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Carbon emissions from buildings based on a life cycle analysis: carbon reduction measures and effects of green building standards in China

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Abstract

Carbon emissions from buildings account for approximately half of China's total social carbon emissions. Focusing only on the carbon emissions of building operation tends to neglect the carbon emissions of other related parts of the building sector, thus slowing down the progress of carbon peaking in the building sector. By applying life-cycle analysis to calculate carbon emissions throughout the building's life cycle, the performance of carbon emissions at each stage of building materials, construction, operation and end-of-life demolition can be identified, so that carbon reduction strategies in building design can be selected.. This paper constructed a method for calculating the carbon emissions of green buildings in whole-building life cycle, and conducted a summary analysis of the carbon emissions of 33 projects that were awarded green building certification. The study found that the Chinese *Assessment Standard for Green Buildings* has a significant effect on reducing the carbon emissions of buildings in whole-building life cycle. Compared with the current average operational carbon emissions of buildings in China, the carbon intensity of green public buildings is 41.43% lower under this standard and the carbon intensity of green residential buildings is 13.99% lower. A carbon correlation analysis of the provisions of the current Chinese *Assessment Standard for Green Buildings* was conducted, comparing the changes in the carbon intensity of buildings before and after the revision of the standards. The study concluded that the new version of the standards has a greater impact on public buildings than residential buildings, the requirement of carbon emission reduction in the production stage of building materials is strengthened in terms of carbon emission during the whole-building life cycle. This study addresses the current problem of unclear carbon emission reduction effect of green buildings.

Keywords Life cycle analysis, Building carbon emission, Assessment standard for green buildings, Carbon correlation

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摘要

建筑碳排放约占到中国社会碳排放总量的一半，仅关注建筑运行碳排放容易忽视建筑部门其他相关环节的碳排放，从而拖慢建筑部门碳达峰进度。应用生命周期分析进行建筑全生命期碳排放计算，可以识别建材、建造、运行以及报废拆除各阶段的碳排放表现，从而在建筑设计中更好的制订和实施碳减排策略。中国绿色建筑评价标准主张对建筑进行全生命期碳排放分析，本文构建了绿色建筑全生命期碳排放计算方法，并对获得绿色建筑评价认证的33个项目进行了碳排放情况的汇总分析，发现中国绿色建筑评价标准在降低建筑全生命期碳排放方面作用明显，绿色公共建筑碳排放强度比全国同类建筑运行碳排放低41. 43%，绿色居住建筑碳排放强度比全国同类建筑运行碳排放低13. 99%。对绿色建筑评价标准内容进行了碳相关性分析，对比了修订前后建筑碳排放强度的变化，发现新版标准对公共建筑的影响大于居住建筑，在建筑全生命期碳排放方面，加强了建材生产阶段碳减排的要求。本研究解决了当前绿色建筑碳减排效果不明确的问题。

关键词 生命周期分析，建筑碳排放，绿色建筑评价标准，碳相关性

1 Introduction

On September 22, 2020, China announced its goal of achieving peak carbon dioxide (CO_2) emissions by 2030 and working towards carbon neutrality by 2060 [1]. Compared with the United States, Japan, and the European Union, China has a short time to achieve its carbon peak and carbon neutrality and faces high pressure to meet its target, considering its high total carbon emissions. In 2018, China's total carbon emissions from the full construction process were 4.93 billion tCO_2, accounting for 51.2% of the national carbon emissions. Of this total, carbon emissions from the production phase of building materials were 2.72 billion tCO_2 and carbon emissions from the operation phase of construction were 2.11 billion tCO_2. The average annual growth rate of construction carbon emissions has remained above 3.6% from 2016 to 2018 [2]. Based on the current development pattern, carbon emissions from building operations are expected to peak in 2038–2040, with a peak carbon emission of about 3.15 billion tCO_2 [3]. It is clear that carbon reduction measures and effects from the construction industry can significantly influence the achievement of overall carbon peak and carbon neutrality targets in China.

With buildings, whole-process carbon emissions statistics differ from the whole-life carbon emissions statistics. The whole-process analysis refers to a top-down approach to calculating the production and transportation of building materials, building construction, building operation, and demolition from the building sector in a particular year [4]. In contrast, a whole-life carbon calculation summarizes the carbon emissions of a building from design, construction, and use, to end-of-life. This also includes the production and transportation of building materials, construction, operation, and demolition, but has a different meaning and results from a bottom-up calculation [5]. In calculating carbon emissions over the whole life cycle of a building, approximately 20% of the carbon emissions come from the production phase of building materials, and 80% of the carbon emissions come from the operation phase of the building [6, 7]. Therefore, current controls related to building carbon emissions tend to focus on reducing energy consumption and changing the energy resource structure in building operations. Improving the energy efficiency of buildings is expected to result in carbon emissions from the operation phase of the building making up a smaller proportion of the carbon emissions over the whole life cycle of the building, even though the share of carbon emissions from the production phase of building materials may increase [8].

