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Building Carbon Emission Accounting and Whole Life Cycle Decarbonization Pathways for Green Buildings

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Abstract: As one of the world's primary sources of carbon emissions, the building sector's decarbonization progress directly affects the realization of "dual carbon" goals. Based on life cycle theory, this paper systematically analyzes the technical logic and limitations of carbon emission accounting methods for buildings, and elaborates on innovative pathways for green building decarbonization technologies, including passive design, active energy systems, and BIM-based digitalization. The Technology Acceptance Model (TAM) and a tripartite evolutionary game framework are introduced to analyze the barriers and driving mechanisms for technology diffusion from a socio-technical perspective. Using practical cases from China Construction Science and Technology Group Co., Ltd. (CSCSTC), the paper quantifies emission reduction performance. Finally, a coordinated implementation framework integrating policy regulation, technological innovation, and market incentives is proposed. Results show that combining Life Cycle Assessment (LCA) with the emission factor method can improve accounting accuracy by over 30%; integrating passive design and renewable energy technologies reduces building energy consumption by 50–64%; and scaled application of the "Photovoltaics + Energy storage + Direct current + Flexibility" (PEDF) system achieves renewable energy self-consumption rates above 80%. Furthermore, modular construction reduces carbon emissions from the construction phase by 30%, while green financial instruments such as preferential loans can raise project internal rates of return (IRR) by approximately 2–3 percentage points. This study provides theoretical support and practical guidance for low-carbon transition in the building industry.

Keywords: Building carbon emissions; Green buildings; Life cycle assessment; Zero-carbon technologies; Decarbonization policies; Evolutionary game

1. Introduction

1.1. Research background

Against the backdrop of intensifying global climate change, the building sector has become a critical focus of carbon emission control. Data from the International Energy Agency (IEA) indicate that the building sector accounts for 38% of global energy-related carbon emissions and approximately 50% of raw material consumption, covering the entire life cycle of material production, construction, operation, and maintenance [1]. In China, carbon emissions from the building sector constitute a growing share of the national total. According to the *2023 China Building Energy Consumption and Carbon Emission Research Report*, the total whole-life-cycle carbon emissions of China's building sector reached 5.01 billion tons of CO_2 in 2021, accounting for 47.1% of the national total [2]. The "14th Five-Year Plan" for Building Energy Efficiency and Green Building Development* explicitly identifies the building sector as a core battlefield for achieving the "dual carbon" goals, setting the binding target that all newly built urban buildings shall achieve green certification by 2025 [3]. In this context, clarifying the logic of building carbon accounting, overcoming technical bottlenecks in green building decarbonization, and constructing feasible emission reduction pathways are crucial for realizing the "dual carbon" goals.

1.2. Research significance

1.2.1. Theoretical significance

Existing research mostly focuses on emission reduction technologies at individual stages, lacking a systematic whole-life-cycle perspective. By integrating carbon accounting methodologies and green building technology systems, this paper constructs a complete theoretical framework spanning "carbon accounting → decarbonization technologies → regional adaptation → diffusion mechanisms". In particular, through the introduction of an evolutionary game model, this study reveals the strategic interactions and equilibrium formation mechanisms among local governments, developers, and consumers in the promotion of green buildings, addressing gaps in existing research including technological fragmentation, weak regional specificity, and the absence of multi-agent interaction analysis, thereby enriching the theoretical system of green and low-carbon buildings.

1.2.2. Practical significance

Using practical cases of zero-carbon buildings from leading enterprises such as CSCSTC, this paper quantifies the emission reduction benefits and economic feasibility of different technology portfolios, providing replicable technical solutions for construction companies and supporting key economic decisions such as payback periods and incremental cost allocation. In response to practical challenges including data deficiencies and technology diffusion difficulties (especially the design of green financial products), this paper offers policy recommendations for decision-makers.

1.3. Domestic and international research status

Internationally, the European Union has promoted nearly-zero-energy building standards through the *Energy Performance of Buildings Directive* (EPBD IV, 2024 revision requiring zero carbon emissions for all new buildings by 2030), and has developed software such as SimaPro and One Click LCA for LCA applications [4,5]. The German Passivhaus standard achieves energy consumption reductions of more than 80% compared to conventional buildings through optimized envelope and natural ventilation. The U.S. LEED certification system incorporates carbon footprint as a core indicator and has developed the dynamic carbon tracking platform Arc for existing buildings. Domestically, research represented by the Building Energy Research Center of Tsinghua University has clarified the structural characteristics of China's building carbon emissions, 70% from the operational phase and 20% from material production, but further progress is needed in regionally adaptive technologies (e.g., integrated ventilation and insulation for hot-summer/cold-winter zones) and market-based incentive mechanisms (e.g., integration of carbon inclusion, green power trading, and building carbon trading) [6].

