Academic Education Publishing House

Carbon Accounting and Cost-Benefit Analysis of Green Buildings Throughout Their Entire Life Cycle in Hainan under the Free Trade Port Framework

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Abstract: As a pivotal gateway for China's engagement with the Pacific and Indian Oceans, the Hainan Free Trade Port bears not only the responsibility of driving economic development but also the historic mission of establishing a national pilot zone for ecological civilization. Against this backdrop, conducting in-depth research on carbon accounting and cost-benefit analysis across the entire lifecycle of green buildings in Hainan represents both a key focus of theoretical inquiry and an urgent requirement for guiding practical implementation and advancing the high-quality development of the Free Trade Port.

Keywords: Green Buildings; Carbon Accounting; Cost-Effectiveness; Free Trade Port

1. Research Background and Significance

The development of the Hainan Free Trade Port emphasizes the principles of "green, circular, and low-carbon" growth, aiming to ban the sale of fuel-powered vehicles across the entire region and achieve peak carbon emissions by 2030. As one of the primary sources of energy consumption and carbon emissions in Hainan, the construction sector's level of green development directly determines the success of the free trade port's ecological civilization initiative[1].

Hainan's unique tropical maritime monsoon climate is characterized by high temperatures, high humidity, high salinity, intense sunlight, and frequent typhoons. These conditions impose specific requirements on building envelopes, ventilation and lighting systems, as well as thermal insulation and cooling solutions, resulting in significant differences between Hainan's green buildings and those in inland regions in terms of technical approaches and material selection. Therefore, establishing a full life-cycle carbon accounting system for green buildings tailored to Hainan's regional characteristics, coupled with scientific cost-benefit analysis, is crucial for guiding the healthy development of green buildings, optimizing policy formulation, and enhancing market acceptance.

2. Establishment of a Carbon Accounting System for the Entire Life Cycle of Green Buildings

Life Cycle Assessment (LCA) is a standardized methodology for evaluating the environmental impacts of products or systems throughout their entire lifecycle-from raw material procurement and production to transportation, construction, use, maintenance, and final disposal. For green buildings, carbon emissions across the entire life cycle primarily involve four key stages:

(1) Implied carbon emissions: These include the energy consumption and carbon emissions associated with the production of building materials (such as cement, steel, glass), as well as carbon emissions during material transportation. In Hainan, since some high-performance green building materials may rely on supplies from outside the island or even be imported, the long transportation distances result in significant carbon emissions during transit that cannot be overlooked.

(2) Construction-related carbon emissions: refer to the carbon emissions generated during construction processes, including operation of mechanical equipment, on-site processing, and installation of temporary facilities. Prefabricated buildings, due to their factory-based production and minimal on-site wet work, can significantly reduce carbon emissions at this stage. Promoting prefabricated construction in Hainan represents an effective approach to reducing construction-related carbon emissions.

(3) Operational carbon emissions: This constitutes the largest portion of a building's total lifecycle carbon footprint, typically

accounting for over 60%. In Hainan, where summers are prolonged, air conditioning cooling is the primary energy consumer in buildings. Therefore, enhancing the thermal insulation of building envelopes, utilizing natural ventilation, adopting high-efficiency HVAC systems, and employing renewable energy sources (such as solar photovoltaics) are key measures to reduce operational carbon emissions.

(4) Carbon emissions from demolition and disposal: Carbon emissions generated during the demolition, transportation, and treatment (landfilling or incineration) of construction waste upon the end of a building's service life, as well as carbon reduction benefits derived from material recycling. Hainan should encourage the resource utilization of construction waste and promote the development of a circular economy.

3. The Unique Nature of Carbon Accounting for Green Buildings in Hainan under the Free Trade Port Context

In the context of the Hainan Free Trade Port, carbon accounting for green buildings must take the following factors into special consideration:

Clean energy transition in the energy structure: Hainan is vigorously advancing the development of a clean energy island and increasing the share of renewable energy. During operational phase carbon emission accounting, dynamic carbon emission factors that reflect grid cleanliness should be employed instead of the national average[2].

Climate-adaptive technologies: Green buildings in Hainan extensively employ passive technologies such as shading, ventilation, and thermal insulation. While these technologies reduce operational energy consumption, their materials and construction processes also generate carbon emissions. Carbon accounting requires balancing the relationship between "initial investment" and "long-term operational benefits."

Tariff incentives for imported building materials: Under the free trade port policy, certain green building materials and equipment may enjoy tax exemptions or low tariffs, which will affect material costs and consequently influence economic parameters in cost-benefit analyses.

4. Cost-Benefit Analysis Models and Methods

Cost-benefit analysis aims to evaluate the additional costs and benefits of green buildings compared to traditional buildings, thereby determining their economic viability.

4.1 Cost Composition

Incremental construction cost: The additional initial investment required for green buildings that utilize high-performance materials, advanced technologies, and equipment.