Life Cycle Assessment (LCA) is a common analytical method for conducting environmental impact assessments. ISO14040/44, developed by the International Standardization Organization (ISO), standardizes early LCA studies, specifies the framework for LCA analysis, and clarifies the differences and requirements with respect to a Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) [9]. Based on this, ISO developed ISO 14067:2018 Greenhouse gases—Carbon footprint of products—Quantitative requirements and guidelines, and ISO 21930:2017 Sustainability in construction and civil engineering—Core rules for environmental product declarations for construction products and services. Both standards are used to analyse the environmental impact of a building throughout its life cycle and the associated carbon footprint. The key difference is that ISO 14067 is mostly used to analyse building materials or one of the products that forms a part of a building [10]. In contrast, ISO 21930 is mostly used to analyse the overall building project [11]. Due to the complexity of construction projects and the many building materials and products used, LCA is widely used to analyse and assess the environmental impact of building materials and products. As such, a LCA generally appears in environmental impact assessment studies for construction activities.

Different countries' standards apply LCA-based environmental impact assessments, using the evaluation elements in the *ISO standards.* to guide project scoring. For example, the LEED (Leadership in Energy and Environmental Design, USGBC) and BREEAM (Building Research Establishment Environmental Assessment Method, BRE) standards directly cite the relevant ISO standards, assigning scores to projects that conduct LCA environmental impact assessments [12, 13].

In China, the *Assessment Standard for Green Buildings* (GB/T 50378) was the first Chinese standard to focus on and propose requirements for building carbon emissions. It was revised and upgraded in 2019 to replace the version released in 2014. The calculation of building carbon emissions covers two stages: building design evaluation (pre-certification) and building operation evaluation. Design stage calculations help building designers optimize design strategies and material selection; operation stage calculations provide a new dimension of environmental evaluation for property holders and management organizations to optimize facility operation and property services. GB/T 50378–2019 does not directly cite the ISO standards introduced above, but requires that the LCA method be used to calculate building carbon emissions [14].

The evaluation requirements of green buildings, and the corresponding design measures, can directly or indirectly reduce building carbon emissions. For example, solar photovoltaic or more energy-efficient air conditioning systems may be adopted [15]; or concrete frame masonry infill structures may be used instead of reinforced concrete structures to achieve material reduction [16, 17]. As another example, natural components of clay and bio-based materials are more effective in mitigating carbon emissions than conventional components of reinforced concrete and masonry [18]. These measures result in lower operational carbon emissions [19] and lower embodied carbon emissions [20] in green buildings compared to conventional buildings. In terms of whole-life calculations, different building materials, design measures, and the range of calculations and parameters chosen, can all impact results [21, 22]. Significant research has been conducted about this topic, but few studies have calculated carbon emissions for Chinese buildings, and aligned them against the carbon reduction effects and specific provisions in China's *Assessment Standard for Green Buildings.*

To address this research gap, the following activities were completed for this study:

(1) Conducted a comparative analysis of the differences between China's *Carbon Emission Calculation Standard for Buildings* (GB/T 51366–2019) and ISO 21930:2017, and proposed an improved calculation model.

(2) Verified the comprehensive carbon reduction effect of green buildings, by analysing the results of whole-life carbon emission calculations of 33 certified projects.

(3) Analysed the driving concerns of China's *Assessment Standard for Green Buildings* (GB/T 50378–2019) with respect to reducing carbon emissions from buildings.

2 Methodology for calculating carbon emissions from buildings

ISO 21930 is based on ISO 14025 and ISO 14044, and establishes principles, specifications, and requirements for environmental product declarations (EPDs) with respect to building products and services, building components, and integrated technical systems used in construction projects [11]. It provides a product category rule (PCR) for the construction industry under the framework of ISO 14025. ISO 21930 specifies that the whole-life carbon emissions of buildings are to be divided into embodied carbon and operational carbon. Embodied carbon, in turn, is divided into upfront carbon (A1-3 and A4-5), use embodied carbon (B1-5), and end-of-life carbon (C1-4). Figure 1 shows the relationship between each stage of carbon, and the associated subcategories, from the perspective of the whole life cycle of a building. Operational carbon refers only to the B6 stage, the carbon emissions from the energy used in the building, and does not include water. Water is not an energy source, and as a resource it is too complex to handle, and for different buildings, water carbon footprint varies greatly and is more suitable for exploration and statistics at the level of urban areas, so it is out of scope.

A comparison of the Chinese national standard *Carbon Emission Calculation Standard* GB/T51366 [23] with ISO 21930 reveals differences in the provisions used to assess the production phase, construction phase, and use phase of building materials. Table 1 provides a comparative analysis of the two standards.

There are other, more specific differences in the standards. For example, the Chinese standard defines the carbon sink as "the amount of carbon dioxide absorbed and stored by greenery and plants from the air within the scope of a defined building project". In contrast, the ISO 21930 standard states that the carbon sink of a building is the carbon dioxide stored or sequestered in building materials. The above difference comes from different understandings of the meaning of GHG sink [10] in ISO14067:2018.

