Research on the Improvement of Energy Economic Efficiency of Green Buildings Based on the SD-CWM Model

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Abstract. Under the dual pressures of global climate change and environmental pollution, improving the energy - economic efficiency of green buildings is a key path to achieving the "dual carbon" goals. Aiming at the optimization of the energy - economic efficiency of green buildings, this study innovatively proposes a collaborative analysis framework based on the System Dynamics (SD) model and the Combined Weight Method (CWM). By constructing an SD model, the dynamic feedback mechanism of multiple elements in the green building energy system is revealed, and the complex trade - off relationships among energy consumption, carbon emissions, and economic returns are quantified in combination with CWM. Taking urban residential green buildings in Shandong Province as the research object, the evolution paths under high - carbon, low - carbon, and benchmark policy scenarios from 2016 to 2035 are simulated. The study finds that the intensity of policy intervention and residents' low - carbon awareness are the core factors driving the improvement of green building energy efficiency. Under the low - carbon policy scenario, the building carbon emission intensity can be reduced by 38.7%, and the economic returns can increase by 23.4% simultaneously. This study provides methodological innovation for the multi - objective collaborative optimization of green buildings and offers empirical evidence for policymakers to design carbon - emission reduction paths.

Keywords: Green Buildings; Energy Economy; System Dynamics Model; Combined Weight Model.

1. Introduction

Under the dual pressures of global climate change and environmental pollution, countries around the world have successively formulated response strategies, and the "dual carbon" goal has become a key strategy for many countries to achieve sustainable development. As a key area of energy consumption and carbon emissions, the green transformation of the construction industry is extremely urgent. According to relevant research, the energy consumption for the production and operation of buildings accounts for 30% - 45% of the total energy consumption in various countries, and the pollutants emitted account for 10% - 20% of the total amount of various pollutants [1]. Therefore, improving the energy economic efficiency of buildings is of great significance for global sustainable development.

Green buildings have multiple important significances. It is a comprehensive concept that covers attributes such as resource consumption, ecology, safety, and health [2]. Compared with traditional buildings, green buildings can significantly reduce energy consumption, decrease pollutant emissions, and protect the ecological environment. For example, by adopting advanced technologies such as passive solar buildings and green building materials, as well as introducing green building management models such as BIM technology and whole-process management, the energy-saving and environmental protection performance of buildings can be improved. At the same time, green buildings focus on land saving, water saving, and material saving during the design and construction process to improve resource utilization efficiency. In addition, green buildings can also reduce the energy consumption and environmental pollution levels of cities, improve the quality of life and health of residents, and attract more talents and enterprises to settle in the city.

However, the development of green buildings also faces many challenges [3]. Firstly, the initial investment cost is high. The procurement and installation costs of advanced technologies and environmentally friendly materials used in green buildings are relatively high, making the initial investment increase by 20% - 30% compared with traditional buildings, which discourages many developers and property owners. Secondly, there is a shortage of professional talents. The development of green buildings requires compound talents who understand both architecture and environmental protection and energy conservation. However, currently, such talents are relatively scarce, and some people also have insufficient understanding of green buildings, which affects the market demand. Thirdly, the market policies are unstable. The incoherence of policies and the low recognition of green building technologies in the market hinder the promotion and application of these technologies. The differences in green building standards among different countries and regions also increase the difficulty of certification and evaluation. Fourthly, the operation and management are imperfect. Green building property management companies have deficiencies in aspects such as technical equipment maintenance, energy management, and indoor environment monitoring, resulting in a decline in energy-saving effects.

This study focuses on the key issue of improving the energy economic efficiency of green buildings. It aims to analyze the dynamic feedback mechanism of multiple elements in the energy consumption system of green buildings through the System Dynamics (SD) model, and use the Combined Weight Method (CWM) to quantify the complex trade-off relationships among multiple objectives. By simulating the evolution paths of the energy consumption, carbon emissions, and economic benefits of green buildings under different policy scenarios, identifying the key driving factors, and proposing synergistic and optimal promotion strategies for green buildings, this study provides theoretical support and practical paths for the global construction industry to achieve the "dual carbon" goal.

