Research on the low carbonization of clean energy use in rural residential buildings in China under the background of "carbon peaking and carbon neutrality"

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Abstract

As an important part of the construction industry, rural residential buildings are characterized by low energy utilization, unreasonable structures and low consumption levels, and it is particularly important to study their low-carbon transformation and evaluation system. In view of the many low-carbon transformation needs of rural residential buildings, the existing research results were analyzed in depth, and the coefficient of variation method was used to identify the important factors affecting the low-carbon transformation of rural residential buildings, and the evaluation system of rural residential buildings' low-carbon transformation was determined by Analytic Hierarchy Process (APH), and the system was used in a rural residential building low-carbon evaluation study. The results show that the influence of "energy use", "envelope structure" and "economic factors" on the decarbonization of buildings is obvious, with the weights of 36.4%, 24.5% and 19.5% respectively. Among the secondary indicators, "clean energy utilization", "electricity consumption", "external wall insulation system" and "window performance" are the most important factors in reducing carbon emissions in rural areas. The most critical influencing factors for the low carbonization level of clean energy in rural residential buildings are "window performance". Finally, based on the constructed low carbonization evaluation system, we propose a targeted solution strategy to provide a theoretical basis for the establishment of an effective low carbonization evaluation system for clean energy in rural residential buildings.

1 Introduction

With the rapid economic development in recent years, China's total carbon emissions have also jumped to the top of the world, increasing from 1.500 billion tons in 1980 to 11.470 billion tons in 2021, showing a large increase and high emissions [1-3]. At the 75th UNGA video conference in 2020, General Secretary Xi Jinping proposed that China had decided to strive to reach peak CO_2 emissions by 2030 and to achieve the goal of carbon neutrality by 2060. This marks a gradual transition in China's energy consumption structure from being dominated by traditional energy sources to a two-wheel drive and synergistic development of traditional and new energy sources [4, 5].

According to statistics, China's total energy consumption in the construction industry in 2019 is 2.233 billion tons of standard coal, and the total carbon emissions in the construction process is 4.997 billion tons of carbon dioxide, accounting for about half of the total carbon emissions in the country [6]. On the other hand, rural residential buildings, as an important part of China's building sector, account for about 25% of the total building energy consumption in the country; however, due to the low energy utilization rate, unreasonable structure and low consumption level of rural residential buildings, the energy consumption of rural residents has been increasing year by year [7, 8]. Therefore, it is of great significance to study the evaluation of low carbonization of rural residential buildings for rural revitalization and energy conservation [9].

Scholars at home and abroad have conducted research on how to achieve a low-carbon transition in rural residential buildings, with research focusing on both rural energy use and energy evaluation. Filippo Padovani et al [10] examined the technical characteristics of electrification for sustainable heating in remote rural areas in the Midwest of the United States, showing that if the goal of using all renewable energy is achieved, building carbon emissions will be reduced. Dominguez Cristina et al [11] analyzed the pathways to clean energy transition in rural Kenya and showed that women play a key role in the energy transition as decision makers, with female-headed households preferring to switch to cleaner fuels at an early stage. Zhang [12] studied how the development of clean heating in rural areas can be optimized, using TRNSYS software to simulate energy consumption in combination with a study of 500 typical farm households to simulate the current status of heating in farm houses in Shandong, the current status of maintenance structure, heating energy structure and other major influencing factors, and to design five clean heating options for economic and environmental benefit analysis in rural areas of Shandong. Yuan et al [13] carried out a questionnaire survey on the construction of farm houses for farmers in the rural areas of Chang'an District, Xi'an, and categorized and analyzed them from a low-carbon perspective. The survey results show that scholars at home and abroad are fully aware of the importance of low-carbon technologies in rural housing. It can be seen that scholars at home and abroad have fully affirmed the importance of low-carbon rural residential buildings, analyzed the problems of low-carbon development of rural residential buildings and proposed corresponding solutions. However, there is still a lack of research on the topic of low-carbon transformation of rural residential buildings, which does not match the scale of the total floor area of rural residential buildings in China. Moreover, the assessment of clean energy use in rural residential buildings rarely uses multiple indicators to measure the low-carbon nature of energy use, and the low-carbon evaluation of clean energy use in rural residential buildings is insufficient.

Based on the existing research results, this paper identifies the important factors affecting the low-carbon transition of rural residential buildings from the perspective of sustainable development of building low-carbonization, determines the low-carbon evaluation system of rural residential buildings by APH, and applies the system to a rural residential building low-carbon evaluation study, and then proposes targeted low-carbon strategies to provide a theoretical basis for the establishment of an effective rural residential building clean energy low-carbon evaluation system.