Based on the comparative analysis of the elements above, the formula for calculating the carbon emissions of green buildings throughout their life cycle should

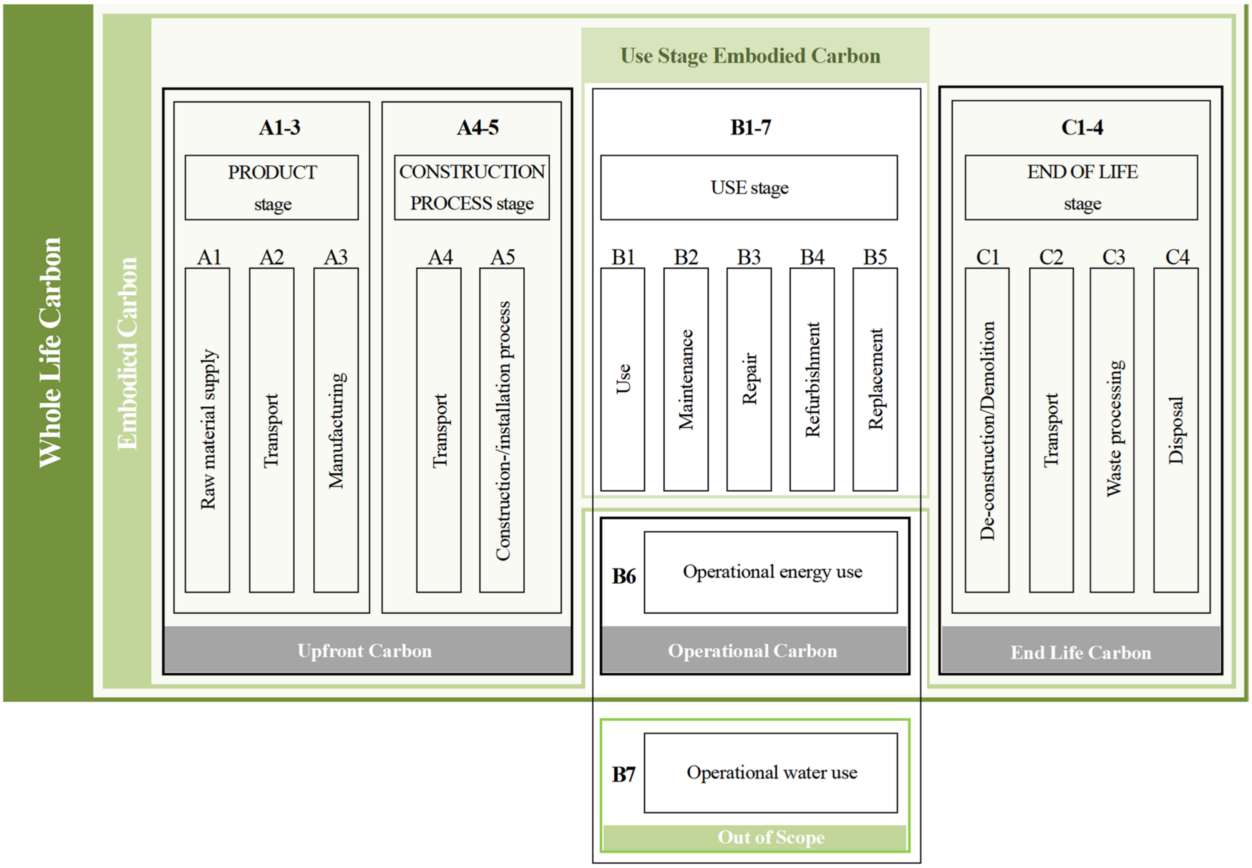

Fig. 1 Processes and modules for conducting a life cycle assessment of building-related carbon emissions, according to ISO 21930:2017

include the embodied carbon and operational carbon, as shown in formula (1).:

$$C_l = C_E + C_M \tag{1}$$

The embodied carbon is generated not only during the production phase of building materials and the construction phase of the building, but also during the use (B1-B5 stage) and end-of-life stage of the building, and should be calculated using the following formula (2).

$$C_E = C_{JC} + C_{JZ} + C_{SY} + C_{BF} \tag{2}$$

The C_{JC} was calculated according to the following formula (3 and 4), which should include the extraction, transportation and processing and manufacturing of raw materials for each building material used in the building.

$$C_{JC} = \sum_i C_{jc,i} \tag{3}$$

$$C_{jc,i} = \sum_j C_{rm,j} + \sum_j M_{rm,j} D_j T_j + \sum_j E_{jc,j} EF_j \tag{4}$$

The C_{JZ} was calculated according to the following formula (5).

$$C_{JZ} = \sum_{i=1}^{n} E_{jz,i} EF_i \tag{5}$$

The embodied carbon in the use stage is the carbon dioxide released from the use, maintenance, repair or refurbishment, and replacement transport of renovated building materials or their ancillary products. Carbon emissions from the use of these products are referred to in the building materials carbon emissions formulas (3) and (4). The carbon emissions from repair or refurbishment work activities are referred to in construction carbon emissions formula (5).

