SEQUENCING THE CARBON EMISSION CYCLE OF GREEN BUILDINGS IN CHINA BASED ON AN ECOLOGICAL CITY PERSPECTIVE

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Reception: 03/03/2023 **Acceptance**: 17/04/2023 **Publication**: 16/05/2023

Suggested citation:

Wang, Y. (2023). **Sequencing the carbon emission cycle of green buildings in China based on an ecological city perspective**. *3C TIC. Cuadernos de desarrollo aplicados a las TIC, 12(2)*, 117-135. https://doi.org/10.17993/3ctic.2023.122.117-135

ABSTRACT

As people's basic material living standards continue to rise, the demand for a better living environment and a better life is becoming increasingly strong. Since the 18th and 19th National Congresses of the Party proposed to carry out ecological civilization construction and build a beautiful China, carrying out ecological city construction has become one of the effective ways to solve the current urban development problems. In this paper, we summarise the latest research on green building assessment systems, life-cycle carbon emissions and life-cycle costs of buildings. We find that China's green building assessment system still has many shortcomings compared to the world's advanced green building assessment systems. Based on this, we have conducted a sequencing analysis of the life cycle carbon emissions of green buildings in China, so that buildings can meet the green building rating and at the same time achieve energy and carbon savings. The results of the study show that the building use phase has the highest carbon emissions in the building life cycle, accounting for 77% of the life cycle carbon emissions.

KEYWORDS

Ecological cities; green buildings; carbon emissions; cycle sequencing; accounting

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https://doi.org/10.17993/3ctic.2023.122.117-135

4. DISCUSSION

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https://doi.org/10.17993/3ctic.2023.122.117-135

1. INTRODUCTION

The city is a living organism, and the construction of an eco-city is aimed at achieving the harmonious development of man and nature and establishing a virtuous cycle of urban ecology. It emphasises the harmonious development and overall ecology of society, economy, culture and nature [1,2]. For a long time, China's urban construction has mainly been based on the model of rough and loose growth, which has led to the incompatibility between urban development and ecology and subsequently to the emergence of many urban problems. Against this background, urban ecological civilisation has emerged as an urgent solution to urban problems and a healthy, green living environment for human beings [3-5]. In addition, as the global climate problem continues to be serious, people are paying more and more attention to the issue of greenhouse gas emissions [6,7]. As the construction sector accounts for about one-third of global greenhouse gas emissions, reducing greenhouse gas emissions in the construction sector is a major concern worldwide. Among the necessary ways to reduce low carbon emissions in the building sector are not only improving building energy efficiency and reducing building energy consumption, but also increasing research and investment in clean energy and renewable energy technologies [8-10].

In recent years, theoretical and practical research on ecological cities has gradually become a new direction for urban construction in the new era. In urban construction, planners and city builders must adhere to the principle of eco-friendly construction, strictly adhere to the 'ecological bottom line', form a rational structure of production, living and ecological space, and improve the efficiency of land use. Supriana et al[12] argue that a city's knowledge management system is important to encourage people to create, share and use knowledge. Dai et al.[13] summarised different urban lighting projects in the context of eco-city construction. They found that there are currently three main indicators for urban lighting projects, which are energy saving, environmental protection and intelligence. Then, based on the above research summary, they provide an outlook on the application of artificial intelligence technology in urban lighting engineering and put forward ideas related to the construction of intelligent infrastructure. shu et al [14] analysed the current status of eco-city development in China, taking the Sino-Singapore Tianjin Eco-city as an example. They analysed the daily lifestyle of the city's residents based on the results of several interviews and potential field observations, and found that China is gradually beginning to pay attention to environmental protection and is striving to find a path that harmonises economic and environmental protection. Drawing on the experiences of international countries, China has gradually explored an eco-city development path with Chinese characteristics. xu et al[15] studied the relationship between urban environmental image and urban eco-efficiency and innovatively used a national garden city image scheme to examine the improvement of eco-efficiency. The results showed that this programme significantly improved the eco-efficiency of the city by expanding the green area of the city, optimising the industrial structure and bringing in talented residents. This impact was significant for western China, but somewhat marginal for developed eastern cities.Azambuja et al [16] found that rapid population growth and urbanisation caused problems such as environmental pollution and shortage of natural resources. The existence of these problems has driven a shift from traditional urbanisation models to eco-smart cities. Based on the UN Sustainable Development Goals, they proposed a new conceptual framework of smart sustainable cities and elaborated on smart governance approaches to ultimately achieve coordinated and sustainable development of economic development, ecological civilisation construction and environmental protection. li et al[17] pointed out that building circular economy eco-cities is the most effective way to solve the problem of sustainable urban development. They assessed the sustainability of these cities using an energy value approach through a study of daylighting in coastal Central and Eastern European countries. The study shows that the utilisation rate of non-renewable resources has a significant impact on the economic development of a city. As the recycling rate of these non-renewable resources increases, the energy value sustainability index and the development index first decrease and then increase, which helps to resolve the contradiction between environmental superiority and economic backwardness.