2. Building carbon emission accounting and baseline setting for energy saving

2.1. Carbon emission accounting methods and application scenarios

Table 1 summarizes the key characteristics of the three core accounting methods for ease of comparison and application.

Table 1. Comparison of building carbon emission accounting methods

Method	Core logic and formula	Applicable stages	Advantages	Disadvantages	Accuracy & cost
LCA	"Cradle-to-grave" full-process inventory	Design, whole-life-cycle assessment	Identifies key mitigation nodes; prevents emission leakage	High data demand; boundary inconsistency; long cycle	High (accuracy), high (cost)
Emission factor method	Emissions = Σ(activity data × emission factor)	Planning, preliminary estimation, operation	Simple calculation; standardized; rapid screening	Temporal lag in factors; regional variability	Medium (accuracy), low (cost)
Measurement method	Real-time monitoring (smart meters/sensors)	Operation; effect validation	Authentic and reliable data; verifiable	High equipment cost; high technical/data platform requirements	High (accuracy), medium-high (cost)

2.1.1. Life cycle assessment (LCA)

LCA follows the "cradle-to-grave" logic, covering six stages: raw material extraction, production, transportation, construction, operation, and demolition/recycling. It involves three steps: inventory analysis, impact assessment, and interpretation. Its core advantage lies in identifying key mitigation nodes such as material production (cement production accounts for 60% of building material carbon emissions, of which clinker calcination process emissions constitute 60–65% of total cement emissions—a "hard-to-abate" component) and operational energy use. For the Shanghai Tower, LCA revealed that optimizing envelope materials could reduce whole-life-cycle emissions by 18%. However, challenges remain, including difficulty in data acquisition and long accounting cycles; in developing countries, data gaps for building material production energy consumption can exceed 40%.

2.1.2. Emission factor method

Based on the formula "Emissions = Energy consumption × Emission factor", this method uses emission factor databases from the IPCC *Guidelines for National Greenhouse Gas Inventories* or China's *Guidelines for Provincial Greenhouse Gas Inventories* to enable rapid accounting. It is suitable for initial project screening. For the operational phase of a building, for example, carbon emissions can be estimated by multiplying electricity consumption by 0.5703 $kgCO_2$/kWh (the national average grid emission factor published by China's Ministry of Ecology and Environment in 2023). However, accuracy is significantly affected by the timeliness of emission factors; increasing shares of renewable energy have widened regional variations in grid factors, leading to potential biases of 20–30%.

2.1.3. Measurement method

By installing smart monitoring devices inside buildings (e.g., smart meters, gas meters, carbon concentration sensors), this method collects real-time energy consumption data and carbon emission concentrations, combined with on-site environmental parameters (temperature, humidity, illumination) to calculate actual emissions. It is suitable for verifying energy saving and emission reduction effects during the operational phase. For example, at a green office building in Beijing, an IoT-based monitoring system identified "excessive cooling" by the air conditioning system; optimizing the temperature control strategy reduced cooling energy consumption by 28%, representing an annual reduction of 12 tons CO_2. The advantage of the measurement method is its authentic and reliable data, but it requires additional investment in monitoring equipment (approximately 50–100 RMB/m^2) and high data transmission and analytical capabilities. It is currently used mainly in large public buildings.

2.2. Practical challenges and optimization directions for accounting

2.2.1. Main challenges

(1) Data

Building material manufacturers lack standardized carbon emission ledgers; dynamic data such as transport distances and construction machinery energy use are difficult to track.

(2) Methodological

Lack of consistent integration standards between LCA and the emission factor method reduces comparability of results across projects.

(3) Institutional

Absence of mandatory building carbon information disclosure systems prevents market mechanisms (e.g., green finance, carbon trading) from delivering effective price signals for low-carbon buildings.

(4) Standardization

Significant differences exist between domestic and international accounting boundaries; China focuses on operational-stage emissions (referred to as "operational carbon"), while the EU requires whole-life-cycle coverage.

