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Comprehensive Evaluation of Decarbonization Technologies: A Case Study of Residential Buildings in Zhuzhou City, China

Jianlong Liu [1], Qing Tang [2], Haiyan Chen [3,*], Wenjing Meng [2], Feng Xu [2] and Zhisheng Li [4]

[1] School of Packaging Design & Art, Hunan University of Technology, Zhuzhou 412007, China; jlliu7887@126.com
[2] School of Urban and Environmental Science, Hunan University of Technology, Zhuzhou 412007, China; holly1026tq@163.com (Q.T.); mengwenjing0321@163.com (W.M.); 18922255155@163.com (F.X.)
[3] China Building Materials Inspection and Certification Group Hunan Co., Ltd., Changsha 410006, China
[4] School of Civil and Transportation Engineering, Guangdong University of Technology, Guangzhou 510006, China; chinagzlzs@126.com
* Correspondence: 18224423070@163.com

Abstract: Efficient carbon emission reduction technologies in buildings are necessary for achieving the "Dual carbon" goal in China. In this study, a comprehensive evaluation model is proposed to assess the effect of carbon emission reduction based on the analytic hierarchy process–entropy weight–coefficient of variation model which takes newly built residential buildings in Zhuzhou City as the research object. The results show that the preferred materials for the roof and exterior walls of the building's envelope structure were flame-retardant extruded polystyrene boards, and porous shale bricks were preferred as the main materials for the exterior walls. In addition, the rooftop solar photovoltaic system and energy-saving air conditioning technology were suitable in terms of being renewable and were better utilized. In the end, carbon emissions were significantly reduced when using the building decarbonization technologies. This study provides a new reference for choosing materials and technologies for the design of residential buildings in Hunan Province and even other regions with hot summers and cold winters.

Keywords: Zhuzhou region; combination weighting method; residential building; decarbonization technologies; comprehensive evaluation

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Citation: Liu, J.; Tang, Q.; Chen, H.; Meng, W.; Xu, F.; Li, Z. Comprehensive Evaluation of Decarbonization Technologies: A Case Study of Residential Buildings in Zhuzhou City, China. *Buildings* **2024**, *14*, 1322. https://doi.org/10.3390/buildings14051322

Academic Editors: Yongjian Ke, Jingxiao Zhang, Simon P. Philbin and Yunyang Ye

Received: 8 March 2024
Revised: 19 April 2024
Accepted: 1 May 2024
Published: 7 May 2024

1. Introduction

The Fourth Assessment Report of the IPPC (Intergovernmental Panel on Climate Change) claims that greenhouse gas (GHG) emissions caused by human activities are the main factor leading to the rise in global temperatures [1], and the warming climate has had a serious impact on ecosystems and human development [2–4]. To cope with global climate change, China has formulated a "dual carbon" strategy that involves "carbon peaking and carbon neutrality targets", which seeks to peak by 2030 and achieve complete carbon neutrality by 2060. As one of the important factors in GHG emissions [5], the construction sector plays an important role in coping with global climate change [6]. The construction industry accounts for about 36% of the total global end-use energy consumption and 40% of the total carbon emissions [7,8], so this industry needs to take measures to reduce carbon emissions in buildings from the perspective of the whole life cycle of the buildings [9], and to establish a technical system for building decarbonization. Decarbonization technology refers to a technology adopted in the process of resource utilization of solid waste and wastewater, with the design concepts of green technology, energy saving, and environmental protection, strengthening technological leadership, adopting low-carbon structural forms and building materials, promoting the application of renewable energy, and reducing carbon emissions generated by buildings throughout their entire life cycle.

Research topics related to decarbonization technologies in buildings include the following: evaluation of the energy efficiency and carbon reduction effects of individual technologies [10–12] and exploration of optimal technical practices among them; carbon emission measurement and the decarbonization potential of individual buildings with multiple low-carbon technologies applied [13,14]; research on decarbonization technology practices under the guidance of a single objective [15–19], such as energy use behavior [20], economic costs, or building performance [21], etc.; studies on building optimization development based on the combination of multiple objectives such as light environment optimization, energy efficiency and carbon reduction, and economy and practicality [22–24]; and related research on policy formulation and development in the construction industry [25–27]. To sum up, research on the carbon emissions of urban residential buildings mainly focuses on macro aspects such as carbon emission calculations for individual buildings, low-carbon community creation, and low-carbon renovation of buildings. A variety of green and low-carbon technologies have been used in various urban residential areas, but the relevant research mainly consists of qualitative analyses, with a lack of quantitative research on the application of specific technologies. It is important to establish a systematic and quantitative evaluation system for building decarbonization technology as soon as possible.

On 22 September 2020, China proposed the "double carbon" goal and promoted the "double carbon" strategy, which is the only way to comply with the trend of the times and achieve high-quality economic and social development and sustainable development. In the field of buildings, as the main space carriers of people's lives and one of the three major sources of energy consumption in China, it is difficult to achieve the tasks of carbon peaking and carbon neutrality.

In the face of severe rising carbon emissions, integrating green and low-carbon concepts into the whole process of construction and promoting the use of building carbon reduction technologies will be the basic ways to achieve energy saving and carbon reductions in the building field. The results of this research are aimed at providing more accurate and reliable references for residential buildings when choosing carbon reduction technologies, combined with government policy guidance and the joint role of social groups, to steadily promote carbon reduction in urban residential buildings.

