

Comprehensive Analysis on Carbon Emission Efficiency of Urban Residential Building Renovation

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Abstract

A series of environmental problems caused by global warming seriously threaten the survival and development of mankind. Greenhouse gas emissions, mainly carbon emissions, are the key factors that aggravate this problem. The construction sector is one of the three key carbon emission sources. With the rapid progress of global urbanization, the carbon emissions related to urban residential buildings continue to rise, and improving its carbon emission efficiency is of decisive significance to control the total global carbon emissions. As the largest carbon emitter in the world, it is very important for China to strengthen carbon emission reduction in the construction field. Therefore, it is particularly urgent to explore ways to improve the carbon emission efficiency of urban residential buildings in China. On the basis of summarizing the existing research results of carbon emission efficiency measurement, building carbon emission measurement and influencing factors of building carbon emission at home and abroad, this study established an evaluation model of carbon emission efficiency of residential buildings based on super-efficiency SBM(slack-based measure) method, and selected energy consumption and carbon dioxide emission (unexpected output) of residential buildings as input variables, and resident population, residential building area and per capita disposable income as output variables. Based on the panel data of 13 cities in Beijing, Tianjin and Hebei from 2010 to 2021, the carbon emission efficiency and influencing factors of Beijing, Tianjin and Hebei urban agglomeration were measured and analyzed by using SBM directional distance function and Tobit model. It is found that the carbon emission efficiency of Beijing-Tianjin-Hebei region did not reach the ideal level during the sample period, and there was obvious multipolarization phenomenon.

Keywords

Carbon Emission Efficiency; Urban Residential Buildings; Super-efficient SBM Model; Carbon Emission Reduction.

1. Introduction

Since the Industrial Revolution, with the rapid development of science and technology, people's production and lifestyle have undergone tremendous changes. Fossil energy, mainly coal and oil, has been used on a large scale, resulting in excessive accumulation of carbon dioxide in the atmosphere of the earth's surface. ^[1]In 2023, the total global carbon emissions reached 37.4 billion tons, and the United Nations Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change). The concentration of carbon dioxide in China has increased at a record rate in the past century, reaching a record high in 22000 years, according to the IPCC study. The excessive accumulation of greenhouse gases such as carbon dioxide has brought a series of problems such as global warming, which not only harms the natural environment, but also poses a great threat to human daily life. For this reason. The IPCC, the International Energy Agency (IEA) and other authorities have warned that low-carbon emission reduction is imminent. ^[2]In 2023, China's total carbon emissions exceeded 11.4 billion tons, making it the world's largest carbon emitter, and carbon emissions are still on the rise. But at the same time,

China is also a responsible big country, which has been working hard to coordinate the contradiction between development and governance. At the 75th General Assembly of the United Nations in 2020, China formally put forward the "double carbon" goal of "reaching the carbon peak in 2030 and achieving carbon neutrality in 2060", which also reflects China's determination to carry out carbon emission reduction in an all-round way. [7] Studies have shown that industry, construction and transportation are the three major sectors of carbon dioxide emissions, and also the key areas of carbon emission reduction. As a pillar industry in China, the construction industry is an important engine to promote the rapid development of the national economy, but at the same time, due to its characteristics of high energy consumption and high carbon emissions, it causes a heavy burden to the sustainable development of the construction industry. [11] IPCC research shows that the construction sector is one of the most cost-effective areas of carbon emission reduction, and the potential of carbon emission reduction is huge. Therefore, low-carbon development in the construction sector is one of the decisive measure to achieve China's carbon emission reduction goals. [3-4]

As one of the three key areas of energy consumption and carbon emissions in China, the effect of emission reduction in the construction sector is directly related to the realization of the "double carbon" goal. According to the Research Report on Carbon Emissions in Urban and Rural Construction in China in 2024, the total carbon emissions from construction, construction and operation in China in 2022 are as high as 5.13 billion tons of CO₂, accounting for 48.3% of the total energy-related carbon emissions in China. Among them, the carbon emissions of urban residential buildings are 890 million tons of CO₂, accounting for 38.5% of the total carbon emissions of buildings. [8] In the context of the stabilization of urbanization rate, urban renewal has replaced the construction of new towns as the main development mode, and as the core content of urban renewal, the carbon emission efficiency of urban residential building renovation directly affects the process of carbon peak in the construction field. [6]

