguished, the primary energy consumption is calculated and then the corresponding building carbon emissions data are converted.

Building maintenance and renewal: This refers to the necessary renewal,

maintenance and replacement of equipment during the life cycle of a building to ensure that the building is in a condition that meets all functional requirements. Calculate the types and quantities of materials and equipment that will need to be replaced during the life cycle of the building (based on 50 years) and compare with relevant databases to determine the carbon emissions of the building in the process of maintenance and renewal over the life cycle of the building.

Building demolition and reuse: All building materials and equipment at the end of the building life cycle are classified as recyclable materials and construction waste to be processed. By comparing the relevant databases, data can be obtained on the carbon emissions of the building during dismantling and reuse.

5.2 comparative analysis

In Chapter 1, it was mentioned that the most authoritative and widely applied carbon emission calculation method in the construction field is the carbon emission factor method. The differences in the application of this method between China and foreign countries are mainly reflected in the division and definition of calculation boundaries. The following will focus on the comparative analysis of the division of building carbon emission calculation boundaries and the calculation methods of building carbon emission factors.

5.2.1 Delineation of computational boundaries

First of all, it is necessary to clarify the scope of the accounting boundary is within the full life cycle of the building, from the meaning of the building life cycle (building life cycle), which refers to the whole process from the extraction of raw materials for construction to the disposal of the building dismantling, generally including:

- Raw material extraction and transport.
- Production and processing of materials, parts and components, and construction equipment (hereinafter referred to as 'materials').
- Off-site transport of materials.
- On-site construction, installation and decoration of buildings.
- Operation, repair, maintenance and reinforcement of buildings.
- Building demolition, waste disposal.

At present, there are various ways to divide the phases to which each of the above processes belongs when calculating building life cycle carbon emission, see Table 5.1. Standard For Building Carbon Emission Calculation (GB/T51366-2019) divides the building life cycle into three phases from the perspective of consistency of the calculation methodology: the operation phase, the construction and dismantling phase, and the production and transport of building materials phase. However, most of the current Chinese and international scholars and international standards (e.g. EN 15978: 2011) break down the building life cycle phases into four phases from the perspective of their chronological order and activity characteristics: the production phase, the construction phase, the operation phase and the disposal phase. (In Table 5.2 for the division of phases.) Among them, the production and construction phases are the birth and formation of a building, and are often collectively referred to as the materialization phase; the operation phase is the actual embodiment of the building's functions, and is generally considered to be the main body of traditional building carbon emission; and the disposal phase represents the end of the building's life.

Number	phases
2	construction upstream, construction downstream
2	construction phase, operational phase
3	material production, building construction, building demolition
3	materialization phase, operation and maintenance, dismantling and disposal
3	building construction, building operation, building demolition
4	production, construction, operation, disposal
5	raw material extraction, material production, building construction, usage and maintenance, dismantling and disposal
5	material preparation, building construction, building operation, building demolition, waste disposal and recycling

Table 5.1 phases of the whole life cycle of a building. Source: Xi'an University of Architecture and Technology

China	European
operation phase	production phase
construction and demolition phase	construction phase
building materials production and transportation phase	operation phase
	disposal phase

Table 5.2 Common Building Life Cycle phases in China and Europe. Source: Xi'an University of Architecture and Technology

Depending on the carbon accounting boundary, the system boundary of the building life cycle can be classified as 'cradle to gate', 'cradle to site' and 'cradle to grave'. Cradle to grave' and so on. The "cradle to factory" system boundary

includes the upstream process from the extraction of raw materials to the time when the finished building materials or components leave the factory; the "cradle to site" system boundary adds the transport of building materials and components, construction and lifting, and construction waste, based on the former. Based on the former, the "cradle to site" system boundary includes the transport of building materials and components, construction and lifting on-site and the disposal of construction waste, etc. The cradle-to-grave system boundary, based on the first two, takes into account the subsequent operation, maintenance, demolition and disposal of the building, i.e. LCA in the usual sense.

Scholars around the world have proposed that a hierarchical system boundary can be established based on the time scale, spatial scale and technological objectives of building carbon emission accounting, see Figure 5-1 below.