As one of the eight "Special Pilot Cities of China-Eu Low Carbon Eco-City Cooperation Project", Zhuzhou City has rich experience and achievements in carbon reduction actions. Low-carbon buildings are among the most important parts of low-carbon ecological cities, and there is also the process of low-carbon transformation of urban old industrial bases. For these reasons, Zhuzhou City is representative for studying carbon reduction technology to a certain extent.

2. Related Work

The existing research results have played a theoretical and technical supporting role in the decarbonization of residential buildings, but to systemically and quantitatively study decarbonization technology systems for buildings, the following are the main problems: (1) the research on decarbonization technology is dispersed, and it is important to establish a complete technical system; (2) the evaluation methods are not perfect because of the lack of comprehensive evaluation indicators and multi-dimensional quantitative assessment; (3) the research mainly involves public buildings; there are a large number of residential buildings, but there are few studies on their carbon emissions.

In view of the above problems, taking the residential buildings in Zhuzhou City as an example, this paper conducts a life cycle carbon emission study on 20 decarbonization technologies for residential buildings from the three perspectives of decarbonization effects, economic costs, and social feedback, so as to solve the quantitative problem of comprehensive benefits of decarbonization technologies for urban residential buildings. Its innovation lies in the following: (1) A multi-dimensional evaluation system for residential building decarbonization technology is established, which can be used to select technologies with good decarbonization benefits, has high investment cost-effectiveness, and is suitable for promotion of numerous building decarbonization technologies according to the research path. (2) A mathematical model is constructed based on the hierarchy process–entropy weight–coefficient of variation method, using a combination of subjective and objective methods to calculate the comprehensive weight of indicators and seek the optimal decision solution to obtain more accurate evaluation results. (3) The technology selected from the research results is not only applicable to the Zhuzhou region, but also suitable for urban residential housing in the Hunan region, which is similar to the Zhuzhou region. Through some more comprehensive case studies and investigations, this paper used the combination weighting method to improve the evaluation system for decarbonization technology in residential buildings, better quantify the comprehensive benefits of the technology, and boost the promotion of carbon reduction for urban residential buildings.

Building decarbonization technology can reduce the carbon emissions generated throughout the whole life cycle of buildings [28]. It refers to the design concepts of green technology, energy saving, and environmental protection, the adoption of low-carbon structural forms and building materials [28,29], the promotion of the application of renewable energy, and carrying out the resource utilization process for solid waste and wastewater [30,31]. With the popularization and promotion of low-carbon concepts in the construction industry, the adoption of building decarbonization technology can not only meet the government's requirements [32] for energy efficiency and emission reduction and the guiding policies for the healthy development of this industry [33], but also create a more environmentally friendly and sustainable living environment, in line with the requirements of sustainable green development [34].

3. Construction of Evaluation Index System

Economy and applicability are the most important determining factors for users (design, construction, and operation) when making technology selection decisions. Coupled with the carbon reduction goals that have contemporary and social significance, we need to establish a new value system with a sense of urgency. In order to identify technologies that have good decarbonization benefits and high cost-effectiveness and are convenient for actual construction and follow-up maintenance in practical works, a multi-dimensional evaluation system was established, and comprehensive benefit evaluations were conducted using the decarbonization degree, the economic degree, and applicability as indicators in this study.

3.1. Decarbonization Degree

The decarbonization degree reflects the magnitude of the overall carbon reduction effect of a building after applying a certain technology. For the decarbonization degree of the building envelope structures, a simulation model was established by us based on the various parameters of the case building, and we calculated the carbon emissions of the building's life cycle with the model. Subtracting the annual carbon emissions obtained after the application of each technology from the pre-application carbon emissions, the result is the annual decarbonization. The percentage of annual carbon reduction in the basic annual carbon emissions without using carbon reduction technology is the decarbonization degree expressed by the annual carbon reduction rate. The specific calculation method [22] is as follows, in Equation (1).

$$Y_n = \frac{C_n}{C} (n \text{ takes } 1,\ 2,\ 3,\ 4,\ \ldots, 20) \tag{1}$$

where Y_n refers to the decarbonization degree of the technology, C_n is the annual decarbonization amount (kg) in the application of this technology, and C is the annual carbon emissions (kg) of the case building without additional decarbonization technology.

For the decarbonization degree of renewable energy and resource utilization technology, and high-performance equipment, the annual decarbonization amount and decarbonization degree generated are calculated through the corresponding electricity and water savings values. In the calculation for converting electricity saving and water saving into decarbonization, Equation (2) for electricity saving conversion [35] and Equation (3) for water saving [36] are used.

$$C_{\text{electricity}} = Q \times 0.7035 \tag{2}$$

where $C_{\text{electricity}}$ is the carbon dioxide (CO_2) emissions (kg/a) reduced by the annual electricity savings, and Q refers to the annual electricity savings (kWh/a) after the adoption of a certain technology.

$$C_{\text{water}} = Q_{\text{feedwater}} * W_1 + Q_{\text{drainge}} * (W_2 + C_2) \tag{3}$$

where C_{water} refers to the carbon dioxide emissions (kg/a) reduced by the annual water savings, and $Q_{\text{feedwater}}$ is the annual water supply, in m^3/a. Q_{drainge} refers to the annual water discharge, and W_1 and W_2 are the CO_2 emissions generated by the power consumption of the water supply system and sewage system, and are taken as 0.3 kg/m^3 and 0.25 kg/m^3 apart. C_2 is the CO_2 emissions from the carbon-source conversion of the sewage system, and 0.7 kg/m^3 is taken as the value.