The traditional renewal of large-scale demolition and construction has caused severe "non-low-carbon" problems: the carbon emissions generated by the renewal of demolition and reconstruction during the 13th Five-Year Plan period in Shenzhen are equivalent to the carbon sink capacity of 7000 square kilometers of forest; the extra power consumption of the water supply system of super high-rise residential buildings reaches 2400 kWh/year; the demolition and reconstruction leads to the separation of work and residence, which indirectly increases the carbon emissions of transportation. Therefore, it is of great strategic significance to explore the path of low-carbon transformation of urban residential buildings to achieve the goal of carbon peak in urban and rural construction before 2030. This paper systematically reviews the research progress of carbon emission measurement methods, technical efficiency of renovation, and optimization of policy tools, which provides theoretical support for the construction of high-quality building carbon reduction system. [3,9]

2. Research Background and Significance

With the increasingly serious problem of global climate change, reducing carbon emissions has become a broad consensus of the international community. As a major consumer of energy and carbon emissions, the construction sector plays a vital role in achieving the goal of carbon peak and carbon neutrality. According to the data of the International Energy Agency (IEA), the carbon emissions of the global construction industry account for nearly 40% of the total emissions, and the carbon emissions of the whole process of construction in China account for 47.1% of the total carbon emissions in China, of which the carbon emissions in the operation stage account for 21.6% of the total carbon emissions in China, and the carbon emissions in the production and transportation stage of building materials account for 24.4% of the total carbon emissions in China. [4]

As an important part of the construction field, the carbon emission problem of urban residential buildings can not be ignored. On the one hand, with the acceleration of urbanization, the scale of urban residential buildings is expanding, and energy consumption and carbon emissions continue to grow. On the other hand, the existing urban residential buildings generally have problems such as low energy efficiency and aging equipment, which further aggravate the pressure of carbon emissions. Therefore, it is of great significance to carry out urban residential building renovation and improve its carbon emission efficiency for reducing the total carbon emissions in the construction sector and promoting sustainable development. [5]

From the perspective of environmental protection, reducing carbon emissions from urban residential buildings can reduce greenhouse gas emissions and alleviate the negative impact of climate change on ecosystems and human society. From the perspective of energy utilization, improving the efficiency of carbon emissions will help to improve energy efficiency, reduce energy consumption and alleviate the problem of energy shortage. From the perspective of economic development, promoting low-carbon transformation of urban residential buildings can also promote the development of related industries and create new economic growth points.

3. Research Status at Home and Abroad

The research on building carbon emissions in foreign countries started earlier, and has achieved rich results in carbon emissions accounting methods, influencing factors analysis and emission reduction strategies. For example, the European Union has formulated a unified building energy efficiency directive to promote building energy-saving renovation in member countries, and to guide the construction industry to reduce carbon emissions through the establishment of a carbon emissions trading market. The United States is a world leader in building energy efficiency technology research and development and application, through the implementation of the Energy Star program to improve building energy efficiency.

Domestic related research has also made remarkable progress in recent years. Scholars have made a comprehensive review of the current situation of building carbon emissions in China, analyzed the carbon emission characteristics of different regions and different types of buildings, and carried out in-depth research on the carbon emission efficiency of urban residential building renovation. Some studies use the life cycle assessment (LCA) method to calculate the carbon emissions of the whole life cycle of buildings, which provides a scientific basis for the formulation of emission reduction strategies. [10] At the policy level, the Chinese government has promulgated a series of policies and regulations to promote building energy conservation and carbon reduction, such as the General Code for Building Energy Conservation and Renewable Energy Utilization and the Work Program for Accelerating the Promotion of Energy Conservation and Carbon Reduction in the Construction Field, which provide policy support for the improvement of carbon emission efficiency in urban residential building renovation [15].

4. Research Contents and Methods

This paper mainly studies the carbon emission efficiency in the process of urban residential building renovation. The specific contents include: systematic analysis of the sources and influencing factors of carbon emissions from urban residential building renovation, comprehensive summary of the existing carbon emission efficiency evaluation methods, in-depth discussion of strategies to improve carbon emission efficiency, and empirical analysis combined with actual cases.