2. Research Methods and Model Construction

2.1 System Dynamics Model (SD Model)

The basic principles of the system dynamics model include accumulation and flow, feedback loops and delay effects, nonlinear dynamics and complexity [4]. Through the method of system dynamics, it can help us understand the key factors and complex relationships in the coordinated development process of green buildings and the social economy, and guide decision-makers to formulate more scientific policies and measures. The system dynamics model constructed in this study is shown in Figure 1.

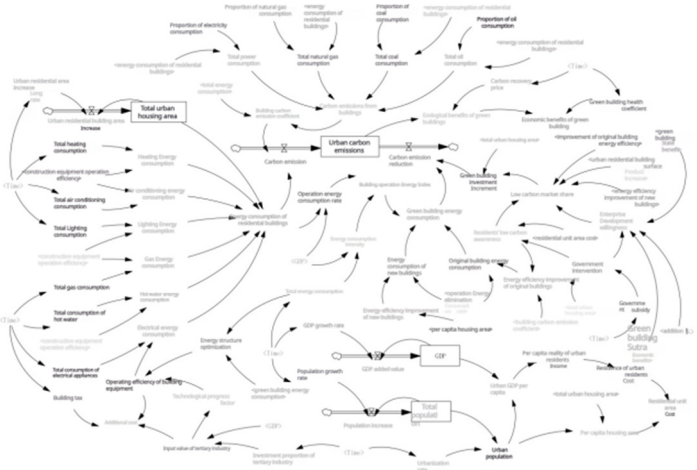


Figure 1. The System Dynamics Model Constructed in This Study

1.Assumptions and Variable Determination of the System Dynamics Model

The carbon emissions and energy consumption of urban buildings are affected by many intertwined factors such as policies, technologies, and markets. In order to sort out the core relationships, eliminate secondary interferences, enhance the operability of this study, and make the research conclusions more targeted, this study hereby makes necessary simplifications to the model. Therefore, the assumptions set in this study are as follows:

(1) It is assumed that factors such as the future economy and society will develop steadily, and the growth of energy consumption will be stable.(2) Only carbon dioxide is considered for environmental indicators, and the emission impacts of other greenhouse gases are not considered.(3) For the energy consumption of public buildings, only six main sources of energy consumption are considered, namely heating, air conditioning, lighting, cooking, hot water, and electrical appliances.(4) The model only considers the relationships among various factors within the system, and ignores the influences of other external factors.(5) The operation efficiency and operation energy consumption of various types of equipment are kept consistent, and the influences of other consumptions are ignored.

2.Boundaries of the Research Object

This chapter defines the boundaries of the model system as the carbon emissions, ecological benefits, and economic benefits of urban residential green buildings in Shandong Province. It focuses on analyzing the dynamic interactive relationships among elements such as the energy structure, economic growth, expansion of the building scale, population growth rate, degree of government intervention, residents' low-carbon awareness, and the development speed of urbanization. By using the simulation function of the Vensim software, the mutual restraint relationships among these variables and their dynamic change trends are revealed.

The time boundary of this model is from 2016 to 2035. The historical data collection period is from 2016 to 2022, and the simulation period is from 2024 to 2035. The time span unit is one year.

2.2 Combined Weight Model (CWM Model)

The Combined Weight Method is a multi-index comprehensive evaluation method. By assigning weights to different indicators, multiple indicators are integrated into an overall evaluation value. Its core idea is to reasonably allocate weights according to the importance of each indicator, so as to more scientifically reflect the comprehensive level of the evaluation object.