3.2. Economic Degree

The economic degree represents the initial investment required for technology application, and the larger the economic degree indicator, the greater the pre-investment required for the technology. After the manufacturer's inquiry and expert consultation, the cost data under the corresponding basic working conditions of each technology are obtained. Then, the incremental cost per unit building area before and after the application of each carbon reduction technology is calculated using the case building as the research object. And then, according to the incremental cost data, the economic degree data processing is performed, as is shown in Equation (4):

$$\mathrm{Y_{n\ eco-degree}} = \frac{\mathrm{e_n}}{\mathrm{MAX_{en}}} \tag{4}$$

where $\mathrm{Y_{n\ eco-degree}}$ represents the economic degree of the corresponding decarbonization technology; $\mathrm{e_n}$ refers to the incremental cost per unit building area (CNY/m^2) of the corresponding technology; and $\mathrm{MAX_{en}}$ is the value with the highest incremental cost per unit floor area of the research technology. The unit prices of various building materials come from market research. The incremental cost per unit area of energy-saving doors and windows is equal to the product of their increased price unit area and the window–floor ratio in this type of typical building.

3.3. Applicability

Applicability refers to the recommended level for promotion and use of different technologies derived from local design, construction, and practices. For example, when the design takes into account the building functionality and aesthetic, this will increase the difficulty of construction. To leave room for users, the design challenge increases accordingly. In addition, various decarbonization technologies have different efficiencies during the construction process. In order to better understand the acceptance of and satisfaction with different decarbonization technologies in the design and construction process among construction practitioners, we invited them to rate the applicability of the technologies, and the results will serve as an important reference for the promotion and application of technologies in practice.

Practitioners (especially referring to design and construction personnel) scored the technology adoption on a five-point system: a score of one indicates that this technology faces significant challenges and difficulties in design or construction; a score of five indicates a high degree of fitness with the design and construction of residential buildings and that the technology is suitable for promotion and application in the region. Scores from one to five gradually increases, and the higher the score, the higher the applicability of the technology and the more suitable it is for promotion and use.

4. Research Methodology and Case Study

4.1. A Comprehensive Assessment Method Based on the Combination Weighting Method

After analyzing each technology based on its carbon reduction, economy, and applicability, in order to further evaluate the comprehensive performance of each technology, the hierarchy process–entropy weight–coefficient of variation method is adopted to further evaluate the technology comprehensively.

The essence of the analytic hierarchy process [36,37] (AHP), entropy weight method, and coefficient of variation method is to standardize the data and assign corresponding weights to each index to combine the data into a column. The AHP [36,37] is mainly based on subjective judgement, while the other two assign weights based on the distribution of index data. These three weighting methods can solve the problem of single coefficient testing, but each algorithm has its own advantages and disadvantages. The results obtained by the subjective judgement and objective evaluation methods are different. However, by combining these three evaluation algorithms with the CRITIC [36,37] method, a more reasonable evaluation result can be obtained. Meanwhile, the results of various algorithms before combination can be calculated, and the results can be taken as the variance in the overall evaluation, that is, its upper and lower bounds.

The CRITIC [38] objective combination weighting method focuses on the contrast and contradiction of indicators, where contrast reflects the difference between various evaluation indicator methods for the same indicator weighting value. The jth indicator contrast can be determined by the standard deviation represented by σ_j. The contradiction reflects the correlation between different indicators. The smaller the value of the contradiction, the more significant the positive correlation. The formula is as follows; r_{ij} represents the correlation coefficient between the i and j indicators.

$$\textstyle\sum_{i=1}^{n}(1-r_{ij}) \tag{5}$$

C_j is defined as the information carrying capacity of the j index. C_j is expressed as follows:

$$C_j = \sigma_j \sum_{i=1}^{n}(1-r_{ij})\, j = 1, 2, \ldots, m \tag{6}$$

The information carrying capacity C_j reflects the importance of indicator j, and the expression for the comprehensive weight is as follows:

$$\theta_j = \frac{C_j}{\sum_{j=1}^{m} C_j}\, j = 1, 2, \ldots, m \tag{7}$$

4.2. Comprehensive Evaluation Process Based on Combination Weighting Method

To further evaluate the comprehensive performance of various technologies, the analytic hierarchy process–entropy weight–coefficient of variation method is used to further evaluate the values of various technologies based on the decarbonization degree, the economic degree, and applicability. The evaluation process is shown in Figure 1.

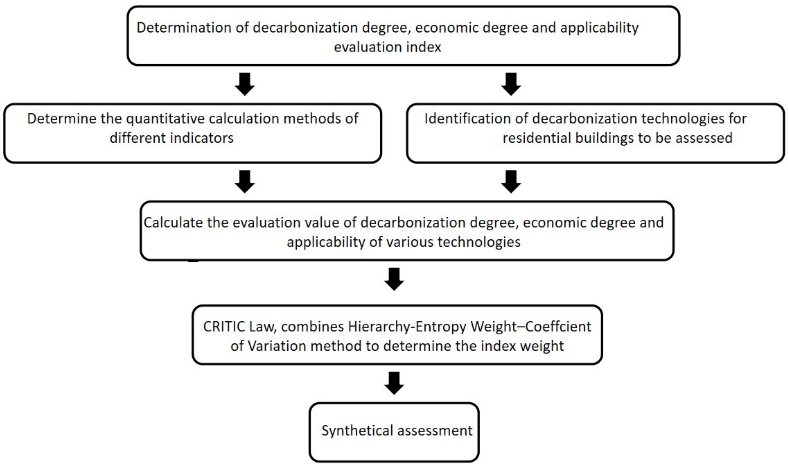


Figure 1. The evaluation process based on the AHP-EW-C method.