The construction industry is a major contributor to China's carbon emissions, accounting for 30% to 50% of society's total carbon emissions each year. In order to achieve the goal of carbon neutrality, the construction industry is bound to face a huge transformation challenge. Green buildings, as a sustainable building type, are an effective way to achieve carbon neutrality in buildings [18-22].Fan et al [23] established a multi-objective optimisation scheme for green building modelling. The multi-objective optimisation of the construction effect of the project was carried out by combining the resource allocation and weather condition factors such as temperature, humidity and precipitation of the project site. The results show that this optimisation approach can reduce the total cost of the project and provide new ideas for the development of unconstrained optimisation. pu et al [24] applied BIM technology to the field of green building. bim technology can quantify and manage the life cycle of green buildings, thus stepping out of the traditional model and making the design and construction process more accurate. They summarised the current situation and advantages and disadvantages of using green building and BIM in the actual construction process, and analysed the prospects for the application of BIM technology in the construction field. The results show that combining BIM technology with green building and applying it in the construction field is a green path that can make the construction process more standardised and increase the life cycle of green buildings. yu et al [25] applied deep learning neural networks to green building energy consumption in order to avoid problems such as local pole skewing, slow convergence and incomplete data collection brought by traditional neural network models data model. A generative adversarial network-based model for building energy consumption data generation in green buildings was finally implemented. They found that the model can learn hidden patterns in the original data and generate some virtual data. They then validated this model with real building energy consumption data. Ferrari et al [26] argue that in order to improve the sustainability of buildings, it is necessary to rate green buildings. They point out that the Level(s) proposed by the EU in 2018 have become a common framework for assessing the sustainability continuation of buildings across Europe, becoming a uniform standard for the European building industry. The proposed rating system can promote competition among those in the construction-related industries and enable the construction industry to flourish. Ykj et al [27] developed a two-stage data mining model based on 354 building profiles and a neural network prediction model in Taiwan to analyse the types, grades, and technologies of these buildings. The results showed that different green buildings have different construction processes. For example, high-grade residential communities focus more on the indoor air environment as well as the surrounding living environment. Chen et al [28] used building-integrated photovoltaic (BIPV) technology to reduce CO_2 emissions from buildings. BIPV low-carbon design involves five major aspects: energy, materials, environment, management and innovation, with the first two being the main influencing factors. Accordingly, they proposed a framework of indicators related to carbon emission control to guide the low carbon design approach for buildings. Lu et al [29] summarised their research on carbon emissions in the green building construction industry from three aspects: policy, technology and management models. They found that current research hotspots focused on life cycle modelling, energy efficiency and the environment, which have limitations. They concluded that combining decarbonisation design into building design is a feasible path, which can be optimally analysed by establishing a multi-objective decision model for decarbonisation design and renewable energy.