The operational carbon refers to carbon emissions from building energy use (B6 stage), which can be divided into electricity and non-electricity according to the type of energy, and the calculation formula (6) is as follows.

$$C_M = \sum_{i=1}^{n} (E_i EF_i) + E \bullet EF \tag{6}$$

Table 1 Comparison of ISO 21930 and GB/T 51366

	ISO 21930		GB/T 51366	Description
Construction works life cycle information within the system boundary	PRODUCTION Stage	A1 Extraction and upstream production	The carbon emission factor of the production of building materials includes the extraction and transportation of raw materials, the carbon emission of purchased energy, and the direct carbon emission of the production process	Both encourage carbon footprint analysis of building materials to highlight the differences in carbon emissions of different building materials
		A2 Transport to factory		
		A3 Manufacturing		
	CONSTRUCTION Stage	A4 Transport to site	Consolidated into "building materials production and transportation phase"	National standard applies a building materials supply perspective, not a construction procurement perspective
		A5 Installation	Considers the total amount of energy in the construction phase, the calculation of energy consumption of sub-projects, and other factors	No difference between standards
	USE Stage	B1 Use	Unspecified	National Standard calculations: 1) Are more oriented to new buildings, renovations can be quantitatively analysed using multiple calculations in the "construction and demolition" phase 2) Consider the energy consumption required to create the built environment, and does not include the energy consumption of electrical appliances and carbon emissions 3) Deduct the carbon sink of the building green space
		B2 Maintenance		
		B3 Repair		
		B4 Replacement		
		B5 Refurbishment		
		B6 Operational energy use	Carbon emission calculation for HVAC, domestic hot water, lighting and elevator, renewable energy, and building carbon sink systems	
	END of life stage	C1 De-construction/Demolition	Calculation of carbon emissions by total energy, manual mechanical demolition energy	National standard is divided into "construction and demolition phase"
		C2 Transport to waste processing or disposal	Same production phase transportation method	
		C3 Waste processing	Based on 50% of the carbon emissions of primary raw materials that can be replaced by construction waste	National standard based on carbon emission factor method for building materials
		C4 Disposal of waste	Not considered	National standards do not account for the environmental impact of non-recyclable parts of building materials

During the design stage, the activity data should be obtained from the project budget list, and for the operational energy consumption, it can be simulated and predicted by the building energy analysis software. When the building is completed and delivered for use, the activity data should be obtained from the final project budget list, and the operational energy consumption data should be the result of the actual energy consumption bill or the energy consumption monitoring system records.

3 Results

This study included an analysis of whole-life carbon emission reports for 25 public building projects and 8 residential building projects in China, using two editions of the GB/T 50378 standard (2014 Edition and 2019 Edition). The 25 public building projects include 21 “2014 Edition” standard projects and 4 “2019 Edition” standard projects. The “2014 Edition” projects include 5 two-star projects, referred to as Cases 1–5; and 16 three-star projects, referred to as Cases 6–21. The “2019 Edition” projects include 2 two-star projects, referred to as Cases 22 and 23; and 2 three-star projects, referred to as Cases 24 and 25. The calculation results of the carbon emissions for the “2014 Edition” projects, excluding the effect of extreme values of individual projects, show that the average carbon emissions intensity is 3.15 tCO_2/m^2. Under the “2014 Edition,” the carbon emissions are calculated for the whole life cycle of projects, based on a 50-year service life, using area-weighted average processing. For the “2019 Edition” projects, the average carbon emission intensity of the standard project is 1.78 tCO_2/m^2. Under the 2019 standard, the full life cycle carbon emissions are calculated based on a 50-year life cycle, using area-weighted averaging. Figure 2 shows the data distribution; “2014 Edition” projects are shown as blue points; “2019 Edition” projects are shown as green points.

From a whole life cycle perspective, after the revision of the standard in 2019, the carbon emission intensity of public buildings was reduced from 3.15 tCO_2/m^2 to 1.78 tCO_2/m^2, a reduction of 43.49%. Further, the effect of carbon reductions in the whole process remains significant. The average proportions of carbon emissions in building materials and operation, which account for a large proportion of carbon emissions, were 28.64% for building materials and 61.86% for operations before the revision (“2014 Edition”), and 26.34% for building materials and 67.99% for operations after the revision (“2019 Edition”). The change of the ratio reflects the difficulty of reducing carbon emissions in the building use phase based on the total reduction, with the goal of maintaining higher performance and better health and comfort in the building.

Of the eight residential building projects, six are “2014 Edition” projects (Cases 1–6) and two are “2019 Edition” projects (Cases 7 and 8). The statistical results in Fig. 3 show that revision had little impact on building carbon emissions, likely for two key reasons. First, there are too few data available for analysis, and more case support is needed. Second, the residential building projects for carbon emission calculation are all three-star, and the projects themselves have high design standards. Centralized heating and cooling equipment is commonly used to create a controlled and comfortable indoor heat and humidity environment; the revised requirements between the 2014 and 2019 Editions did not significantly impact building equipment performance and indoor heat and humidity control.

The two cases with more significant carbon intensity (Cases 3 and 8) are projects that face high heating demands in winter. This finding is consistent with other studies on carbon emissions from the building sector.