4.3. Selection of Decarbonization Technologies for Typical Buildings in Zhuzhou City

It is necessary and urgent to conduct in-depth research on decarbonization technologies because the traditional construction industry is a high-energy-consuming industry, and residential buildings account for a large proportion of this consumption. In order to ensure that the selected technology meets local standard requirements and is suitable for local practice [37], this paper explored comprehensive decarbonization channels for the whole life cycle of residential buildings, referring throughout to the investigation and analysis of green energy-saving building technologies in the Zhuzhou region. With the development of economy and society, the progressiveness of Zhuzhou’s buildings has reached its peak in the past three years. Using the archived data of the Zhuzhou Construction Science and Technology and Building Energy Conservation Association, we screened 98 new projects with complete and effective parameters, all of which serve to support this paper.

In addition, this paper summarizes 14 related technologies for enclosure structures, 3 technologies for renewable energy and resource utilization, and 3 technologies for high-performance equipment by extracting relevant technologies based on the provisions on energy conservation, water conservation, and carbon emissions in GB/T50378-2019 [39]“Green Building Evaluation Standards”, GB/T 51366-2019 [40] “Building Carbon Emission Calculation Standards”, GB/T 55015-2021 [41] “General Specification for Building Energy Conservation and Renewable Energy Utilization”, and JGJ/T 449-2018 [42] “Green Performance Calculation Standards for Civil Buildings”. XPS and SEPS refer to extruded polystyrene boards and graphite polystyrene boards, SRC is steel-reinforced concrete, and PV means photovoltaic. The content is shown in Table 1.

Table 1. The 20 selected decarbonization technologies for typical buildings in Zhuzhou.

S/N	Location	Technical Measures	Thicknesses
1	Exterior-wall insulation material	Non-inflammable XPS	25–45
2		Foam cement insulation board	30–40
3		Foam glass insulation board	25–50
4		SEPS	30–40
5		Polyurethane foam panel	20–35
6	Exterior-wall main material	SRC	200
7		Porous shale bricks	190
8		Autoclaved aerated concrete block wall	200
9	Roof insulation material	Non-inflammable XPS	30–70
10		Polyurethane foam panel	10–30

Table 1. *Cont.*

S/N	Location	Technical Measures	Thicknesses
11		SEPS	30–60
12	Exterior window 1	Insulated Al alloy hollow glass windows (6Low-E low transmittance + 12a + 6)	
13	Exterior window 2	Insulated Al alloy hollow glass windows (6Low-E middle transmittance + 12a + 6)	-
14	External window 3	Insulated Al alloy hollow glass windows (6Low-E high transmittance + 12a + 6)	-
15	High-performance equipment	Energy-saving air conditioning technology	-
16		Energy-saving lamps	-
17		Rainwater recycling	-
18	Technologies related to renewable energy and resource utilization	Air source heat pump water heater	-
19		Water-saving appliances	-
20		Roof solar PV system	-

4.4. Overview of Case Architecture

A survey shows that building altitude is generally below 100 m among the new residential buildings in Zhuzhou, and residential buildings with a linear layout account for about 79%. According to the statistical data [43] on 98 newly built residential buildings from 2018 to 2021, about 83% of the shape coefficient is between 0.3 and 0.4, and the value for the households with elevators accounts for more than two elevators and 4 households. And in terms of the number of building floors, the buildings are mainly high-rises.

When selecting cases, based on the classification of the building area, green space rate, standard floor area, shading, window-to-wall ratio, height, number of floors, and body shape coefficient, we used the k-means clustering algorithm of SPSS to cluster 98 existing residential building cases, and at the same time referred to the conventional house types and parameters approved by the housing and urban–rural development department in the past three years to choose the houses closest to the clustering center. The case building is a 32-story concrete residential building, mainly used for residential functions, located in Zhuzhou, Hunan Province. It has a linear layout, facing north to south, with a fig. coefficient of 0.34. Its standard floor plan is shown in Figure 2.

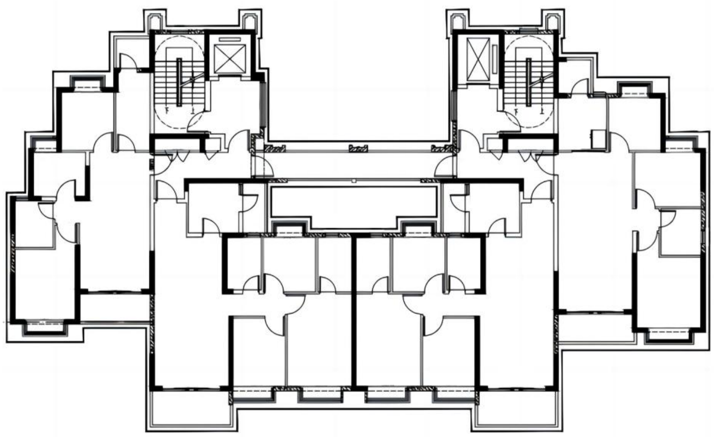


Figure 2. Case building's standard floor plan.