To sum up, in order to better achieve energy saving and emission reduction in the construction industry, the development of green buildings is comprehensively promoted. Green building evaluation standards are a tool to measure the energy and carbon reduction capacity of green buildings, and the higher the green building rating, the more energy and carbon efficient the building is. However, the actual research process has found that some buildings are obsessed with the pursuit of green building rating, making their building carbon emissions increase instead [30-32]. In response to the problems found, this paper injects the concept of 'eco-city' into the green building industry. Through the study and understanding of existing eco-cities, the research focuses on the renewal of land use in eco-cities, emphasising the importance of the 'ecological' concept. The aim is to evaluate the current state of green buildings from an ecological perspective, without being limited to traditional evaluation methods and renewal strategies, so that buildings can meet green building ratings while saving energy and reducing carbon.

Table 1. Main modes of green ecological agriculture

Agricultural model	Features
space-time structure	According to the biological, ecological characteristics and a rationally formed ecosystem of mutually beneficial symbiotic relationships between organisms
food chain	A virtuous cycle agro-ecosystem designed according to the energy flow and material cycle laws of the agro-ecosystem
Integrated spatiotemporal food chain	The organic combination of space-time structure type and food chain type is a mode type with moderate input, high output, less waste, no pollution and high efficiency

2. LIFE CYCLE CARBON ACCOUNTING MODEL FOR GREEN BUILDINGS

2.1. GREENHOUSE GAS ACCOUNTING

The contribution of different greenhouse gases to global warming varies, with carbon dioxide at 76%, methane at 14.3%, nitrous oxide at 7.9%, and other overall contributions of less than 2%. The Intergovernmental Panel on Climate Change (IPCC) uses the GWP of carbon dioxide as a benchmark for converting the GWP caused by other greenhouse gases over a period of time (usually on a 100-year basis) into carbon dioxide equivalents, using the following formula:

$$CO_2eq_i = GM_i \times GWP_i \tag{1}$$

Among them, CO_2eq_i is the carbon dioxide equivalent of the i greenhouse gas, GM_i is the emission of the i greenhouse gas, and GWP_i is the GWP value of the i greenhouse gas.

2.2. METHODOLOGY FOR CALCULATING CARBON EMISSIONS AT VARIOUS STAGES OF THE LIFE CYCLE OF A GREEN BUILDING

The formula for calculating carbon emissions at each stage of the full life cycle of a green building is as follows:

$$C = AD \times EF \tag{2}$$

Where C denotes the carbon emissions at each stage of the full life cycle of a green building, AD denotes data on the level of direct or indirect activity throughout the life cycle of the building, and EF denotes the carbon dioxide equivalent generated per unit of building activity data, also known as the carbon emission factor.

https://doi.org/10.17993/3ctic.2023.122.117-135

The total carbon emissions for the life cycle of a green building are the sum of the carbon emissions at each stage and the mathematical expression is calculated as follows:

$$E_{\text{sum}} = E_d + E_{pt} + E_c + E_{om} + E_{end} \tag{3}$$

Of these, E_d are carbon emissions from the design decision phase, E_{pt} are carbon emissions from the production and transportation of building materials, E_c are carbon emissions from the construction phase, E_{om} are carbon emissions from the operation and maintenance phase and E_{end} are carbon emissions from the demolition and disposal phase.

The annual carbon emission per unit of floor area, GE is selected as the evaluation index of life-cycle carbon emission of green buildings, and its expression is as follows.

$$GE = \frac{E_{\text{sum}}}{Y \times A} \tag{4}$$

Where Y is the full life cycle time of the building and A is the floor area.