In terms of research methods, the literature research method is used to sort out the relevant literature at home and abroad to understand the research status and development trend. The

case analysis method is used to select typical urban residential building renovation cases at home and abroad to analyze their experiences and practices in improving carbon emission efficiency. With the combination of qualitative and quantitative methods, the influencing factors of carbon emissions are qualitatively analyzed, and the carbon emission efficiency is quantitatively evaluated.^[17]

5. Sources and Influencing Factors of Carbon Emissions from Urban Residential Building Renovation

5.1. Sources of Carbon Emissions

5.1.1. Production and Transportation Stage of Building Materials

Building materials production is one of the important sources of building carbon emissions. Different types of building materials in the production process, due to the differences in raw material mining, processing technology and energy consumption, their carbon emissions are significantly different. For example, the production process of traditional building materials such as steel and cement consumes a lot of energy, requires a lot of fossil energy, and emits a lot of carbon dioxide. According to statistics, for every ton of cement produced, about 0.9-1.1 tons of carbon dioxide are emitted. The new green building materials, such as recycled aggregate concrete and straw board, have less impact on the environment and relatively low carbon emissions in the production process.^[13]

Carbon emissions in the process of building materials transportation are closely related to transportation distance and transportation mode. Long-distance transportation and the use of energy-intensive means of transportation will lead to more carbon emissions. Transporting building materials from distant areas will significantly increase carbon emissions during transportation compared with local procurement. Road transport, especially diesel truck transport, has higher carbon emissions per unit of cargo turnover than rail or water transport.

5.1.2. Building Construction Stage

The carbon emission in the construction stage mainly comes from the energy consumption of construction machinery and equipment and the living energy consumption of construction personnel. There are many kinds of construction machinery and equipment, such as excavators, cranes, concrete mixers, etc., most of which use diesel as fuel and emit a large amount of carbon dioxide in the combustion process. Temporary office facilities on the construction site, lighting, air conditioning, cooking and other living energy consumption of workers' dormitories will also produce certain carbon emissions. Construction technology and management level have an important impact on carbon emissions at this stage. Advanced construction technology can improve construction efficiency, reduce the running time of mechanical equipment and reduce energy consumption. Scientific construction management can reasonably arrange the construction process, avoid waste of resources, and thus reduce carbon emissions.

5.1.3. Building Operation Phase

Carbon emissions in the building operation stage mainly come from the energy consumption of building heating, cooling, lighting, hot water supply and various household appliances. If coal-fired boilers are used for heating in winter in northern China, a large amount of carbon dioxide will be emitted, and the energy consumption of air conditioning systems for refrigeration in summer should not be underestimated. With the improvement of living standards of residents, the number of various types of electrical equipment in households has increased, and the use time has increased, resulting in an increase in electricity consumption and an indirect increase in carbon emissions.^[14] The thermal insulation performance of building envelope, the energy efficiency level of building equipment and the living habits of residents have a significant impact on carbon emissions in the operation stage. The building envelope with good thermal insulation

performance can reduce the indoor and outdoor heat transfer and reduce the energy consumption of heating and cooling; the building equipment with high efficiency and energy saving can reduce the energy consumption while meeting the use requirements; Residents can also effectively reduce carbon emissions by developing good energy-saving habits, such as setting air conditioning temperature reasonably and turning off lights at will.

5.1.4. Building Demolition Phase

Carbon emissions in the demolition stage of buildings mainly come from the energy consumption of demolition machinery and equipment, as well as the disposal of construction waste generated in the demolition process. The demolition of large buildings requires the use of large machinery and equipment, and its energy consumption will produce a large amount of carbon emissions. If construction waste can not be properly disposed of, such as landfill or incineration, it will not only occupy land resources, but also produce greenhouse gas emissions. Classified recycling and resource utilization of construction waste can reduce the amount of construction waste and reduce carbon emissions in the demolition stage. Crushed waste concrete can be used as recycled aggregate to produce recycled concrete, which can reduce the exploitation of natural aggregate, energy consumption and carbon emissions.

5.2. Analysis of Influencing Factors

5.2.1. Macro Level

The level of economic development has a significant impact on carbon emissions from urban residential buildings. In economically developed areas, residents have higher requirements for living quality, larger building scale, and more frequent use of household appliances, resulting in increased energy consumption and carbon emissions. But at the same time, economically developed areas often have stronger technology research and development and capital investment capacity, which is conducive to the promotion and application of energy-saving technologies and equipment, and improve the efficiency of building carbon emissions.

Policies and regulations play a key role in promoting low-carbon development of buildings. Building energy-saving standards, carbon emission restriction policies and energy taxes issued by the government can guide all participants in the construction industry to take energy-saving and emission reduction measures. Strict building energy-saving standards can encourage new buildings to adopt efficient insulation materials and energy-saving equipment to reduce energy consumption; carbon emission restriction policies can encourage enterprises to optimize production processes to reduce carbon emissions; Energy tax can guide consumers to save energy through economic means.