The original construction method for the principal envelope structure of the case building without any decarbonization technology installed is shown in Table 2.

Table 2. Original construction methods for case buildings.

Roof Structure		Exterior-Wall Construction	
Material Name	Thickness (mm)	Material Name	Thickness (mm)
C20 fine AC	40	Cement mortar	20
Cement mortar	20	SRC	200
Lc 5.0 LWAC	30	Cement mortar	15
		Papered gypsum board	10

4.5. Analysis of Technique Application

4.5.1. Analysis of Decarbonization Degree in Technique Application

According to the above parameters, the authors established the model of the building envelope structure and the energy efficiency ratio of the corresponding air conditioning with Green Building CEEB, and selected the other parameters of the model based on the general usage conditions of domestic buildings, and then performed a simulation to obtain the annual carbon emissions; the model establishment is shown in Figure 3.

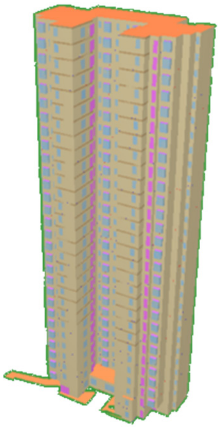


Figure 3. Schematic diagram of a typical building model.

Finally, the authors calculated the carbon emission data of the building's life cycle and the carbon emission index per unit area to obtain the carbon emissions corresponding to the original structure, as shown in Table 3.

Table 3. Original carbon emissions of case buildings.

Items	**Annual Carbon Emissions per Unit Area (kgCO$_2$/m^2·a)**	**Carbon Emissions per Unit Area (kgCO$_2$/m^2)**	**Annual Carbon Emissions (tCO$_2$/a)**	**Total Carbon Emissions (tCO$_2$)**
Quantity	49.51	2476.20	585.07	29,253.60

By modeling and calculating the project with software, we selected the minimum value that meets the energy-saving requirements of the construction industry (65% energy saving) when using the corresponding technology, in order to determine the appropriate thicknesses of different materials. And the various carbon emissions after replacing the corresponding envelope structure constructions are shown in Table 4. In 1980–1981, the energy consumption of the local representative residential buildings from summer air conditioning plus winter heating [converted into square meter of building area per year for summer air conditioning and winter heating energy consumption, KW h/(m^2, year)] was based on a standard of 65% savings. And the "Hunan Provincial Residential building energy saving Standard" puts forward the mandatory energy-saving standard of 65%.

Table 4. Carbon emissions of various technologies in case buildings.

S/N	Technical Measures	Thickness (mm)	Annual Carbon Reduction (tCO_2/a)	Decarbonization Rate
1	Non-inflammable XPS	25	167.452	28.62%
2	Foam cement insulation board	40	167.439	28.62%
3	Foam glass insulation board	45	165.371	28.27%
4	SEPS	30	174.150	29.77%
5	Polyurethane foam panel	20	172.495	29.48%
6	SRC	200	167.452	28.62%
7	Porous shale bricks	190	174.606	29.84%
8	Autoclaved aerated concrete block wall	200	185.931	31.78%
9	Non-inflammable XPS	35	167.452	28.62%
10	Polyurethane foam panel	30	167.595	28.65%
11	SEPS	35	167.413	28.61%
12	Insulated Al alloy hollow glass windows (6Low-E low transmittance + 12a + 6)		48.640	8.31%
13	Insulated Al alloy hollow glass windows (6Low-E middle transmittance + 12a + 6)		44.230	7.56%
14	Insulated Al alloy hollow glass windows (6Low-E high transmittance + 12a + 6)		43.010	7.35%
15	High-performance air conditioning equipment		46.690	7.98%
16	Energy-saving lamp use		23.380	4.00%
17	Rainwater recycling system		4.000	0.68%
18	Air source heat pump water heater		29.040	4.96%
19	Water-saving appliances		5.280	0.90%
20	Solar PV system		35.250	6.02%

According to Table 4, in terms of carbon reduction, among the three types of technologies, enhancing the insulation and thermal insulation of the enclosure structure, using renewable energy, and using high-performance equipment, the carbon reduction brought by enhancing the insulation and thermal insulation of the enclosure structure was significantly higher than that achieved with the other two types. In the enclosure structure, the carbon reduction degree of the main material of the peripheral enclosure structure is slightly greater than that of the external wall insulation material, while the use of high-performance doors and windows has a relatively small impact on the overall carbon reduction degree of the building. From the perspective of carbon reduction benefits, it is recommended to prioritize the use of high-quality main material- and insulation material-related technologies for enclosure structures, especially for autoclaved aerated concrete block walls, as the changes in insulation performance of the enclosure structure can produce significant carbon reduction benefits.

4.5.2. Economic Analysis of Technique Application

The unit prices of the various building materials were obtained from market research, and detailed information can be found in Appendix A. The incremental cost per unit area of energy-saving doors and windows is equal to the ratio of the increased price per unit area of energy-saving doors and windows to the window–floor ratio of this type of typical building. The corresponding incremental cost per unit building area and economic degree of the case building under the application of the technologies are shown in Table 5.

Table 5. Different technical and economic degrees of case buildings.