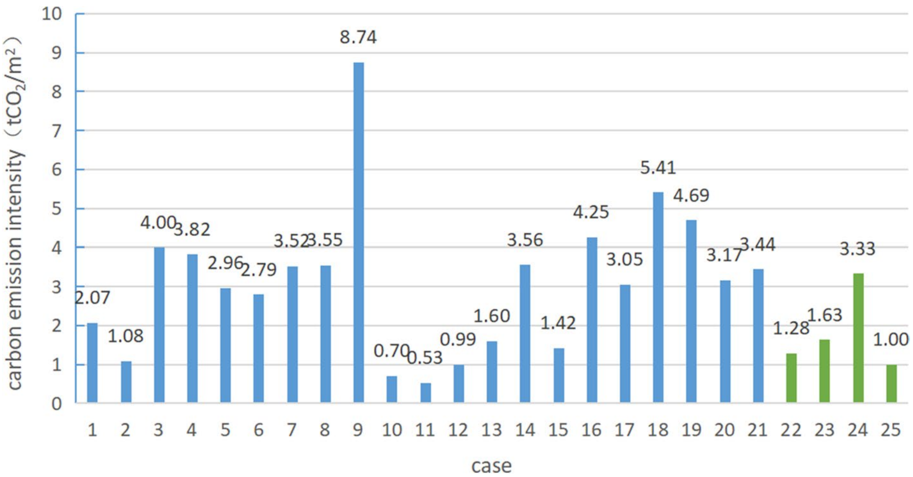

Fig. 2 Carbon emission intensity of green building projects (public buildings) (tCO_2/m^2)

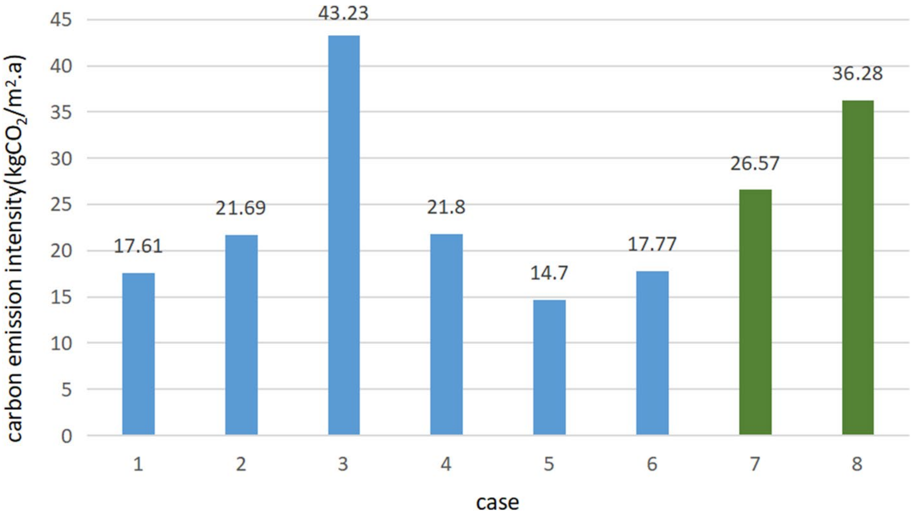

Fig. 3 Carbon emission intensity of green building projects (residential buildings) (kgCO$_2$/m^2·a)

The weight and impact of carbon emissions from heating, as a component of the overall building carbon emissions, is a challenge that needs to be directly addressed to reduce the carbon intensity of buildings.

From a comprehensive perspective, the carbon emission intensities of projects adopting the 2019 edition of GB/T 50,378 are somewhat reduced by different amounts compared to the 2014 Edition. The trend is clearer for public buildings than residential buildings. Compared with the national average, the average carbon emission per unit building area of public buildings is 35.60 kgCO$_2$/(m^2·a), which is 41.43% lower than the national average of 60.78 kgCO$_2$/(m^2·a) [2]. The average carbon emission per unit building area of residential buildings is 24.96 kgCO$_2$/(m^2·a), which is 13.99% lower than the national average of 29.02 kgCO$_2$/(m^2·a) [2].

4 Discussion

The case study shows that green buildings have a significant effect of reducing the total amount and intensity of building carbon emissions. The whole-life carbon emission intensity of buildings is close to or lower than the current national operational carbon emission intensity in China. Compared with conventional buildings, green buildings are regulated and evaluated using significantly different provisions (divided into direct carbon reduction measures and indirect carbon reduction measures).

4.1 Basic provisions

Article 3.2.8 of the GB/T 50378 establishes the starting point for determining the energy-saving levels associated with one-star, two-star, and three-star green buildings (see Table 2). These include the control indexes of thermal performance of the building envelope; and the heat transfer coefficient and airtightness of exterior windows, which is critical in the passive energy-saving design of buildings and directly affect the heating and air conditioning loads of buildings. The energy consumption of these control points accounts for approximately 40–60% of the overall energy consumption of buildings. Therefore, further improving energy saving requirements

Table 2 GB/T 50378–2019 Basic energy saving and emission reduction requirements for one-star, two-star, three-star green buildings

Performance Requirements	One-star	Two-star	Three-star
The proportion of the improvement in the thermal performance of the envelope, or the proportion of reduction of the building heating and air conditioning load	5% increase in envelope or 5% decrease in load	10% increase in envelope or 10% decrease in load	20% increase in envelope or 15% decrease in load
Percentage reduction in heat transfer coefficient of exterior windows of residential buildings in severe and cold regions	5%	10%	20%
Airtightness of exterior windows	Consistent with the provisions of the relevant national energy-saving design standards, and the combination of the exterior window openings and the exterior window body parts should be tight		

should start from the source of the energy demand and reduce the carbon emissions generated by building operations.