2.3. CALCULATION OF CARBON EMISSIONS AT THE DESIGN DECISION STAGE

In this paper, two main aspects are considered when calculating the carbon emissions at this stage: on the one hand, the carbon emissions resulting from the energy consumption of the designers in using the relevant equipment for the design of the architectural drawings; on the other hand, the carbon emissions resulting from the project-related activities occurring during the travel of the designers for the construction project. Therefore, the formula for calculating carbon emissions at the design decision stage is

$$E_d = P_e + P_b \tag{5}$$

Where P_e is the design equipment's carbon emissions and P_b is the travel carbon emissions.

$$P_e = \sum_{i=1}^{n} DM_i \times T_i \times EF_c \tag{6}$$

Where n is the number of designer categories, DM_i is the number of designers in category i, T_i is the average number of computer hours used by designers in category i, and EF_c is the carbon emission factor for computer operation.

$$P_b = \sum_{i=1}^{n} \sum_{j=1}^{z} D_{ij}' \times EF_{i,j}' \tag{7}$$

https://doi.org/10.17993/3ctic.2023.122.117-135

Where n is the number of business trips, z is the number of types of transport taken, $D_{ij}{}'$ is the distance traveled by the i business traveler in the j mode of transport, and $EF_{i,j}{}'$ is the carbon emission factor per unit distance for a single person in the j mode of transport.

2.4. CALCULATION OF CARBON EMISSIONS DURING THE PRODUCTION AND TRANSPORTATION PHASES OF BUILDING MATERIALS

The building material production and transport phase can be further divided into material production and material transport phases. Namely

$$E_{pt} = P_p + P_t \tag{8}$$

Where P_p is the material production carbon emissions and P_t is the material transport carbon emissions.

$$P_p = \sum_{i=1}^{n} m_i \times EF_{m_i} \tag{9}$$

Where n is the number of building material types, m_i is the amount of building materials used in category i and EF_{mi} is the carbon emission factor for category i.

$$P_t = \sum_{i=1}^{n} \sum_{j=1}^{z} m_{ij} \times D_{ij} \times K_y \times EF_{i,j} \tag{10}$$

Where z is the number of transport mode categories, m_{ij} is the mass of building materials of category i transported by the jth transport mode, D_{ij} is the average transport distance of building materials of category i transported by the j transport mode, K_y is the empty vehicle correction factor, and $EF_{i,j}$ is the carbon emission factor per unit mass per unit transport distance of the j transport mode.

2.5. CALCULATION OF CARBON EMISSIONS DURING THE CONSTRUCTION PHASE OF BUILDING

During the construction phase, site formation begins and people, machinery and materials enter the site one after another. The carbon emissions during this phase mainly come from the carbon emissions generated during the use of machinery and equipment on site. Therefore, the formula for calculating carbon emissions during the construction phase is as follows

$$E_c = P_c + P_r \tag{11}$$

Where P_c is the carbon emissions from construction machinery and P_r is the carbon emissions from construction personnel.

$$P_c = \sum_{i=1}^{n} TB_i \times EF_{e,i} \tag{12}$$

Where n is the number of machinery and equipment categories, TB_i is the number of machinery and equipment shifts in category i, and $EF_{e,i}$ is the carbon emission factor per unit shift of machinery and equipment in category i.

$$P_r = \sum_{i=1}^{n} T_i \times EF_{r,i} \tag{13}$$

Where n is the number of construction personnel, T_i is the number of man-days and $EF_{r,i}$ is the manual carbon emission factor.

2.6. CALCULATION OF CARBON EMISSIONS DURING THE OPERATION AND MAINTENANCE PHASE

The operation and maintenance phase can be subdivided into an operation phase and a maintenance phase, so the carbon emissions from the operation and maintenance phase are made up of these two components, as in the following equation.

$$E_{om} = P_o + P_m \tag{14}$$

Where P_o is the operational phase carbon emissions and P_m is the maintenance phase carbon emissions.

$$P_o = \left(\sum_{i=1}^{n} E_i \times EF_{e,i} + W \times EF_w + P_l - \sum_{i=1}^{n} R_i \times EF_{e,i} - GS \right) \times Y \tag{15}$$

Where n is the number of energy types, E_i is the annual consumption of the i energy type, $EF_{e,i}$ is the carbon emission factor of the ith energy type, W is the annual consumption of water systems, EF_w is the carbon emission factor of water, P_l is the annual carbon emission of land development and use, R_i is the annual saving of the ith energy type, GS is the annual carbon reduction of greening systems, and Y is the life of the building.