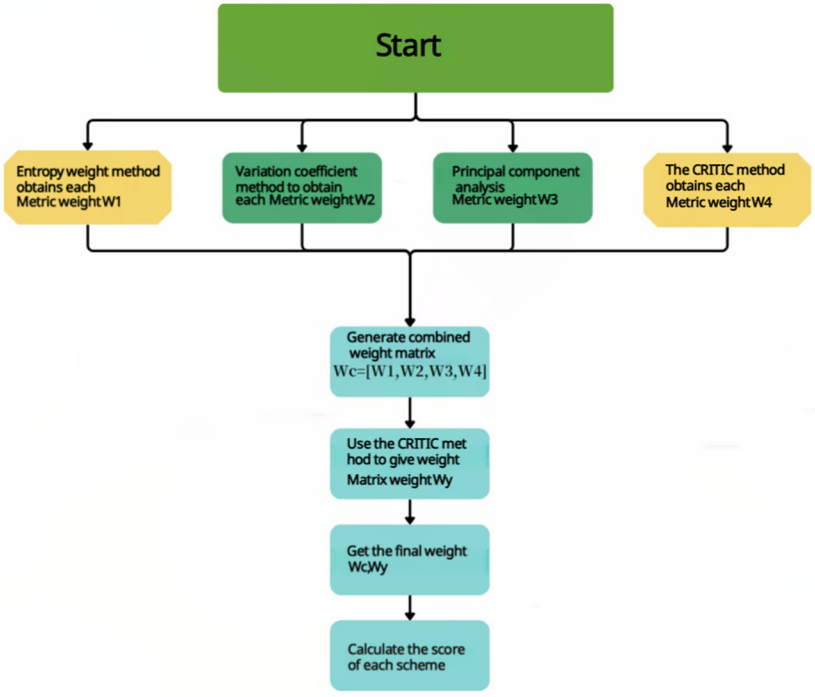


Figure 2. Steps for Determining Weights

The steps for determining the weights of the model in this study are shown in Figure 2.The determination of weights is the core of the Combined Weight Method. Weights are assigned through

the combination of the subjective weighting method and the objective weighting method. The subjective weighting method is a method for determining the weights of indicators based on expert experience, knowledge, or preferences. It has the advantages of relying on expert experience and being suitable for qualitative indicators. The objective weighting method, through a data-driven approach, avoids the biases brought about by subjective judgments and can more accurately reflect the effects and impacts of policy implementation. Therefore, this paper uses four methods, namely the Entropy Weight Method (EWM) [5], the CRITIC Method [6], the Principal Component Analysis Method (PCA) [7], and the Coefficient of Variation Method (CVM) [8], to determine the weight allocation of relevant indicators.

Combine the weights of the subjective weighting method and the objective weighting method to generate a weight combination matrix. Use the Kendall's Coefficient of Concordance Test Method to conduct a consistency test on various weighting methods. Use the CRITIC objective combined weighting method to obtain the optimal combined weights, and then score various schemes.

The weight indicators obtained by using the four methods of the Entropy Weight Method, the CRITIC Method, the Principal Component Analysis Method, and the Coefficient of Variation Method are respectively W_1, W_2, W_3, W_4. Use the Kendall or Pearson's coefficient of consistency for testing. Here, the four weights need to be tested. If the test passes, it indicates that the weights have synergy. If the test fails, it indicates that there is no synergy, meaning that the differences between the weights are relatively large. The formula for calculating the total weight is as follows.

$$W_c = \frac{\left(w_1 + w_2 + w_3 + w_4\right)}{l} \tag{1}$$

If the consistency test passes, it means that the weights calculated by each method do not have significant differences. If the test fails, it means that the weights calculated by each method have relatively large differences. Then, use the CRITIC method to calculate their weights. The calculation formula is as follows.

$$C_j = \sigma_j \sum_{i=1}^{m} \left(1 - r_{ij}\right) \tag{2}$$

Where, r_{ij} represents the correlation coefficient between weight *i* and weight *j*, and σ_j represents the standard deviation of weight *j*. C_j is the information carrying capacity of the *j*th indicator, which reflects the importance of indicator *j*.