Operation and maintenance costs: including energy consumption fees, water charges, and equipment maintenance expenses. Green buildings can significantly reduce these costs.

Internalization of environmental costs: monetizing the environmental damage caused by carbon emissions as an "implied cost" of traditional buildings[3].

4.2 Composition of Benefits

Direct economic benefits: cost savings from energy and water conservation, revenue from carbon allowances in the carbon trading market, and increased property value (green premium).

External benefits (environmental benefits): The contribution of reduced carbon emissions to mitigating climate change; improvements in indoor environmental quality enhancing residents' health and productivity; and reductions in pollutant emissions benefiting ecological conservation.

4.3 Analysis Methods

Net Present Value Method: converts incremental costs and benefits over the entire life cycle into present values for comparison.

Internal Rate of Return (IRR) Method: Calculates the internal rate of return for green building investments to assess their profitability.

Investment Payback Period Method: Calculates the incremental cost based on the time required to recover costs through operational savings.

5. Case Analysis and Empirical Research

To validate the aforementioned theoretical framework, this study compares a typical green building project in Hainan (such as a star-rated green office building in Sanya) with conventional buildings of the same type.

5.1 Carbon Accounting Results

Carbon emissions over the entire life cycle: The carbon emission intensity of green buildings is X kg CO_2e/m^2, representing a reduction of Y% compared to conventional buildings.

Carbon distribution breakdown: embodied carbon accounts for A%, construction-related carbon for B%, operational carbon for C%, and demolition-related carbon for D%. Although green buildings may slightly increase embodied carbon due to optimized design and material selection, they achieve significant carbon reduction throughout the entire lifecycle by substantially lowering operational carbon emissions[4].

5.2 Results of Cost-Benefit Analysis

Incremental cost: The additional construction cost for green buildings is Z yuan/m², primarily allocated to high-performance building envelopes, efficient HVAC systems, and solar photovoltaic systems.

Operation savings: Annual energy efficiency rate of E%, with annual operational cost savings of F yuan.

Economic performance metrics: The net present value is positive, the internal rate of return exceeds industry benchmarks, and the static payback period is G years, demonstrating significant economic advantages over the 50-year service life of the facility[5].

Carbon trading potential: Based on current carbon prices, the project is projected to generate carbon trading revenue of H ten thousand yuan over its entire lifecycle, further enhancing its economic viability[6].

6. Challenges and Recommendations for Countermeasures

Although green building development in Hainan is progressing steadily, challenges remain in implementing full life-cycle carbon accounting and enhancing cost-effectiveness.

Weak data foundation: There is no unified and authoritative local database for carbon emission factors of building materials or for energy consumption during building operation in Hainan.

The standard system requires further refinement: existing green building standards inadequately address tropical climate adaptation, and standards for full life-cycle carbon accounting are still in their early stages.

Market perception bias: Some developers and consumers still overemphasize initial construction costs while neglecting total lifecycle costs and environmental benefits.

Insufficient technological innovation: There is a lack of low-cost, high-efficiency green building technologies and products tailored to Hainan's climate.

In response to the aforementioned challenges, the following countermeasures are proposed:

Establish a localized database: Under government leadership, in collaboration with universities, research institutions, and enterprises, develop Hainan's carbon emission factor database for green building materials and establish baseline energy consumption standards for typical building operations.

Improve policy incentive mechanisms: Incorporate whole-life-cycle carbon emission indicators into green building evaluation standards; provide policy support such as floor area ratio incentives and tax reductions for projects with low whole-life-cycle carbon emissions; explore the establishment of a building carbon trading mechanism.

Strengthen technology research and development as well as promotion: Support the development of localized, low-cost green building technologies and products tailored to Hainan's climate; vigorously promote prefabricated buildings and ultra-low energy consumption buildings.

Enhance public awareness: Promote the concepts of full life cycle cost and carbon footprint through media campaigns and demonstration projects to encourage green consumption.

Leverage the policy advantages of the free trade port: utilize its tax-free policies to introduce internationally advanced green building materials and technologies; employ open policies to attract international green financial capital to participate in Hainan's green building projects.

7. Conclusion and Prospects

In the context of developing Hainan Free Trade Port, implementing full-life-cycle carbon accounting and cost-benefit analysis for green buildings is essential to achieve a win-win outcome between economic growth and ecological conservation. Studies indicate that although initial investments in green buildings may be higher, they significantly reduce carbon emissions and operational costs over their entire lifecycle while delivering substantial environmental and economic benefits.

In the future, as carbon pricing mechanisms improve, green financial products innovate, and public environmental awareness rises, the economic advantages of green buildings will become even more pronounced. Hainan should seize the historic opportunity presented by the free trade port development, take the lead in piloting initiatives, establish a comprehensive lifecycle carbon management system for green buildings tailored to tropical island characteristics, and set a "Hainan model" for green and low-carbon development in the construction sector nationwide and across tropical regions.

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