- Takes the time scale as the boundary and expands it into six phases by considering the upstream and downstream links of industry based on the four basic phases of production, construction, operation and disposal.
- Takes the spatial scale as the boundary and divides the system boundary into the scales of the main structure, individual buildings, building districts, urban and rural building clusters and regional construction industry.
- Based on the technical objectives, the system boundary is divided into three levels: 'Considering All Factors', 'Considering Key Factors' and 'Considering Differentiation Factors', which are respectively applicable to the comprehensive estimation and accounting of building carbon emissions, the general analysis of building carbon emission levels and reduction potentials, and the comparison and optimization of carbon emissions of different design and technical solutions.

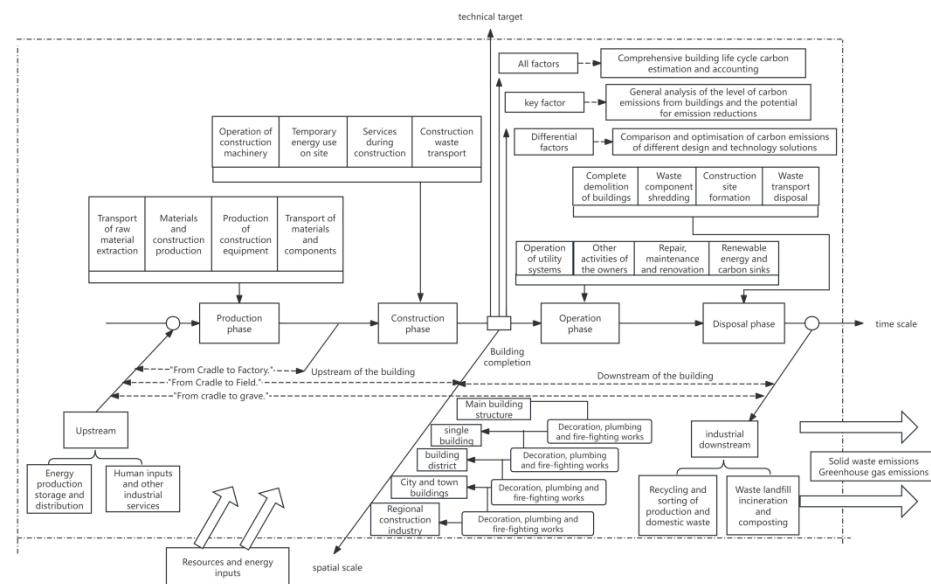


Fig. 5-1 Boundary diagram for calculating carbon emissions of common buildings in China and abroad. Source, Xi'an University of Architecture and Technology

A comparative analysis of the building carbon emission accounting boundary and the calculation methods of building carbon emission factors shows that there are both similarities and differences between Europe and China in terms of building carbon emission calculation. In terms of the accounting boundary, the difference in phase classification reflects the difference in emphasis between the two sides in considering the whole life cycle of buildings. The classification of system boundaries reflects the different needs for depth and breadth of accounting boundaries. These differences also prompt us to think about how to learn from each other's advantages in future building carbon emission calculations and continuously improve their respective calculation systems, to more accurately measure the carbon emissions of the whole life cycle of buildings, provide more

solid data support and decision-making basis for carbon emission reduction in the building sector, and promote the development of the global building industry in a greener and more sustainable direction. With the deepening of the research, it is believed that both sides will continue to make new progress in the field of building carbon emission calculation, further narrowing the gap and jointly addressing the challenges of global climate change.

5.2.2 Methodology for calculating carbon emission factors

As the theoretical basis of the carbon emission factor method, the carbon emission factor largely determines the accuracy of the carbon emission calculation of buildings, so it is particularly important to research and apply standardised methods for it. European scholars have conducted a series of research on carbon emission factor calculation, and the ISO 14044 and EN 15804 standards have proposed carbon emission factor calculation methods based on product category declaration (EPD) and life cycle assessment (LCA). The EPD method refers to the testing and evaluation of building materials or products during the production process to derive the value of their carbon emission factors.