4.2 Evaluation terms

4.2.1 Direct carbon reduction related articles

Direct carbon emission reduction-related provisions refer to those that directly reduce building energy or improve the building energy structure, and directly reduce the building's carbon emissions. These provisions are most easily understood in relation to building energy consumption. For example, Article 7.1.2 states: "Measures shall be taken to reduce the energy consumption of heating and air conditioning systems under partial load and partial space use". Article 7.2.6 states: "take effective measures to reduce the energy consumption of the end systems of heating and air conditioning systems and transmission and distribution systems." In addition, some of the envelope thermal performance, lighting, electrical, and renewable energy applications are also direct carbon emission reduction measures. Of these, photovoltaic renewable energy may be used to adjust the building's energy structure, or the core of the building, from the end of energy use to the end of capacity.

GB/T 50378 includes several chapters that include provisions for directly reducing build carbon emissions: Chapter 5, health and comfort; Chapter 6, convenience of life; Chapter 7, resource conservation; Chapter 8, environmental liveability; and Chapter 9, improvements and innovation. There are 39 total provisions, including 17 control items, 19 scoring items, and 3 extra points. Figure 4 shows the distribution of items.

In terms of points, the provisions directly related to carbon emission reduction in buildings represent a total of 406 points (10 points for each control item), accounting for 36.91% of the total points (out of 1100 points). The points associated with different direct carbon emission reduction measures are presented here in declining order, to illustrate which elements have the most impact on the total score: HVAC (175 points), electrical and lighting (69 points), building materials (54 points), water supply and drainage (49 points), and landscape greening (26 points); these account for 15.91%, 6.27%, 4.91%, 4.45%, and 2.36% of the total points, respectively.

4.2.2 Indirect carbon reduction related articles

Indirect carbon emission reduction refers to provisions that do not directly reduce the consumption of building energy and resources, or reduce building carbon emissions, but do indirectly achieve resource and energy savings through technical measures. These indirect measurements are generally related to building design standards and user behaviour. For example, Article 4.2.6 of the GB/T 50378 standard proposes to "take measures to improve the adaptability of the building". The goal of this provision is to extend the service life of the building and avoid the abandonment or demolition of the building, because internal functions no longer meet changes in user demand. From the perspective of carbon emissions across the whole life cycle of a building, approximately 30% of carbon emissions come from the physical

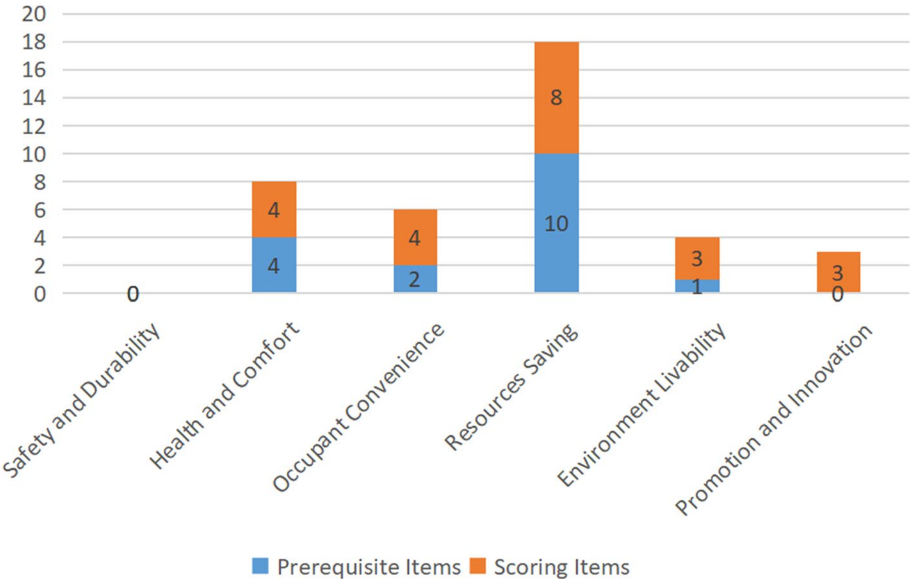

Fig. 4 Distribution of direct carbon reduction provisions

phase. In the case of completed projects, if the carbon emission (annual) remains stable, extending the service life of the building is clearly an effective carbon reduction measure. The newly revised third edition of the standard 2019 emphasizes the importance of this provision, and more clearly visualizes provisions related to energy saving behaviour. The most intuitive point is that the monitoring of the indoor environmental parameters of the building should be visualized and adjustable within a certain comfort range. This ensures the high quality of the building, and ensures that building performance remains at a high level. Behavioural energy-saving effects created by good usage habits can reduce the carbon emissions of the building operations phase by about 15% [24]. Given the scale and time effects of building operation and use, the agglomeration effect is significant, even though the proportion of savings is not very high.