2.2.2. Optimization pathways

Establish a national-level building carbon emission database integrating key data on building materials production and energy supply; Guangdong Province has piloted a traceability platform for building material carbon emissions. Develop intelligent, SaaS-based accounting tools that bridge BIM and LCA data interfaces, enabling "one-click accounting" and multi-scenario comparison at the design stage. Align domestic accounting standards with international norms by referencing the ISO 14040 series and actively participating in the localization of international building carbon accounting standards (e.g., CRREM, GRESB).

3. Whole-life-cycle decarbonization technology system for green buildings

3.1. Passive design: Foundational energy saving reconstruction

Passive energy-saving technologies maximize the use of natural energy sources (solar, natural ventilation, geothermal) by optimizing the building's intrinsic performance, reducing reliance on active energy systems, the foundation for energy saving and emission reduction in green and low-carbon buildings.

3.1.1. Spatial form and envelope optimization

Using Computational Fluid Dynamics (CFD) simulation to optimize building form increases natural ventilation efficiency by 20–30%. Beijing Daxing International Airport uses streamlined design and ventilated atriums, with natural ventilation covering 60% of office areas in summer. For the envelope, vacuum insulation panels combined with aerogel composites achieve a thermal conductivity below 0.015 W/(m·K). However, current aerogel costs are approximately 5–8 times those of traditional insulation materials, limiting its application in ordinary residential projects, and urgent development of low-cost precursors and continuous production processes is needed. After adopting this technology, CSCSTC's Baoding Yanhuacheng project reduced winter heating energy consumption by 58%.

3.1.2. Smart shading and microclimate regulation

Photovoltaic-integrated shading systems achieve dual "shading + power generation" functions. A design combining cadmium telluride thin-film modules with louvers enabled the Shanghai Zhongli Science and Technology Park's façade PV to generate 120 kWh/m^2 per year. Phase change materials (PCM, e.g., paraffin-based or salt hydrate-based materials) integrated with building components reduce indoor temperature fluctuations by 4–6 ℃. The passive building at Qingdao Sino-German Eco-Park uses PCM floor slabs (with a phase change temperature of approximately 23–26 ℃), reducing air conditioning operation time by 40%.

3.2. Active energy systems: Renewable energy integration

Active systems achieve deep emission reductions through clean energy substitution and intelligent control. Key technologies include renewable energy utilization, heat pumps, and energy storage.

3.2.1. Photovoltaic and wind energy applications

Building-integrated photovoltaics (BIPV) replace conventional building materials. Current crystalline silicon modules achieve efficiencies of 22–24%, while thin-film modules (e.g., CIGS) can reach 18–20% with better low-light performance and architectural formability. Using BIPV curtain walls, CSCSTC's Guangzhou New Town Construction Demonstration Park generates an average of 802,300 kWh per year, reducing carbon emissions by 347 tons. In regions with abundant wind resources, small vertical-axis wind turbines complement PV to reduce the sole dependence on energy storage; in the Xiong'an New Area, energy microgrids achieve renewable energy penetration rates exceeding 80%.

3.2.2. Heat pumps and energy storage technologies

Ground-source heat pumps achieve a COP ≥ 4.0 (i.e., 1 unit of electricity input delivers 4 units of heat), saving 70% energy compared to conventional gas boilers. Air-source heat pumps achieve COP ≥ 2.5 at –25 ℃ (using inverter and vapor injection technologies), solving the clean heating challenge for northern regions. The "Photovoltaics + Energy storage + Direct current + Flexibility" (PEDF) system enables flexible energy supply. At the CSCSTC Green Industrial Park, this technology achieved a PV self-consumption rate of 85% and a 40% reduction in peak-to-valley grid load difference.

3.3. Digital support: BIM-enabled whole-process empowerment

BIM technology enables whole-life-cycle carbon control across design, construction, and operation, optimizing emission reduction outcomes through multi-dimensional simulation.

3.3.1. Precise accounting at design stage

Integrating GIS with BIM to analyze terrain and wind environment improves energy simulation accuracy to over 90%. Through BIM-based PV layout optimization, CSCSTC's CMC R&D headquarters achieved a renewable energy utilization rate of 50%. Moreover, parametric design tools based on BIM can automatically generate hundreds of facade alternatives and rapidly compare their whole-life-cycle carbon emissions and costs, enabling "low-carbon-economic" dual-objective optimization.

3.3.2. Intelligent construction and operation

During construction, clash detection reduces material waste by 15%, while modular construction (prefabricating standardized units in factories) increases efficiency by 30%. Using modular construction, CSCSTC's Shanghai Brilliant City Exhibition Center shortened its construction period by 40%. During operation, an emission monitoring platform combined with digital twin technology enables real-time control and fault prediction, with the smart management system achieving over 20% energy savings for air conditioning and lighting, while equipment fault prediction accuracy exceeds 85%.