Multiply the standardized indicator values by the weights and sum them to obtain the comprehensive evaluation value. The calculation formula is as follows.

$$S = \sum_{i=1}^{n} w_i \times x_i \tag{3}$$

Where, *S* is the comprehensive evaluation value; w_i is the weight of the *i*th indicator; x_i is the standardized value of the *i*th indicator.

2.3 Simulation Scenarios and Policy Settings

This study will select three different policies for simulation. By simulating the energy consumption and benefits of green buildings under different policies, for example, it will analyze the building carbon emissions, the market share of low-carbon products, residents' low-carbon awareness, as well as the ecological and economic benefits of green buildings under high-carbon, low-carbon, and benchmark policies respectively. The descriptions of the three different policy backgrounds are as follows:

High-carbon Scenario: The development of green buildings is hindered. Developers and investors focus on short-term interests, with less application of green building technologies and poor implementation effects. The number of newly built high-energy-consuming projects increases, and the energy-saving renovation of existing buildings stagnates. The region emphasizes the economy,

and the implementation of building energy conservation and emission reduction policies is insufficient. Residents' low-carbon awareness decreases, and there is insufficient motivation for clean energy power generation. All parameter indicators are higher than those in the low-carbon scenario.

Low-carbon Scenario: Green buildings develop rapidly. Newly built buildings fully implement the standards, and ultra-low and near-zero energy-consuming buildings are promoted. Existing buildings undergo large-scale energy-saving renovations, and the energy use in buildings shifts towards low-carbon. Renewable energy and waste heat are widely used, and the level of electrification is improved. It drives the industrial chain and forms an industrial system. On the basis of the benchmark scenario, the growth of the building area is controlled, the industrial and energy structures are adjusted, and the growth of building carbon emissions is slowed down. The policy intensity is increased, residents' consumption awareness and the power of clean energy power generation are improved, and the power generation efficiency is enhanced. The growth rates of the urban population and GDP are consistent with those in the benchmark scenario, and the remaining parameter indicators are smaller than those in the benchmark scenario.

Benchmark Scenario: The development of green buildings is naturally promoted by existing policies and technologies, lacking additional incentives and innovations. Newly built buildings gradually implement the standards, and the promotion of ultra-low and near-zero energy-consuming buildings is slow. The scale and level of energy-saving renovations of existing buildings are limited. The economy and urbanization continue the historical development trend, reflecting the changes in building carbon emissions without additional measures.

The time boundary of the model in this study is from 2016 to 2035. The historical data collection period is from 2016 to 2022, and the simulation period is from 2024 to 2035, with the time span unit being one year.

3. Results

3.1 Simulation Results of The Model

1.Dynamic Change Trends of Energy Consumption

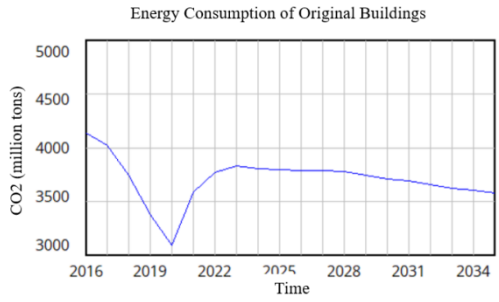


Figure 3. Simulation of Predicted Energy Consumption of Original Buildings

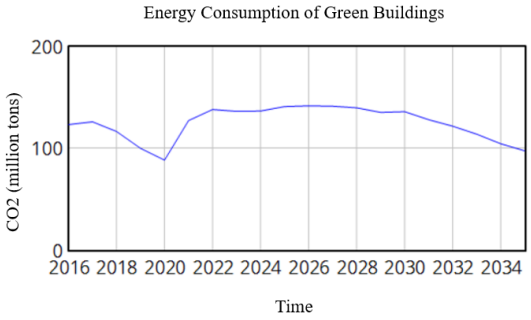


Figure 4. Simulation of Predicted Energy Consumption of Green Buildings

As shown in Figure 3, according to the simulation results, although the energy consumption of the original buildings shows an overall downward trend after 2022, the energy consumption value was 38.274 million tons of CO2 in 2030, and then slowly decreased to 35.8129 million tons of CO2 in 2035, with an average annual decrease rate of 0.8%.As shown in Figure 4, according to the simulation results, the energy consumption of green buildings shows a downward trend after 2022. It is predicted that the energy consumption of green buildings will drop to 764,125 tons of carbon dioxide in 2035.