In addition, ISO 14067 specifies the methods and steps for quantifying carbon emission factors, including defining scope objectives, calculation methods, reporting results, verification and auditing procedures, etc. ISO 14064-2 and ISO 14064-3 describe and qualify the content of carbon emission factors for the energy and transport sectors, such as the calorific value of energy, the carbon content and key factors such as the type of transport vehicle and the type of fuel, and describe and qualify the calculation of carbon emission factors for the energy and transport sectors. ISO 14064-2 and ISO 14064-3 describe and qualify the key factors such as energy calorific value, carbon content type of transport vehicle,

type of fuel, etc., and describe the principle of the calculation method. ISO 21930 requires that the carbon emission factor of building products should be calculated based on the whole life cycle, restricts the unit of the carbon emission factor, data source and updating period, etc., and requires the use of the LCA method to calculate the carbon emission factor.

In fact, although some international standards provide basic guidance on data quality control, methods for assessing the quality of data on building carbon emission factors have not yet been established. With the growing importance of building carbon emission research, the concern and control of data quality has become more important.

In this regard, some scholars have proposed a spectrum matrix evaluation method based on technology representation, time representation, geographical representation and data acquisition method, and evaluated the data quality of each process and phase based on this method in some case studies; while the Swiss Ecoinvent database has further proposed a DQI scoring mechanism based on the basic quality of inventory data of each unit process, which transforms the quality of each inventory data into mathematical parameters. The quality of each inventory data is transformed into the overall uncertainty in the form of mathematical parameters, and on this basis, methods such as error transfer algorithm, weighted average algorithm and Taylor series expansion are proposed to calculate the transfer of the basic uncertainty of each inventory data in the model, which is then transformed into the resultant uncertainty.

In China, other researchers have also conducted preliminary explorations on data quality assessment methods, data quality control methods, and case studies of LCA data quality. However, like the current state of international research, these

methods measure the uncertainty of the inventory data obtained in the process of data collection and rounding holistically. This measurement does not take into account the upstream uncertainty of the initial data as well as the uncertainty caused by the inventory data algorithm itself, so it cannot reflect the influence of the initial data values and the inventory data algorithm on the overall uncertainty of the results. In addition, this method is limited by the subjective feelings and judgements of the assessor during the study, and its scoring system is rather vague, which further weakens the significance of the data quality assessment during the data collection process.

Overall, the limitations of the current state of research on building carbon emission factors due to the delineation of the accounting boundary and the assessment of data quality have led to differences in the overall calculation model and assessment system, so that a standardized process and methodology for the calculation of building carbon emission factors that is highly accepted and scientifically standardized has yet to be established.

6. ANALYSIS OF IMPROVEMENT POTENTIAL IN BUILDING CARBON EMISSION CALCULATION METHODOLOGIES

As an advanced industrialized country, Switzerland has rich experience in carbon reduction in various industries. As shown in Figure 6-1, since 2000, the CO₂ emissions of many industries in Switzerland have been significantly reduced, especially in the construction industry, from 11MtCO₂ in 2000 to 6MtCO₂ in 2022. Based on the advanced experience of Switzerland and Europe, the following section will propose the corresponding direction of improvement in the light of China's national conditions.

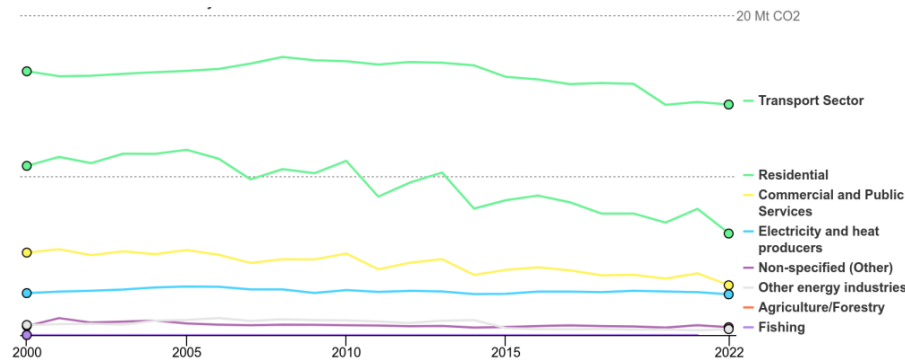


Figure 6-1 Evolution of CO₂ emissions by sector in Switzerland, 2000-2022, Source: IEA Data Services website. (<https://www.iea.org/countries/switzerland/emissions>)