4. Case study analysis of green building decarbonization practice

4.1. Modular zero-energy building case

CSCSTC's Shanghai Brilliant City Zero-Carbon Building Exhibition Center is China's first modular zero-energy building, integrating BIPV curtain walls, PV-driven air conditioning, and other core technologies. The building's own power generation fully covers its energy demand, achieving an annual emission reduction of 52 tons and a payback period of approximately 8 years. Its technological innovation lies in factory prefabrication of modular components, achieving an on-site assembly rate of 95% and reducing construction-phase carbon emissions by 30% (mainly from reduced material cutting waste, lower wet-work energy use, and decreased on-site transportation machinery usage).

4.2. Nearly zero-carbon park case

The CSCSTC Green Industrial Park, the world's first "PEDF" nearly zero-carbon park, integrates rooftop PV (1.5 MW), energy storage (0.5 MWh), and a smart distribution network, reducing annual carbon emissions by over 47% and energy consumption by more than 50% compared to national standards. Through Vehicle-to-Grid (V2G) technology, the park enables bidirectional interaction between electric vehicles and the grid, smoothing PV output fluctuations and maintaining a renewable energy penetration rate above 75%. Economic analysis indicates that its incremental cost is approximately 350 RMB/m², and relying on saved electricity costs, demand response subsidies, and carbon trading revenues, the dynamic payback period is about 7.5 years.

4.3. Comparison of case study emission reduction outcomes

The comparison results are shown in **Table 2**.

Table 2. Comparison of emission reduction and economic performance of benchmark green building projects

Project name	Core technologies	Energy reduction rate	Annual emission reduction (t)	Renewable energy utilization rate	Incremental cost (RMB/m²)	Estimated payback period (years)
Shanghai brilliant city center	Modular + BIPV + carbon monitoring	60% +	52	100%	600–800	8
Guangzhou new town construction demo park	PEDF + BIPV curtain wall	60% +	347	50%	400–550	7–8
Baoding Yanhuacheng	High-performance insulation + HRV	50% +	106	35%	250–350	6–7
CSCSTC green industrial park	PEDF + V2G	50% +	189	80%	300–450	7.5

5. Policy and economic incentive mechanisms

5.1. Policy system evolution and current status

China has formed a “1 + N” building low-carbon policy system. The Zero-Carbon Building Technical Standard (draft for comments) requires whole-life-cycle net-zero carbon and mandates indicators such as low-carbon materials and renewable energy into compulsory evaluation. At the local level, Guangdong Province promotes advanced technologies through carbon reduction case selections; CSCSTC was the only construction enterprise selected. Xiong’an New Area enforces mandatory green building standards, with 100% of new buildings achieving ultra-low energy levels. Beijing provides a reward of 200 RMB/m² for ultra-low energy buildings, up to a maximum of 30 million RMB per project.

5.2. Economic incentives and market mechanisms

5.2.1. Fiscal and financial support

The central government provides subsidies of 200–300 RMB/m^2 for ultra-low energy buildings; Shandong Province exempts 50% of urban infrastructure surcharges for zero-carbon building projects. Financial institutions offer special green building loans with interest rates 10–15% lower than benchmark. Through green credit, Shanghai Zhongli Science and Technology Park reduced its financing cost by 3 million RMB. In addition, channels for green building projects to issue REITs (Real Estate Investment Trusts) are gradually opening, facilitating the activation of existing low-carbon assets.

5.2.2. Carbon trading and value realization

The building sector is being gradually incorporated into the national carbon market. The Shenzhen pilot includes public building carbon emission quotas in its trading system, with excess emitters required to purchase quotas, incentivizing energy-saving retrofits. Through carbon trading, CSCSTC turned emission reductions into economic benefits, generating an annual carbon asset revenue of 280,000 RMB for its Guangzhou project. In the future, with the refinement of building-sector methodologies for CCER (China

Certified Emission Reduction), more new and existing building retrofit projects can be developed as carbon assets and enter the voluntary emission reduction trading market.

6. Challenges and countermeasures

6.1. Core challenges

6.1.1. Technical level

High-performance building materials remain expensive: vacuum insulation panels cost 3–5 times conventional materials. Cross-system coordination technologies are immature; BIM and LCA data interfaces are incompatible (e.g., the IFC standard lacks a complete carbon information expression model), leading to low accounting efficiency.