$$P_l = \sum_{i=1}^{n} S_i \times EF_{l,i} \tag{16}$$

Where n is the number of land use types, S_i is the area of land type i and $G_{e,i}$ is the carbon sequestration factor for land type i.

https://doi.org/10.17993/3ctic.2023.122.117-135

$$GS = \frac{\sum_{i=1}^{n} G_{e,i} \times A_{e,i} - 600 \times R \times A_s}{40} \tag{17}$$

Where n is the different planting methods in the greening system, $G_{e,i}$ is the 40-year carbon sequestration per unit area for the ith planting method, $A_{e,i}$ is the green area for the ith planting method, R is the green space ratio and A_s is the total building site area.

2.7. CALCULATION OF CARBON EMISSIONS DURING THE MAINTENANCE PHASE

Carbon emissions from the maintenance phase include carbon emissions from the production of building materials and the energy consumption of machinery and equipment used for transport and maintenance, resulting from the aging of building materials or components.

$$P_m = \sum_{i=1}^{n} \left(m_{s,i} \times EF_{m,i} + P_{t,i}\right) \times k_i + \sum_{k=1}^{q} TB_k \times EF_{e,k} \tag{18}$$

$$P_{t,i} = \sum_{j=1}^{z} m_{ij} \times D_{ij} \times K_y \times EF_{t,j} \tag{19}$$

$$k_i = \frac{Y}{Y_m} - 1 \tag{20}$$

Where n is the type of maintenance material, $m_{s,i}$ is the mass of maintenance material of category i, $EF_{m,i}$ is the carbon emission factor of maintenance material of category i. k_i is the transportation carbon emission of maintenance material of category i, TB_k is the maintenance factor of maintenance material of category i. is the number of maintenance equipment shifts of category k, $EF_{e,k}$ is the carbon emission factor per unit shift of category k maintenance equipment, $m_{i,j}$ is the transport quality of the jth transport mode of the maintenance material of category i. $D_{i,j}$ is the transport distance of the jth transport mode of the maintenance material of category i, K_y is the empty vehicle correction factor, $EF_{t,i}$ is the carbon emission factor of the j transport mode, Y is the service life of the building design, and Y_m is the service life of the building material.

2.8. CALCULATION OF CARBON EMISSIONS DURING THE DISMANTLING AND DISPOSAL PHASE

$$E_{end} = Q_c + Q_t + Q_h + Q_m \tag{21}$$

Where Q_c is construction demolition carbon emissions, Q_t is construction waste transportation carbon emissions, Q_h is construction waste disposal (including landfill and incineration) carbon emissions and Q_m is construction waste recycling carbon emissions.

This section establishes a life cycle carbon accounting model for green buildings based on the life cycle assessment (LCA) approach. The purpose and scope of accounting for green building life-cycle carbon emissions, system boundaries, and functional units are firstly determined. This is followed by an analysis of the sources of green building carbon emissions in five stages of the building life cycle: design decision, production and transportation of building materials, construction, operation and maintenance, and demolition and disposal, and the establishment of a carbon emission calculation method for each stage. A theoretical model is established for the subsequent discussion.

3. RESULTS AND DISCUSSION

This paper analyses a typical case of a residential community in a city in China, which covers an area of 28,000 square metres, with a building area of 76,500 square metres and a green space ratio of 48%. There are eight high-rise residential buildings in it.

In this paper, we analyse one of the green buildings in the context of an eco-city, and analyse its carbon emission cycle sequencing. The residential building is 18 storeys above ground, with a building height of 55.35m; reinforced concrete shear wall structure, seismic intensity 8 degrees; there are 4 units, each with one staircase and two households. Each unit has a floor area of 101.4 square metres, with a total of 144 residences and a total floor area of 16,432 square metres. The building has a total floor area of 5,658 square metres and 2,320 square metres of green space (densely planted bushes). The carbon emissions of the building were calculated for the entire life cycle of the building by separating the building phase, the building use phase and the end-of-life phase of the building. The highest carbon emissions were analysed to provide theoretical guidance for energy saving and emission reduction in green buildings.