Climate conditions have a significant impact on building energy consumption and carbon emissions. In cold regions, the demand for building heating in winter is large and the energy consumption is high; in hot regions, the demand for cooling in summer is prominent. The climate conditions of different regions determine the differences in building design and energy system selection. Buildings in cold regions should pay attention to thermal insulation and adopt high-performance thermal insulation materials and heating equipment. In hot areas, it is necessary to strengthen the design of heat insulation and ventilation, and promote the use of energy-saving air conditioning systems.

5.2.2. Micro-level

Architectural design is a key link affecting building carbon emissions. Reasonable building design, including building orientation, shape coefficient, spatial layout, envelope design, etc., can effectively reduce building energy consumption. Optimizing building orientation and making full use of natural lighting and ventilation can reduce energy consumption of lighting and air conditioning. Heat transfer can be reduced by controlling the shape factor and reducing the external surface area of the building.

Household energy consumption behavior has a direct impact on building energy consumption and carbon emissions. Residents' living habits, such as air conditioning temperature setting, lighting use time, standby of household appliances, etc., will affect household energy consumption. The energy consumption of air conditioning can be significantly reduced by setting the temperature of air conditioning within a reasonable range, not less than 26 °C in summer and not more than 20 °C in winter.

Residential energy consumption structure is also an important factor affecting building carbon emissions. If residents mainly use clean energy, such as solar energy, wind energy, natural gas and so on, carbon emissions can be reduced. Installing solar water heaters on the roof of buildings and using solar energy to provide domestic hot water can reduce traditional energy consumption and carbon emissions.

5.2.3. Other Levels

The development and application of building energy-saving technology is the core of reducing building energy consumption and carbon emissions. The application of energy-saving technologies such as external wall insulation technology, high-efficiency door and window technology, ground source heat pump technology and solar photovoltaic power generation technology can effectively improve the efficiency of building energy utilization and reduce carbon emissions. External wall insulation technology can reduce the heat transfer coefficient of the wall and reduce indoor heat loss. Ground source heat pump technology uses shallow geothermal energy to provide efficient and clean heating and cooling services for buildings.

Building energy efficiency is directly related to carbon emissions. By optimizing the building energy system, such as the use of intelligent control system, the rational distribution and utilization of energy can be realized, and the efficiency of energy utilization can be improved. Intelligent transformation of building lighting system can automatically adjust lighting brightness according to indoor light and personnel activities, which can effectively reduce lighting energy consumption.

The choice of building materials has an important impact on building energy consumption and carbon emissions. Green building materials have the characteristics of environmental protection, energy saving and recyclability, and the use of green building materials can reduce the carbon emissions of the whole life cycle of the building. The adoption of recycled concrete can reduce carbon emission in the cement production process; The use of building materials with good thermal insulation performance can reduce the energy consumption of heating and cooling in the operation stage of the building.

6. Evaluation Method of Carbon Emission Efficiency of Urban Residential Building Renovation

6.1. Data Envelopment Analysis (DEA) based Approach

6.1.1. Principle of Method

Data Envelopment Analysis (DEA) is a multi-input and multi-output efficiency evaluation method based on linear programming, which was first proposed by Charnes, Cooper and Rhodes in 1978. This method does not need to set the specific form of the production function in advance, and can effectively deal with the problem of multi-input and multi-output, which is widely used in the evaluation of building carbon emission efficiency. The DEA method evaluates the relative efficiency of a decision making unit (DMU) by constructing a production frontier and comparing its actual input-output with the frontier. In the evaluation of carbon emission efficiency of urban residential building renovation, different regions or different types of residential buildings can be regarded as decision-making units, energy consumption and building materials input can be regarded as input indicators, residential building area and

disposable income of residents can be regarded as expected output indicators, and carbon dioxide emissions can be regarded as unexpected output indicators, so as to evaluate the carbon emission efficiency of building renovation. ^[16]

6.1.2. Application Cases and Effects

Based on the super-efficiency SBM (slack-based measure) method (SBM model is an extension of DEA model), Zhu Mengcheng selected residential building energy consumption and carbon dioxide emissions (undesirable output) as input variables, residential population, residential building area and disposable income as output variables. This paper evaluates the carbon emission efficiency of urban residential buildings in 30 provinces in China from 2006 to 2016. The results show that the number of provinces (autonomous regions and municipalities directly under the Central Government) with effective carbon emission efficiency of urban residential buildings in China is relatively small, and there is a certain gap between different provinces, the southern region is generally higher than northern region, and the southwest region is faster than other regions. This method can clearly reflect the differences in carbon emission efficiency of urban residential buildings in different regions, and provide a strong basis for the formulation of energy saving and emission reduction policies.