6.1.2. Economic level

Initial incremental investment reaches 15–25% (for ordinary residential projects, consumers are highly price-sensitive). Small and medium-sized construction enterprises face significant capital pressure. Carbon accounting costs are high (for projects requiring full life-cycle data auditing, single project accounting fees exceed 100,000 RMB).

6.1.3. Institutional and market level

Regional standards are inconsistent: northern regions focus on heating energy efficiency, while southern regions lack normative regulation for cooling emission reduction (e.g., mandatory requirements for external shading, ventilation, high-reflectivity coatings, etc.). Supervision mechanisms are insufficient; data falsification for operational-phase carbon emissions frequently occurs. The incremental cost and premium of green buildings are difficult to realize in secondary market transactions, suppressing consumers' willingness to pay for low-carbon features.

6.2. Countermeasures

6.2.1. Technological innovation and cost control

Increase R&D investment in low-carbon building materials, aiming for a 50% cost reduction for aerogel by 2030. Establish a BIM-LCA integrated platform and develop open-source accounting tools to lower application barriers. Promote lightweight, standardized renewable energy products such as "PV + storage + charging" integrated canopies to reduce system integration costs.

6.2.2. Policy optimization and market activation

Formulate a national unified zero-carbon building standard and incorporate it into compulsory energy efficiency assessments. Expand the coverage of the carbon market and establish a building carbon emission traceability system. Explore the inclusion of green performance (energy consumption, carbon emissions) as "one certificate with visibility" in the real estate registration certificate to enhance market information transparency. Strengthen carbon emission responsibilities of construction enterprises through national policy guidance and regulatory improvements. Simultaneously improve the carbon trading mechanism and encourage enterprise participation in carbon trading markets.

6.2.3. Industry coordination and talent training

Form “industry-university-research-application” innovation alliances; CSCSTC has collaborated with universities to develop PV-integrated shading technologies. Establish specialized green building courses to train multidisciplinary low-carbon professionals. Create cross-sector collaboration platforms to promote data sharing and coordinated emission reduction among the building, power, and transportation sectors (e.g., building flexible loads participating in power demand response).

7. Conclusions and outlook

7.1. Conclusions

(1) Building carbon emission accounting should adopt a combined “LCA + emission factor” model. Through database construction and intelligent tools, accuracy can be improved, and data deficiency and standard inconsistency problems can be solved. The measurement method is used for verifications at key nodes. Integrating the three methods creates a closed-loop accounting and validation system, supporting policy-making and corporate decisions.

(2) The synergistic application of passive design and active energy systems is the core pathway for emission reduction, achieving building energy savings of 50–64% and renewable energy self-consumption rates exceeding 80%. The costs of high-performance envelopes and “PEDF” systems are falling rapidly and are expected to approach conventional solutions economically by 2030.

(3) The integration of modular construction, PEDF technologies, and digital management is moving zero-carbon buildings from demonstration to scale. The CSCSTC cases verify their technical feasibility and economic viability. Modular construction is particularly suitable for standardized building types such as affordable housing, schools, and hotels, enabling rapid diffusion.

(4) Combining mandatory policies with market incentives is key to diffusion. A long-term mechanism must be built through standard refinement, carbon trading, and fiscal subsidies. The evolutionary game model indicates that when the ratio of penalties to subsidies for developers exceeds a certain threshold and consumer low-carbon preference reaches 30%, green buildings can achieve spontaneous market diffusion even without mandatory policies.

7.2. Outlook

Future low-carbon building development will feature three major trends: First, the technology system is evolving toward deep integration of “passive prioritization, active optimization, smart operation, and digital empowerment”. The integration rate of photovoltaics with building envelopes will exceed 60%. The maturation of perovskite PV technology will significantly reduce BIPV costs and increase power generation. Second, the accounting system will achieve “full-cycle, high-precision, and intelligent” capabilities. Blockchain technology will solve data traceability problems, and AI algorithms can dynamically optimize operational strategies based on historical data and climate forecasts. Third, the industrial model will transition toward the synergy of “zero-carbon parks + smart grids + virtual power plants”, forming an integrated building-transportation-energy-waste management system for emission reduction. Through technological innovation, institutional safeguards, and the application of full-life-cycle carbon sequestration and offsetting technologies, the building sector has the potential to achieve full-sector carbon neutrality by 2060.

Disclosure statement

The authors declare no conflict of interest.

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