3.1. CARBON EMISSIONS DURING THE BUILDING PHASE

The residential building was completed as a rough building, so the main statistics are for the materials used in the civil construction and installation of the building. The carbon emissions per unit area produced at each stage of the building, including the extraction of raw materials, production of building materials, on-site processing of components, construction and installation, land use and the buildingisation stage, were also counted. The statistical results are shown in Table 1 below.

According to the definition of greenhouse gases, greenhouse gases from the combustion of fossil fuels and land use during the on-site processing of components, construction and installation sub-stage of the physical phase are classified as direct emissions. The greenhouse gas emissions from the use of electricity in the on-site processing of components, construction and installation sub-stage and the greenhouse gas emissions from the extraction of raw materials and the production of building materials are classified as indirect emissions. Based on the calculations, it can be concluded that the sub-stage with the highest proportion of carbon emissions in the physical phase of the building is the land use, followed by the production of building materials and the extraction of raw materials, which account for 94% of the physical phase, while the construction phase only accounts for 6% of the total carbon emissions. Direct carbon emissions in the physical phase account for about 41%; indirect carbon emissions account for about 59%.

Table 2. Carbon emission statistics per unit area for each sub-stage in the physical phase of the building $(kgCO_2e/m^2)$

Stage	CO_2	CH_4	N_2O	Total calculation
Raw material extraction	185	5.08	5	195
Building material production	253	633	1.03	254
On-site machining of structural components	8.34	263	176	8.78
Construction and installation	42.9	1.36	904	45.2
Land use	317	0	0	317
Building materialisation phase	806	7.33	7.11	820

3.2. CARBON EMISSIONS DURING THE USE PHASE OF THE BUILDING

Carbon emissions from the day-to-day operation of buildings include greenhouse gas emissions directly or indirectly from the (1) use phase of buildings due to the consumption of energy such as fossil fuels, electricity and heat, (2) the use and discharge of water resources, and (3) the leakage of refrigerants. In residential buildings energy consumption specifically includes elements such as heating, air conditioning, lighting, lifts, other appliances, natural gas for cooking and domestic hot water.

The residential building is heated in winter by a natural gas wall-hung stove as the heat source and radiant floor heating as the end; in summer the cooling is by split type air conditioning. The thermal efficiency of the natural gas fireplace is 91% and the electrical power of the circulating water pump is 130 W. The split air conditioner is energy efficiency class 2 with an energy efficiency ratio of 3.4. The heating period is from November 15 to March 15 and the air conditioning period is from June 15 to August 31. The electricity consumption of lighting equipment accounts for a significant

https://doi.org/10.17993/3ctic.2023.122.117-135

proportion of the life-cycle energy use of a home, and the energy consumption of lighting equipment is closely related to the choice of lighting and usage habits. The power consumption of lighting equipment can be calculated as the product of building lighting power density and lighting time. According to the Building Lighting Design Standard GB 50034-2004, the annual lighting energy consumption of the residential building can be calculated as the remaining carbon emissions of each building's daily use as shown in Table 2.

Table 2 shows that air conditioning and heating are the largest contributors to carbon emissions, with a combined total of 42%; refrigerants, although smaller in mass, account for 25% of carbon emissions during the building use phase due to their large GWP values; and water supply and drainage also contribute 5% of carbon emissions and cannot be ignored. According to the definition of greenhouse gases, carbon emissions from the combustion of natural gas and refrigerant leakage during the daily use phase of the building are direct emissions, while carbon emissions from electricity and water supply and drainage are indirect emissions. According to the calculations, direct emissions are 30% higher than indirect emissions.