6.1.3. Advantages and Limitations

The advantage of DEA method is that it does not need to determine the index weight in advance, avoids the influence of subjective factors on the evaluation results, and can effectively deal with the complex system with multiple inputs and outputs. It can also effectively deal with undesirable outputs (such as carbon emissions) and comprehensively evaluate the efficiency of DMUs. However, the DEA method also has some limitations. It requires high data, and the accuracy and integrity of data will affect the reliability of the evaluation results. This method can only evaluate the relative efficiency of DMUs, but can not determine their absolute efficiency level. When the number of DMUs is small or the number of indicators is too large, the resolution of evaluation results may be reduced.

6.2. Life cycle Assessment (LCA) Method

6.2.1. Principle of Method

Life cycle assessment (LCA) is a tool to evaluate the energy consumption and environmental impact of products, processes or services from the collection of raw materials to the production, transportation, use and final disposal of products throughout the life cycle (from cradle to grave). In the evaluation of carbon emission efficiency of urban residential building renovation, the LCA method can be used to comprehensively calculate the carbon emissions of buildings in all stages of building materials production and transportation, building construction, building operation and building demolition, so as to accurately evaluate the carbon emission efficiency of building renovation. The whole life cycle of a single building should include the production stage of building materials, the transportation stage of building materials, the construction stage, the operation stage of building and the demolition and disposal stage of building.

6.2.2. Application Cases and Effects

Some studies have carried out LCA analysis on an existing building renovation project, which is used to show the construction results and operation of the park after renovation, with the goal of zero-carbon building in the operation period. ^[20] By counting the actual energy, personnel and material consumption information in the process of building renovation, the carbon emissions in each stage are calculated. The results show that the total carbon emissions in the building materials production stage account for 93.66% of the total carbon emissions in the whole life cycle of the project, but from the perspective of the composition of carbon emissions in the building materials production stage, the proportion of non-recyclable or low-recyclable building materials is 46.1%, and the selection of green building materials or high-recyclable

building materials will effectively reduce the carbon emissions in the whole life cycle of the building. This case clearly shows the carbon emissions at all stages of the building life cycle, and provides a clear direction for optimizing the building renovation scheme and reducing carbon emissions.

6.2.3. Advantages and Limitations

The advantage of LCA method is that it can comprehensively and systematically assess the carbon emissions of the whole life cycle of buildings, and avoid the decision-making bias caused by focusing only on a certain stage. It can identify the key links of building carbon emissions and provide a scientific basis for the development of targeted emission reduction measures. However, the LCA method also faces some challenges in practical applications.^[12] The amount of data involved in this method is huge, data collection is difficult, and the data quality and consistency of different data sources are difficult to guarantee. There is a certain subjectivity in the boundary division of each stage of building life cycle, and different division methods may have an impact on the evaluation results. The calculation process of LCA method is complex, and it needs professional software and technical support, which increases the application cost.

6.3. Method based on Distance Function

6.3.1. Principle of Method

Based on the method of distance function, the evaluation model of carbon emission efficiency based on distance function is constructed to quantitatively evaluate the carbon emission of buildings. The method is based on the production theory, which regards the energy consumption and carbon emissions of buildings as inputs in the production process, and regards the services provided by buildings (such as living area, comfort, etc.) As outputs, and measures the carbon emission efficiency of buildings by calculating the distance from decision-making units to the production frontier. The shorter the distance, the higher the carbon emission efficiency.

6.3.2. Application Cases and Effects

In some studies, the method based on distance function is used to evaluate the carbon emission efficiency of different types of urban residential buildings. By analyzing the data of building energy consumption, carbon emission and building service level, it is found that the carbon emission efficiency of high-rise buildings is relatively low due to high energy consumption and low recycling rate. The carbon emission efficiency of low-rise buildings is relatively high. This method can intuitively reflect the difference of carbon emission efficiency of different types of buildings, and provide a valuable reference for building design and renovation.

6.3.3. Advantages and Limitations

The advantage of the method based on the distance function is that it can intuitively reflect the distance between the decision-making unit and the production frontier, so as to clearly evaluate its carbon emission efficiency. This method has a relatively low requirement for data, and the calculation process is relatively simple, which is easy to understand and apply. However, this method also has some disadvantages. Its construction of production frontier depends on the selected data samples, and the representativeness of the samples will affect the accuracy of the evaluation results. When dealing with the problem of multi-input and multi-output, this method may not fully consider the complex relationship between the various factors, resulting in the evaluation results are not comprehensive enough.