As shown in Figure 5 and Figure 6, according to the simulation results, the carbon emissions of urban buildings show an upward trend after 2022. The carbon emissions of urban buildings reached 88.5559 million tons of carbon dioxide in 2023 and 91.1554 million tons of carbon dioxide in 2035. The operational energy consumption of urban buildings shows an upward trend after 2022. The operational energy consumption of urban buildings reached 424.95 million tons of carbon dioxide in

2023 and 822.849 million tons of carbon dioxide in 2035. This is because with the development of the building scale, the consumption of heating, air conditioning, cooking, lighting, and electrical appliances will continue to increase, resulting in the continuous increase of the operational energy consumption and carbon emissions of urban buildings.

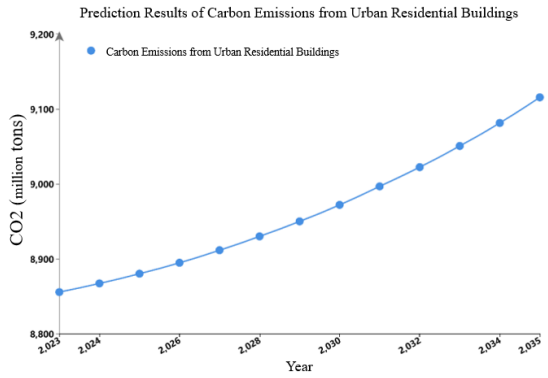


Figure 5. Prediction Results of Carbon Emissions from Urban Residential Buildings

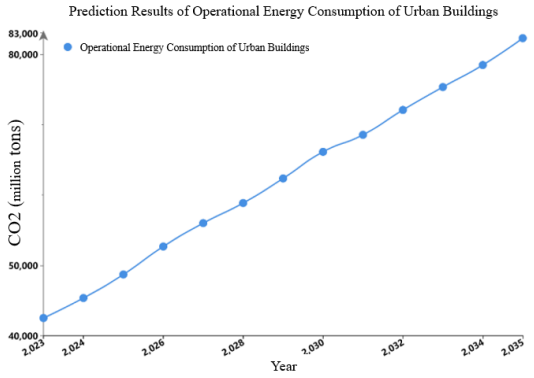


Figure 6. Prediction Results of Operational Energy Consumption of Urban Buildings

2.Comparison of Indicators under Different Policies

Select five relatively representative variables from the system model to observe whether the various results of green buildings are more in line with the current low-carbon policy implemented by the state. The five indicators are the ecological benefits of green buildings, residents' low-carbon awareness, the market share of low-carbon products, building carbon emissions, and the economic benefits of green buildings. Compared with the low-carbon policy, the benchmark policy deletes the two auxiliary variables of the degree of government intervention and the factor of technological progress; compared with the low-carbon policy, the high-carbon policy reduces the government subsidies and the proportion of natural gas consumption; and increases the proportions of electricity consumption, coal consumption, and liquefied petroleum gas consumption.