S/N	Technical Measures	Incremental Cost per Unit Building Area (CNY/m^2)	Economic Degree
1	Exterior-wall inflammable XPS	12.50	0.125
2	Exterior-wall foam cement insulation board	16.00	0.160
3	Exterior-wall foam glass insulation board	45.00	0.450
4	Exterior-wall SEPS	16.50	0.165
5	Exterior-wall polyurethane foam panel	26.00	0.260
6	Exterior-wall SRC	100.00	1.000
7	Exterior-wall porous shale bricks	57.00	0.570
8	Exterior-wall autoclaved aerated concrete block wall	54.00	0.540
9	Roof inflammable XPS	17.50	0.175
10	Roof polyurethane foam panel	39.00	0.390
11	Roof SEPS	19.25	0.192
12	Insulated Al alloy hollow glass windows (6Low-E low transmittance + 12a + 6)	58.40	0.584
13	Insulated Al alloy hollow glass windows (6Low-E middle transmittance + 12a + 6)	44.92	0.449
14	Insulated Al alloy hollow glass windows (6Low-E high transmittance + 12a + 6)	35.94	0.359
15	Energy-efficient air conditioning technology	16.66	0.166
16	Energy-saving lamps	5.81	0.058
17	Rainwater recycling system	3.39	0.034
18	Air source heat pump water heater	33.33	0.333
19	Water-saving appliances	3.55	0.036
20	Roof solar PV system	1.21	0.012

According to Table 5, in terms of economy, the cost required to enhance thermal insulation of the enclosure structure is relatively high compared with those of the other two types. Compared to the technologies using in exterior wall, roof and others, high performance doors and windows have the lower cost and higher economic efficiency. The rooftop solar photovoltaic system has the lowest economic efficiency among the remaining technologies. If considering economic costs alone, it is recommended to prioritize the use of renewable energy, high-performance equipment, and other technologies to achieve carbon reduction goals.

4.5.3. Analysis of Technology Applicability

The questionnaire was distributed online. Experts in design and construction who participated were asked to rate the challenges and difficulties faced with 20 technologies in design or construction. The scores were set at 1–5 points, with higher values indicating fewer challenges and difficulties, making the technologies more suitable for promotion and use. The experts who completed the review are from the expert group of the Zhuzhou Construction Technology and Building Energy Conservation Association, and are all construction experts or related practitioners from the Changsha Zhuzhou Xiangtan area of Hunan Province. We sent a questionnaire to the group and asked the experts to fill it out randomly. We received a total of 81 questionnaire responses, and as the respondents have undergone targeted screening, 74 out of the 81 questionnaires are defined as having valid results here.

In order to maintain consistency for economic efficiency and carbon reduction in terms of the digital scale, and to better introduce the model for the next comprehensive evaluation, the numerical representation of applicability was controlled within a value of 1. Therefore, the average scores were reduced by five times, and the summary results of the technological applicability assessment are shown in Table 6.

Table 6. Summary of technical applicability assessment results.

S/N	Technical Measures	Average Score	Applicability
1	Exterior-wall non-inflammable XPS	3.78396	0.8084
2	Exterior-wall foam cement insulation board	3.65600	0.6486
3	Exterior-wall foam glass insulation board	3.92106	0.6768
4	Exterior-wall SEPS	4.04902	0.7614
5	Exterior-wall polyurethane foam panel	4.17698	0.8272
6	Exterior-wall SRC	4.17698	0.8272
7	Exterior-wall porous shale brick masonry	4.30494	0.799
8	Exterior-wall autoclaved aerated concrete block wall	4.17698	0.7332
9	Roof non-inflammable XPS	4.17698	0.8272
10	Roof polyurethane foam panel	4.17698	0.7896
11	Roof SEPS	4.30494	0.7708
12	Insulated Al alloy hollow glass windows (6Low-E low transmittance + 12a + 6)	3.65600	0.7802
13	Insulated Al alloy hollow glass windows (6Low-E middle transmittance + 12a + 6)	3.52804	0.8554
14	Insulated Al alloy hollow glass windows (6Low-E high transmittance + 12a + 6)	4.30494	0.7351
15	Energy-saving air conditioning technology	3.92106	0.7644
16	Energy-saving lamps	3.55212	0.6972
17	Rainwater recycling	3.31188	0.6720
18	Air source heat pump water heater	3.92106	0.6804
19	Water-saving appliances	3.55212	0.7224
20	Roof solar PV system	3.55212	0.7022

According to Table 6, it can be seen that in terms of applicability, overall, the applicability of the two major categories of technologies, namely the use of renewable energy and the use of high-performance equipment, is similar, while the applicability of maintaining the thermal insulation performance of structures fluctuates greatly. Specifically, in the relevant technologies in external enclosure structures, the applicability values of exterior graphite polystyrene boards and exterior foam cement insulation boards are less than 0.7, while the applicability values of thermal insulation aluminum alloy hollow glass windows (translucent + 12a + 6 in 6Low-E), roof flame-retardant extruded polystyrene boards, exterior reinforced concrete, exterior foam polyurethane boards, and exterior flame-retardant extruded polystyrene boards are higher than 0.8, with the highest recognition. The applicability of other technologies ranges from 0.7 to 0.8. In the use of renewable energy-related technologies, the applicability of rooftop solar photovoltaic systems and water-saving appliances exceeded 0.7, while the applicability of air source heat pump hot water systems is relatively low. Regarding high-performance equipment, the applicability of energy-saving technology for air conditioning is significantly higher than that of the other two.