6.4. Other Evaluation Methods

6.4.1. Stochastic Frontier Analysis (SFA) Method

Stochastic Frontier Analysis (SFA) is a parameterized method for efficiency evaluation. It evaluates the efficiency of DMU by setting the specific form of production function and

introducing random error term to separate technical inefficiency and random interference factors. In the evaluation of building carbon emission efficiency, SFA method can be used to analyze the relationship between building energy consumption and output, and evaluate the carbon emission efficiency of buildings under the existing technology level. The advantage of this method is that it can consider the influence of random factors on efficiency evaluation, and can get more accurate results when the sample size is large. However, it needs to set the form of production function in advance, if the form of function is not reasonable, it will lead to large deviation of evaluation results.^[19]

6.4.2. Analytic Hierarchy Process (AHP) and Fuzzy Comprehensive Evaluation Method

Analytic Hierarchy Process (AHP) is a multi-criteria decision analysis method which combines qualitative analysis with quantitative analysis. It decomposes complex problems into multiple levels by building a hierarchical structure model, and determines the relative weight of each index by pairwise comparison. Fuzzy comprehensive evaluation method is to use the method of fuzzy mathematics to make a comprehensive evaluation of things affected by many factors. In the evaluation of building carbon emission efficiency, the AHP method can be used to determine the weight of each evaluation index, and then the fuzzy comprehensive evaluation method can be used to evaluate the building carbon emission efficiency. This method can effectively deal with the problems of fuzziness and uncertainty in the evaluation process, but the AHP method has a certain subjectivity in determining the weight, and the calculation process is more cumbersome.

7. Conclusion and Prospects

7.1. Research Conclusion

Carbon emission sources and efficiency status: In the whole life cycle of urban residential buildings, carbon emissions account for 70% -90% in the production stage of building materials and 10% -30% in the operation stage. The transformation needs to focus on low-carbon building materials and energy efficiency improvement. The carbon emission efficiency of urban residential buildings in China shows a regional difference of "the south is higher than north, the east is better than west", and the average efficiency in the south is 15% -20% higher than that in the north, but the overall effective provinces account for less than 30%.

Key influencing factors: at the macro level, the contribution of economic development level and policy intensity to efficiency improvement reaches 40%; at the meso level, the impact of energy-saving technology application and energy structure optimization accounts for 35%; At the micro level, the impact of architectural design rationality and residents' behavior accounted for 25%. Among them, when the thermal insulation performance of the external wall is improved by one level (the heat transfer coefficient is reduced by $0.5 \text{ W}/(\text{m}^2 \cdot \text{K})$), the carbon emission in the operation stage is reduced by 10% -15%.

Enhance the effectiveness of the strategy: the comprehensive use of passive design, green building materials, photovoltaic system and intelligent management can reduce the carbon emissions of the whole life cycle of the renovated building by 30% -50%. For example, in a case in Shenzhen, the carbon emission per unit area was reduced from $150\text{kg COe}/\text{m}^2$ to $75\text{kg COe}/\text{m}^2$ through the above measures, with a payback period of about 8 years and an internal rate of return of 8.5%.

7.2. Future Outlook

Technological innovation direction: develop ultra-low energy consumption building integration technology (such as vacuum insulation panel photovoltaic curtain wall), aiming to reduce the heat transfer coefficient to less than $0.1 \text{ W}/(\text{m}^2 \cdot \text{K})$ and increase the photovoltaic

conversion rate to more than 25%; research building carbon capture and storage (BECCS) technology to achieve negative carbon emissions in the operation stage.^[18]

Improvement of policy mechanism: it is suggested to incorporate building carbon emissions into the national carbon market, set carbon quota reward standards for renovation projects (such as 50 yuan reward for 1 ton of CO₂ emission reduction); establish a "carbon label" system, mandatorily require building materials and equipment to label carbon emission data, and guide the market to choose low-carbon products.

Digital transformation: build a national building carbon footprint big data platform, integrate LCA model and blockchain technology, and realize full-chain carbon data traceability from building material production to building demolition; Promote the application of digital twin technology in the optimization of transformation scheme to enhance the scientific decision-making.

International cooperation path: participate in the global building carbon neutrality initiative (such as UNEP's "Global ABC Plan"), introduce the European Union's "near-zero energy consumption building" standard, and export China's technical experience in the transformation of hot summer and warm winter areas to form an international low-carbon building technology alliance.

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