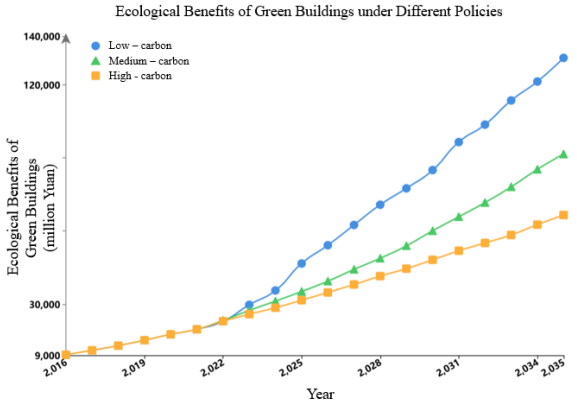


Figure 7. Ecological Benefits of Green Buildings

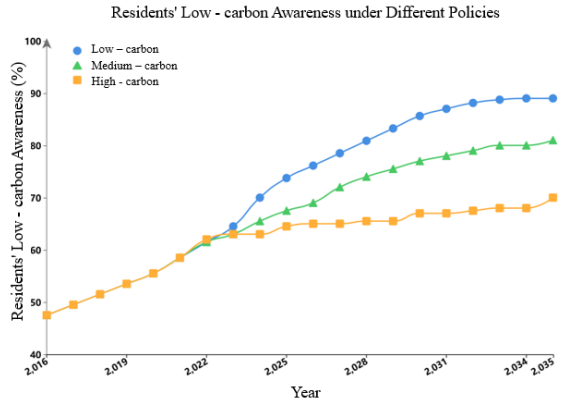
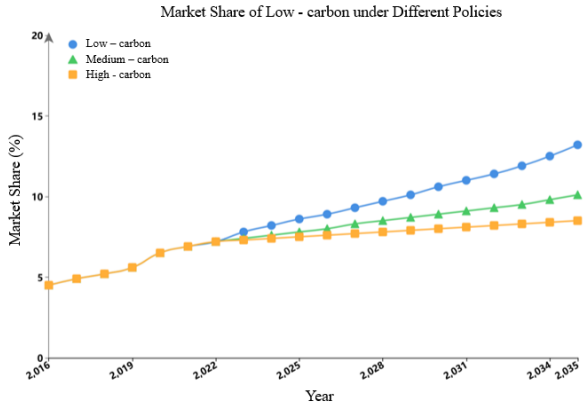


Figure 8. Residents' Low-carbon Awareness

As can be seen from Figure 7, the ecological benefits of green buildings under the low-carbon policy are the highest, followed by those under the standard policy, and the ecological benefits of green buildings under the high-carbon policy are the lowest. As shown in Figure 8, residents' low-carbon awareness is the highest under the low-carbon policy, followed by that under the benchmark policy, and residents' low-carbon awareness is the lowest under the high-carbon policy.

As can be seen from Figure 9, the market share of low-carbon products under the low-carbon policy is the highest, followed by that under the standard policy, and the market share of low-carbon products under the high-carbon policy is the lowest. As can be seen from Figure 10, the building carbon emissions under the high-carbon policy are the highest, followed by those under the standard policy, and the building carbon emissions under the low-carbon policy are the lowest.



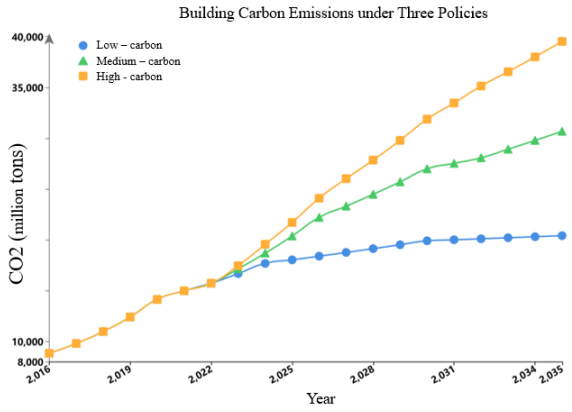


Figure 9. Market Share of Low-carbon Product **Figure 10.** Building Carbon Emissions