GB/T 50378 includes provisions that are indirectly related to building carbon emissions reduction in: Chapter 4, safety and durability; Chapter 6, convenience of living; Chapter 7, resource conservation; and Chapter 8, environmental liveability. This reflects a total of 24 items, including 5 control items, 5 scoring items, and 1 extra point. Figure 5 shows the distribution of items.

In terms of points, there are a total of 254 points associated with provisions that reflect indirect impacts in the GB/T 50378 standard, accounting for 23.09% of the total score (out of 1100 points, with each control item calculated as 10 points). The points associated with different indirect carbon emission reduction measures are listed in descending order here to illustrate their relative impacts: construction (132 points), management services (40 points), building materials (39 points), water supply and drainage (23 points), and HVAC (20 points); these account for 12.00%, 3.64%, 3.55%, 2.09%, and 1.82% of the total points, respectively.

4.2.3 Analysis of the effect of carbon reduction evaluation requirements

It is clear that the equipment, technical measures, or design objectives required by the *Assessment Standard for Green Buildings* have the effect of reducing building carbon emissions, regardless of whether they are direct or indirect carbon reduction requirements. It is easier to quantify the effect of the direct carbon reduction evaluation provisions. In contrast, because many factors and variables influence the effect of the indirect carbon reduction evaluation provisions, the correlation mechanism is less certain. Using the example of adjustable shading required by the direct carbon reduction evaluation provisions, when considering the four orientations (north, south, east, west) of exterior window shading systems, shading the south orientation has the greatest impact on the building load throughout the year; a mid-mounted roller blind is the shading form with the highest reduction rate for the building load, reaching up to 35%; and the built-in horizontal louver shading has the lowest reduction rate for the building load, at about 10% [25].

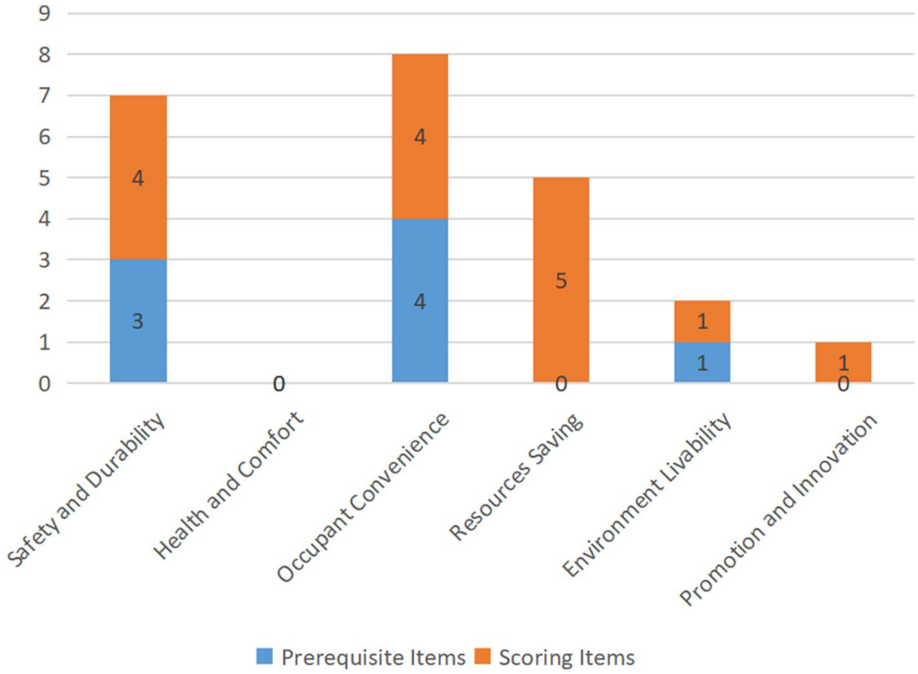

Fig. 5 Distribution of indirect carbon reduction provisions

Load reduction cannot be directly equated with reductions in indirect building carbon emissions; however, a lower load is associated with less energy use, which naturally results in lower carbon emissions under the same conditions. There is a clear linear relationship between the two.

Evaluating the carbon reduction effect is complex, as there are large differences between north and south China, differences in the design parameters of different building thermal partitions, and different concerns with respect to energy efficiency in buildings. Using the effect of heat islands on building heating and air conditioning energy consumption as an example, in Hot Summer and Warm Winter regions, the growth rate of total energy consumption due to the heat island effect is about 8.55%/0.5 °C. In regions with a Hot Summer and Cold Winter, the difference between the increase in air conditioning energy consumption and the decrease in heating energy consumption due to the heat island effect is not large, and the total energy consumption remains essentially the same. In contrast, residential buildings are dominated by heating energy consumption, and the reduction of total energy consumption due to the heat island effect is about 1.74%/0.5 °C and 2.97%/0.5 °C, for Severe Cold regions and Cold regions [26]. These differences also have a different impact on building carbon emissions.