Table 3. Greenhouse gas emissions during the use phase of residential buildings

$(kgCO_2e/m^2)$

Projects	CO_2	CH_4	N_2O	HFC	Total
Heating	599	262	1.03	0	600
Refrigeration	377	0.0988	1.69	0	379
Elevator	110	0.0289	493	0	111
Lighting	271	71	1.21	0	273
Other household appliances	157	0.0411	701	0	158
Domestic gas	126	0.0627	0.0974	0	126
Drainage	85.6	0.00794	135	0	85.7
Refrigerant	0	0	0	587	587
Total	1730	573	5.35	587	2320

3.3. CARBON EMISSIONS AT THE END-OF-LIFE STAGE OF THE BUILDING

According to the national standard, the carbon emissions of building demolition, recycling/reuse of building materials/equipment and waste disposal can be calculated separately. The total carbon emissions from the demolition of the building are 40.7

$kgCO_2e/m^2$, the total carbon emissions from the recycling/reuse phase are 41.3 $kgCO_2e/m^2$, and the total carbon emissions from the waste disposal phase are 8.32 $kgCO_2e/m^2$. Therefore, it can be found that the carbon emissions from the end-of-life phase of the building mainly come from the demolition and recycling/reuse phases of the building.

3.4. BUILDING LIFE CYCLE CARBON EMISSIONS

The carbon emissions of the residential building in each sub-stage of its life cycle are shown in Table 3. The life-cycle carbon emission of the building is about 4000 $kgCO_2e/m^2$, and its carbon footprint is 80 $kgCO_2e/m^2$. From Table 3, it can be seen that the highest carbon emission in the whole life-cycle of the residential building is the daily operation stage of the building, which reaches 2320, accounting for 58.03% of the whole life-cycle carbon emission. This is followed by the land use, building repair, building materials production and building renovation phases, which generate 7.93%, 6.60%, 6.35% and 6.30% of the carbon emissions of the whole life cycle, respectively.

Table 3. Carbon emissions of residential building life cycle sub-stages ( )

Stage	CO_2	CH_4	N_2O	HFC	Total
Raw Material Mining	185	5.08	5	0	195
Building materials production	253	633	1.03	0	254
On-site processing of structural parts	8.34	263	176	0	8.78
Construction and Installation	42.9	1.36	904	0	45.2
Land Use	317	0	0	0	317
Daily operation of the building	1730	573	5.35	587	2320
Building Maintenance	48.9	733	711	0	50.3
Building Restoration	257	3.85	3.73	0	264
Building Updates	196	2.93	2.84	0	201
Building renovation	244	3.66	3.56	0	252
Demolition of buildings	38.7	1.22	814	0	40.7
Recycling/reuse	36.2	941	4.15	0	41.3
Waste disposal	8.3	0.00772	0.0207	0	8.32
Full Lifecycle	3360	21.2	28.3	587	4000

The proportion of carbon emissions from each sub-stage of the building's life cycle is shown in Figure 1. It can be seen from the figure that the proportion of carbon emissions from the daily operation of the residential building is the largest, reaching

58%, while the whole building use phase accounts for 77% of the life-cycle carbon emissions, reaching 3087 $kgCO_2e/m^2$. Carbon emissions from the physical phase of the building account for 20.5% of the life-cycle carbon emissions, at 820 $kgCO_2e/m^2$. The carbon emissions from the end-of-life phase of the building account for 2.2% of the life-cycle carbon emissions, at 91 $kgCO_2e/m^2$.