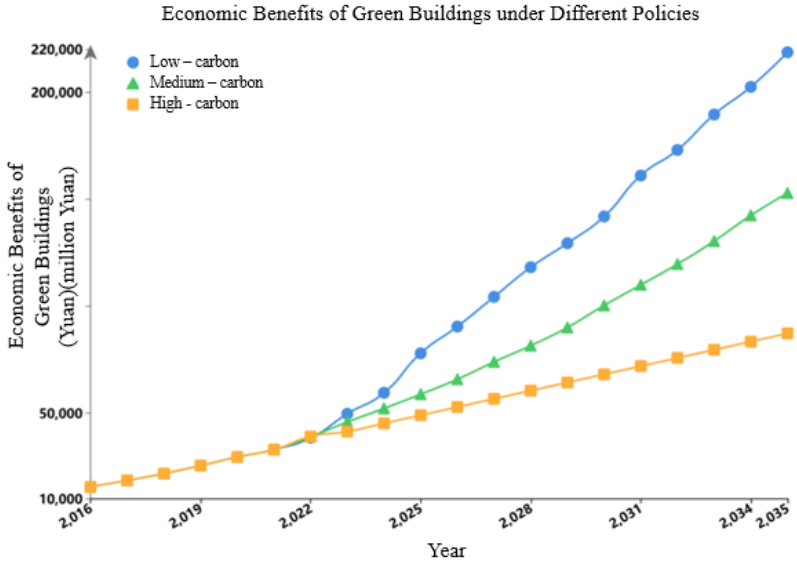


Figure 11. Economic Benefits of Green Buildings

As shown in Figure 11, the economic benefits of green buildings under the low-carbon policy are greater than those under the benchmark policy, and the economic benefits of green buildings under the benchmark policy are greater than those under the high-carbon policy.

In conclusion, the low-carbon policy can better promote the development of green ecology, and green buildings are more adaptable to the low-carbon policy.

3.2 Evaluation of Green Building Policies

According to the results of the previous Vensim simulation, select the values of each indicator under the three different policies in 2035. Among the five selected indicators, the market share of low-carbon products, the ecological benefits of green buildings, the economic benefits of green buildings, and the public's low-carbon awareness are positive indicators, while the building carbon emissions are a negative indicator. Process the positive and negative indicators according to the calculation formulas mentioned above. Then, calculate the relevant weights of each indicator through the four methods of the entropy weight method, the CRITIC method, the principal component analysis method, and the coefficient of variation method. Use MATLAB software to calculate the results, as shown in Table 1.

The calculated scores are as follows: Low-carbon: 100, Standard: 66.7, High-carbon: 0. In conclusion, it can be seen that the low-carbon policy is most suitable for the promotion and development of green buildings.

Table 1. Calculation Results Table

Calculation Method	Market Share of Low-carbon Products	Ecological Benefits of Green Buildings	Economic Benefits of Green Buildings	Public Low-carbon Awareness	Building Carbon Emissions
EWM	0.1815	0.1869	0.1821	0.1904	0.2592
CVM	0.2124	0.1914	0.2152	0.2321	0.1489
CRITIC	0.1239	0.1219	0.1236	0.1215	0.5092
PCA	0.2008	0.2004	0.2009	0.1998	0.1981

4. Conclusion

This study uses the SD-CWM model to deeply explore the collaborative optimization of the energy consumption system of green buildings under the background of the "dual carbon" goal. Based on the above model analysis and research on the results, this study draws the following conclusions.

(1) Significant Advantages of the Low-carbon Policy: Strengthening government subsidies, increasing the proportion of clean energy, and enhancing residents' low-carbon awareness can significantly reduce building carbon emissions, maximize the ecological and economic benefits of green buildings, and the energy consumption is lower than that in the high-carbon and benchmark policy scenarios.

(2) Nonlinear Interaction of Multiple Elements: The SD-CWM model reveals that there are complex dynamic feedbacks among factors such as the social economy, policy intervention, and technological application. For example, government subsidies and tax incentives can enhance the willingness of enterprises to develop green buildings, promote the increase of market share, and reduce building carbon emissions.

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