5. Results and Discussion

The authors imported data from 20 technical measures into MATLAB in the order of economic degree, decarbonization degree, and applicability, and wrote them into the code. We then set the model block as (3,1,1), and used the analytical hierarchy process–entropy weight–coefficient of variation method to test their consistency. The weights obtained by various weighting methods are shown in the table below. Class A represents the economic degree, Class B represents the decarbonization degree, and Class C represents applicability.

Table 7 presents a summary of the weights obtained from different weighting methods. After machine calculations, the combined weights of economic efficiency, carbon reduction, and applicability were evaluated and analyzed using the analytic hierarchy process–entropy weight–coefficient of variation method, and the values were 0.1445, 0.1742, and 0.1491, respectively. The next step of the model involves calculating the comprehensive scores of the 20 technologies based on these weights.

Table 7. Summary of weights obtained by different weighting methods.

Weighting Methods	A	B	C
AHP	0.2252	0.1114	0.1359
Entropy method	0.0699	0.2418	0.1589
Coefficient of variation method	0.0984	0.1742	0.1491
Combination weighting	0.1445	0.1742	0.1491

The calculated score based on the percentage system is shown in Figure 4, with the vertical axis representing the evaluation score and the horizontal axis representing the corresponding technical number.

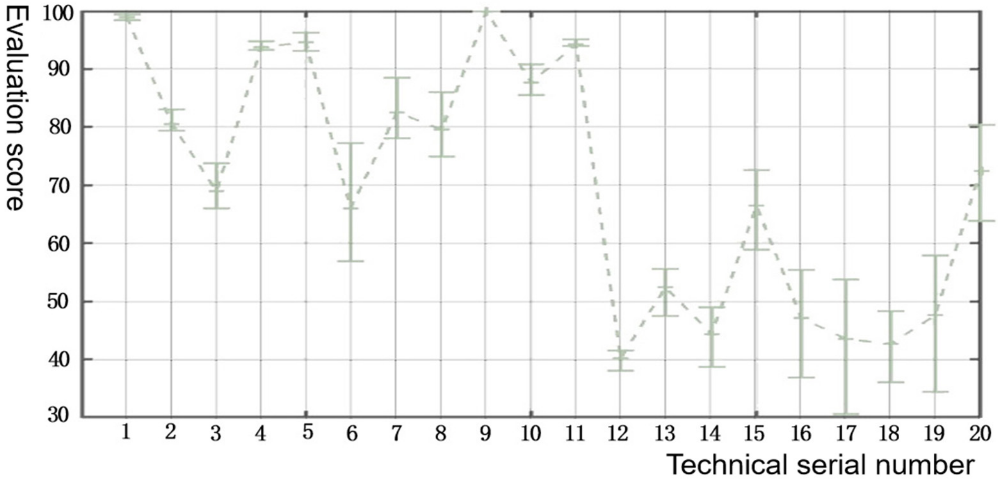


Figure 4. Schematic diagram of the comprehensive evaluation results for decarbonization technology based on the analytical hierarchical–entropy weight–coefficient of variation method.

According to the evaluation results, if the new project pursues the triple goal of carbon reduction, economic effort, and applicability, then the higher the evaluation score corresponding to the technical number, the better the comprehensive evaluation efficiency. It can be seen that the roof non-inflammable XPS with the serial number 9 has the highest technical evaluation score and the best comprehensive benefits; and the serial number 12 represents an insulating Al alloy hollow glass window, the technical score of which (6Low-E low transmittance + 12a + 6) is the lowest, and the comprehensive benefits of which are poor. Technical measures with high evaluation scores can be selected to optimize the project according to the evaluation results shown in Figure 3, and in order to achieve the best comprehensive benefits.

The research results can be used as a reference for how building carbon reduction technologies are applied in the "Chang-zhu-tan District" and other regions with similar climatic conditions and policy backgrounds to Zhuzhou. New building materials and other carbon reduction technologies will be continuously updated as a result of advances in science and technology, and they might have stronger carbon reduction effects in practical applications than the carbon reduction technologies that are the subject of this research.

6. Conclusions and Future Works

This paper has established an evaluation indicator system for the decarbonization degree, economic degree, and applicability of urban residential decarbonization technologies in the Zhuzhou region. The analytic hierarchy process–entropy weight–coefficient of variation method is proposed to determine the weights of various evaluation indicators, and a comprehensive assessment model based on the combination weighting method is constructed. Finally, the comprehensive benefits of corresponding technologies are measured by calculating the evaluation values of various technologies. And the research results show the following:

(1) In terms of the decarbonization degree, the change in the exterior envelope structure has a good decarbonization effect. In particular, the decarbonization rate caused by exterior-wall changes is about 30%, which is higher than that for other types of technologies.
(2) In terms of the economic degree, changing the exterior wall's main materials and exterior windows requires higher economic investment than with other technologies, and is not suitable for selection as a renovation technology.
(3) In terms of applicability, as the selected technologies have a good comprehensive assessment in practical use, the overall evaluation values are relatively high.
(4) In terms of the comprehensive evaluation results, for the design phase of urban residential buildings, it is advisable to optimize the exterior envelope structure, especially by selecting high-quality insulation materials, such as non-inflammable XPS. For completed residential buildings, it is suggested to use the related technologies of renewable energy and resource utilization and high-performance equipment, and to choose energy-saving technologies for air conditioning and roof solar energy technology based on practical feasibility.