5 Conclusion

This study examined the scope and methods used to calculate carbon emissions over the full life cycle of buildings. Using the actual carbon emission statistics for 25 public buildings and 8 residential buildings that received the Green Building Label, several findings can be concluded here.

(1) An LCA-based building carbon emission analysis can effectively reflect the carbon emissions of a building as a product, from the design plan to selection of materials to operation and use to the full process of maintenance and demolition. This differs from the practice of only focusing on carbon emissions during the operation phase and not considering the embodied carbon of the building.

(2) The whole-life carbon emission intensity of projects certified under the *Assessment Standard for Green Buildings* is lower than the current average carbon emission intensity of buildings in China. The carbon emission intensity of green public buildings is 41.43% lower than the national average, and the carbon emission intensity of green residential buildings is 13.99% lower than the national average.

(3) The 2019 Edition of China's *Assessment Standard for Green Buildings* further strengthened the requirements for carbon reduction measures in buildings compared to the 2014 Edition, with 36.91% of the score associated with direct carbon reduction evaluation requirements and 23.09% of the score associated with indirect carbon reduction evaluation requirements.

(4) After the 2019 revision of China's *Assessment Standard for Green Buildings*, the proportion of carbon emissions from the production phase of building materials to the whole life cycle of the building was reduced from 28.64 to 26.34%. This indicates that green buildings consider the requirement to reduce both embodied and operational carbon.

(5) Without considering changes in the carbon emission factor of electricity, the analysis above indicates that the carbon emission intensity of new green public buildings is more likely to meet the 7 $kgCO_2/(m^2 \cdot a)$ reduction in carbon emission intensity of new buildings required by the Chinese full-text mandatory standard "*General Specification for Energy Conservation and Renewable Energy Use in Buildings*" (GB 55015–2021) [27].

Like all studies, this one has limitations. The study cases are not enough, and did not collect further details about the carbon reduction measures taken in the specific green building case studies, which would have helped analyse the impact of these measures with respect to the whole-building life carbon emission. Future research should expand the number of cases studied and focus on building materials, construction practices, and indoor environmental requirements used in different building types in different climatic regions. This would improve the comprehensiveness and accuracy of the analysis of the whole-life carbon reduction effects of green buildings.

The carbon emission data for buildings in this study based on LCA method of the ISO21930, and focus on the final results, do not cover the selection of calculation parameters, such as the carbon footprint of building materials and energy carbon emission factors. Considering the differences in the carbon footprint of building materials produced by different enterprises, the variations in transport distances and modes of transport, and the differential carbon emission factors of purchased energy due to differences in the energy composition of regional power grids (the proportion of renewable energy generation) would be other areas to explore in subsequent studies. These studies will help to promote the application and adaption of ISO21930 in China, and promote the carbon emission assessment of the whole life of buildings to be more scientific and reasonable.

6 Nomenclature

C_L Whole-life emissions of buildings, $\mathrm{tCO_2}$.

C_E Embodied carbon emissions of buildings, $\mathrm{tCO_2}$.

C_M Building operational emissions, $\mathrm{tCO_2}$.

C_{JC} Carbon emissions from the production phase of materials, $\mathrm{tCO_2}$.

C_{JZ} Carbon emissions during the construction phase, $\mathrm{tCO_2}$.

C_{SY} Carbon emissions during the use phase, $\mathrm{tCO_2}$.

C_{BF} Carbon emissions at end-of-life stage, $\mathrm{tCO_2}$.

C_M Building operational emissions, $\mathrm{tCO_2}$.

E_i The i-$^{\mathrm{th}}$ type of non-renewable energy used in the operation of the building, other than electricity.

EF_i Carbon emission factor for energy type i, $kg\mathrm{CO_2}/kWh$ or $kg\mathrm{CO_2}/kg$.

E Amount of purchased electricity used for building operations, kWh.

EF Carbon emission factors for electricity in the area where the building is located, $\mathrm{tCO_2/kWh}$.

$C_{jc,i}$ Product carbon emissions of building material i, $\mathrm{tCO_2}$.

$C_{rm,j}$ Product carbon emissions of the j$^{\mathrm{th}}$ raw material of the i$^{\mathrm{th}}$ building material, $\mathrm{tCO_2}$.

$M_{jc,j}$ Weight of the j$^{\mathrm{th}}$ raw material to produce the i$^{\mathrm{th}}$ building material, t.

D_j Average transport distance of the j$^{\mathrm{th}}$ raw material to produce the ith building material, km.

T_j Carbon emission factor for the j$^{\mathrm{th}}$ mode of transportation of raw materials to produce the i$^{\mathrm{th}}$ building material, $\mathrm{kgCO_2/(t{\cdot}km)}$.

$E_{jc,j}$ jth amount of energy used to produce and manufacture the ith building material, kWh or kg.

EF_j Carbon emission factor for the jth energy source used to produce and manufacture the ith building material, $\mathrm{kgCO_2/kWh}$ or $\mathrm{kgCO_2/kg}$.

$E_{jz,i}$ Total energy use for building construction phase i, $kWhorkg$.

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Authors' contributions
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Availability of data and materials
Due to the nature of this research, participants of this study did not agree for their data to be shared publicly, so support data is not available.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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