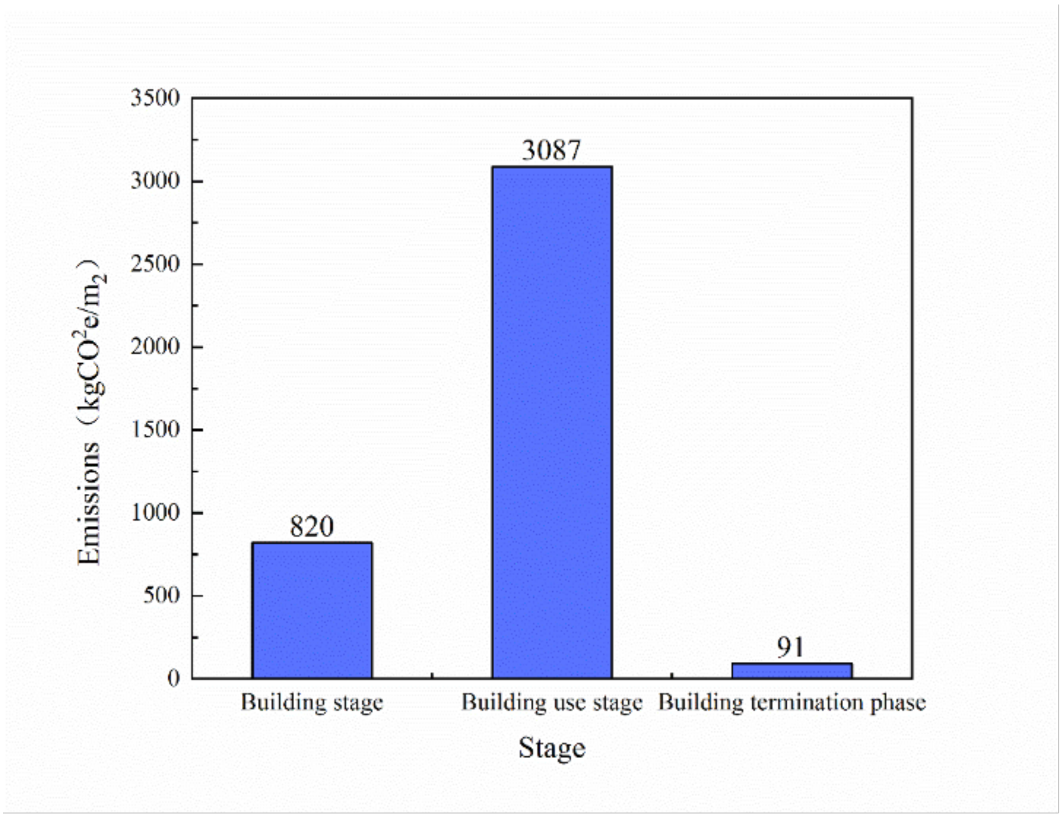

Figure 1. Carbon emissions in the three main stages of the life cycle of a residential building

In summary, the carbon emissions of this residential building were calculated for the three phases of building construction, building use and building end of life, and the highest carbon emissions were found in the building use phase, accounting for 77% of the life cycle carbon emissions. Therefore, in order to reduce carbon emissions, we can start from the use phase of the building.

4. DISCUSSION

In this paper, a typical case study of a mobile high-rise building in a residential community in a Chinese city is analyzed in the context of eco-city. The carbon emissions of the building are calculated in the building construction phase, the building use phase and the building end-of-life phase, and thus the carbon emissions of the building throughout its life cycle are calculated. The highest carbon emissions were analyzed to provide theoretical guidance for energy saving and emission reduction of green buildings. The results of the study are as follows.

1. In the building materialization stage, the sub-stage with the highest proportion of carbon emissions in the building materialization stage is land use, followed

by building materials production and raw materials extraction, which account for 94% of the materialization stage, while the total carbon emissions in the construction stage account for only 6%.

2. In the building use phase, the most carbon emissions are generated by air conditioning and heating energy, the sum of which reaches 42%; although the refrigerant mass is small, the proportion of carbon emissions generated by it accounts for 25% in the building use phase due to its large GWP value.

3. In the end-of-life stage of the building, the total carbon emission from the demolition of the building is 40.7 $kgCO_2e/m^2$, the total carbon emission from the recycling/reuse stage is 41.3 $kgCO_2e/m^2$, and the total carbon emission from the waste disposal stage is 8.32 $kgCO_2e/m^2$. Therefore, the carbon emissions in the end-of-life stage of the building mainly come from the demolition and recycling/reuse stages of the building. In addition, the carbon emissions from the building use phase are the highest in the building life cycle, accounting for 77% of the life cycle carbon emissions.

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