The technologies selected in this paper are used in Zhuzhou City, but are also applicable to urban residential buildings in the Hunan area, which is similar to Zhuzhou, and even in hot-summer and cold-winter areas. The comprehensive evaluation model based on the combination weighting method used in this paper can not only be suitable for the comprehensive evaluation of decarbonization technologies for residential buildings, but also for the multiple-indicator evaluation of other types of buildings.

As for the limitations of this research, on the one hand, this research is based on the simulation of a building. The results could be more accurate and applicable if we added additional building cases from different areas. On the other hand, even if the research object is located in Zhuzhou City, a typical hot-summer and cold-winter area, it is impossible to compare it with similar situations in other climate zones, or to screen and compare the usage preferences and characteristics, due to insufficient existing research conclusions. Promoting energy saving and carbon emission reductions in the construction sector is a key focus of the construction industry at present. And the research results in this paper align with the principles of "passive priority, active optimization, and full utilization of renewable energy". As a result, it is necessary to fully select decarbonization technologies that have better beneficial effects in terms of energy conservation and carbon reduction. In addition, promoting and developing new low-cost building energy technologies is an important trend for following the path of carbon emission reduction in NZEBs.

Author Contributions: Conceptualization, J.L. and H.C.; methodology, H.C.; software, F.X.; validation, J.L., H.C. and Q.T.; formal analysis, W.M.; data curation, H.C. and Q.T.; writing—original draft preparation, J.L. and H.C.; writing—review and editing, Q.T. and H.C.; visualization, Q.T.; supervision, F.X. and W.M; project administration, J.L.; funding acquisition, J.L., H.C. and Z.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Hunan Provincial Natural Science Foundation of China (grant number 2022JJ50069).

Data Availability Statement: The raw data used or analyzed during this study are available by the authors on reasonable request.

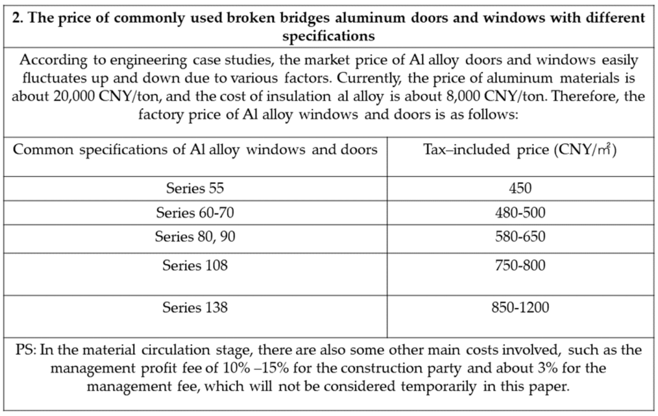
Conflicts of Interest: Author Haiyan Chen was employed by the company China Building Materials Inspection and Certification Group Hunan Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

1. Price of commonly used insulation materials

Position	Name	Thickness	Unit price(CNY/㎡)	Thickness	Unit price(CNY/㎡)	Thickness	Unit price(CNY/㎡)
Exterior wall insulation materials	Non—inflammable XPS	25	12.5	35	17.5	40	20
	Foam cement insulation board	40	16	50	20	60	24
	Foam glass insulation board	45	45	55	55	60	60
	SEPS(graphite polystyrene board)	30	16.5	35	19.25	40	22
	Polyurethane foam panel	20	26	25	32.5	30	39
Exterior wall load-bearing materials	SRC(steel—reinforced concrete)	200	100				
	Porous shale bricks	190	57				
	Autoclaved aerated concrete block wall	200	54				
Roof insulation materials	Non-inflammable XPS	35	17.5	20	10	50	25
	Polyurethane foam panel	30	39	16	20.8	40	52
	SEPS(graphite polystyrene board)	35	19.25	20	11	45	24.75
	Exterior window 1	Insulated Al alloy hollow glass window(6+12a+6)					
	Exterior window 1	Insulated Al alloy hollow glass window(6+12a+6)					

(**a**)



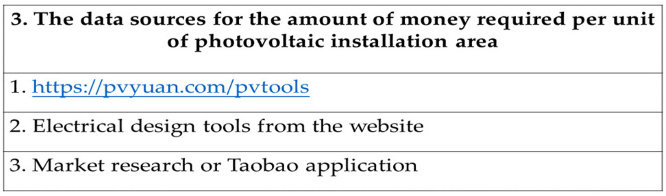
2. The price of commonly used broken bridges aluminum doors and windows with different specifications

According to engineering case studies, the market price of Al alloy doors and windows easily fluctuates up and down due to various factors. Currently, the price of aluminum materials is about 20,000 CNY/ton, and the cost of insulation al alloy is about 8,000 CNY/ton. Therefore, the factory price of Al alloy windows and doors is as follows:

Common specifications of Al alloy windows and doors	Tax–included price (CNY/㎡)
Series 55	450
Series 60-70	480-500
Series 80, 90	580-650
Series 108	750-800
Series 138	850-1200

PS: In the material circulation stage, there are also some other main costs involved, such as the management profit fee of 10% –15% for the construction party and about 3% for the management fee, which will not be considered temporarily in this paper.

(**b**)



3. The data sources for the amount of money required per unit of photovoltaic installation area

1. https://pvyuan.com/pvtools
2. Electrical design tools from the website
3. Market research or Taobao application

(**c**)

Figure A1. The survey data on the economic degree. (**a**) The prices of commonly used insulation materials. (**b**) The prices of commonly used Al alloy windows and doors. (**c**) The source of the PV data.

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