6.1 Deepening the accurate calculation analysis of carbon emission calculations for buildings at different phases of the process

The current definition of building attributes at the design phase essentially determines the carbon footprint of a building over its entire life cycle. However, we have not yet reached the phase of assembly or use of the physical components. The actual process of generating carbon emissions of buildings is closely linked to the production of materials, the construction of the building and the operation phase, which involves relevant sectors that have a direct impact on the low carbon transformation of the building industry. The production of building materials involves a wide range of manufacturing sectors, while the operational phase of the building is linked to almost all sectors.

Therefore, calculating the carbon emissions of buildings in the future will no longer be limited to the full life cycle assessment at the design phase. Stakeholders will need to carry out more detailed calculations and analyses according to the development needs of their own industries. For example, carbon emission factors will become a key indicator for assessing future building materials and construction equipment. Through precise calculations by phase or category, we can continuously improve a library of carbon emission factors that includes materials, energy, construction machinery and so on.

6.2 Expansion of digitalisation and information technology applications

As technology advances, architectural drawings, on which building design and management depend, have evolved from traditional two-dimensional graphical

information to multi-dimensional and digital representations. The introduction of digital design parameters has significantly improved the efficiency and accuracy of computational analysis. Combining digital design with the calculation and analysis of building carbon emissions helps to develop more efficient calculation tools. The application of information technology at both the micro and macro levels of building carbon calculation will be further developed.

For example, the authenticity and reliability of carbon emission data in the construction industry are often questioned by the public, and opaque carbon data management also hinders the healthy development of the carbon trading market. Led or urged by the government to intervene with information technologies such as block chain, the credibility and validity of data sources can be ensured through establishing registration and settlement platforms and constructing monitoring and verification research institutions, thus promoting the benign and orderly development of the construction carbon trading market.

6.3 Integrated platform for carbon emission accounting, evaluation and optimization

The accounting and management of carbon emissions from buildings is becoming a focus of international academic attention and is critical for the building-related industries to meet their 'double carbon' targets. Looking ahead, the field of building carbon accounting is expected to develop carbon monitoring systems and carbon tracking technologies that cover the entire design-build-operate-maintain-demolish (DBM) lifecycle. In the area of building carbon accounting, it is expected that carbon monitoring systems and carbon tracking technologies will be developed that cover the entire design-build-operation-maintenance-demolition (DBM) lifecycle.

In the future, it will also be necessary to develop carbon emission measurement and analysis tools that can be applied at different levels, such as cities, villages, communities and individual buildings, and to propose a low-carbon building rating index system. The construction of a comprehensive carbon emission assessment and analysis model will fully support dynamic assessment and management. In terms of management and control, an intelligent carbon emission management and optimization platform for urban and rural construction will be established through digital modelling combined with artificial intelligence, optimization control and other intelligent technologies. This will achieve measurable, assessable, manageable, and reducible carbon emissions in urban and rural construction, thereby enhancing the intelligence, efficiency, and scientific level of carbon reduction and control in the urban-rural construction sector. It will also drive urban and rural construction toward the direction of green and scientific development.

A1. Reference

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A2. Glossary

CABR	China Academy of Building Research
DP	Demonstration Project
FHNW	University of Applied Sciences Northwestern Switzerland
HSLU	Lucerne University of Applied Sciences and Arts
HVAC	Heating, Ventilation, and Air Conditioning
Mohurd	Ministry of Housing and Urban-Rural Development (China)
NEZB	Net Zero Energy Building
PV	Photovoltaics
SDC	Swiss Agency for Development and Cooperation
SIA	Swiss Society of Engineers and Architects
Willers	Willers Jobst Engineering AG
ZEB	Zero Emission Buildings
ZHAW	Zurich University of Applied Sciences



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