2 Theoretical basis and determination of evaluation indexes

2.1 Theoretical basis

Decarbonization theory: decarbonization generally refers to the use of more efficient energy use and social functioning to promote sustainable urban development through technological advances and changes in social systems in the process of socioeconomic development [14]. In this paper, the main study is the decarbonization of rural residential buildings.

Sustainable development theory: is the replacement of used resources with resources of equal or greater value to maintain the world's productivity without degrading or endangering natural ecosystems. Sustainable development links concerns about the carrying capacity of natural systems to the social, political and economic challenges facing human society. Its development has evolved from academic research to international attention to a broad consensus among major countries around the globe. Sustainable development is a way of organizing society that can endure in the long term and implies taking into account the importance of both the present and the future, such as the conservation of the environment and natural resources, social and economic equity [15, 16].

2.2 Determination of evaluation indicators

(1) Evaluating the low carbonization of clean energy use in rural residential buildings is a systematic project involving complicated influencing factors, and in order to determine the influencing factors more comprehensively and systematically, the evaluation conceptual framework constructed through a large number of analyses of the current research of Chinese scholars in related low carbonization evaluation [17, 18], from six aspects such as energy use, envelope structure, layout design, building materials, behavioral habits, and

economic factors The evaluation system was constructed to initially screen indicators (Fig. 1).

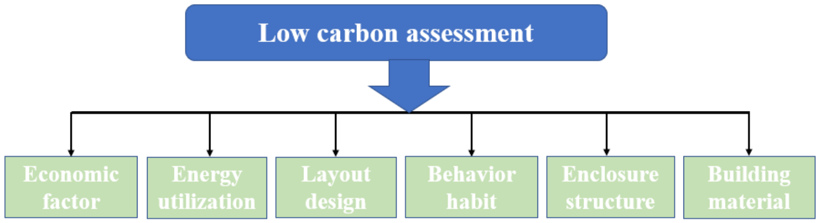

Fig. 1 Conceptual framework for assessment

(2) In order to improve the scientificity and representativeness of the low-carbon evaluation system for clean energy use in rural residential buildings, the variation coefficient method was used to optimize the indicators in the indicator database.

The arithmetic mean, standard deviation and coefficient of variation of the index scores were calculated by Equations 1, 2 and 3, respectively.

$$Q_j = \frac{1}{n}\sum_{i=1}^{n} X_{\mathrm{ij}} \tag{1}$$

where X_{ij} denotes the rating of the j-th index by the i-th respondent and Q_j denotes the arithmetic mean of the j-th index.

$$S_j = \sqrt{\frac{\sum_{i=1}^{n}\left(X_{\mathrm{ij}} - Q_j\right)^2}{n-1}} \tag{2}$$

where S_j denotes the standard deviation of the expert's score for the j-th indicator.

$$N_j = \frac{S_j}{Q_j} \tag{3}$$

where N_j denotes the coefficient of variation of the expert's score on the j-th indicator

As shown in Table 1, the 20 factors that have a significant impact on the evaluation of clean energy decarbonization of rural residential buildings were finally identified.

Table 1 Evaluation index factors of clean energy decarbonization of residential buildings

Assessment factors for clean energy decarbonization of rural residential buildings	Tier 1 Indicators	Secondary indi
	Energy Use	Clean Energy
		Coal use
		Share of electr
	Enclosures	Window to wa
		Window Perfo
		External wall i
	Layout design	Building orien
		Geographical l
		Living space p

Assessment factors for clean energy decarbonization of rural residential buildings	Tier 1 Indicators	Secondary indi
	Construction Materials	Utilization rat
		Building mate
		Building mate
	Behavioral habits	Energy-saving
		Low Carbon B
		Water conserv
		Domestic wast
	Economic Factors	Annual househ
		Clean Energy
		Clean Energy
		Building renov

3 Build the hierarchical model

3.1 Model Methodology

Analytic Hierarchy Process (AHP) decomposes the elements related to the decision object into goal level, indicator level and other levels, etc. It is an easy way to make decisions for some more complex and ambiguous problems, and the analysis process is more suitable for multi-level interleaved goal systems, and the goal values are difficult to describe the decision problem quantitatively [19, 20]. The steps to construct the hierarchical model are as follows.

(1) Construct a pairwise comparison judgment matrix.

(2) The matrix weights are calculated by normalizing the matrix corresponding to the maximum eigenvalue $\lambda_{\max}$.

$$\lambda_{\max} = \frac{1}{n}\sum_{i=1}^{n}\frac{BW_n}{W_i} \tag{4}$$

(3) The eigenvectors corresponding to the maximum eigenvalues are used as the weight vectors to compare the influence of each factor on a factor in the upper level. The consistency index is calculated as.

$$CI = \frac{\lambda - n}{n-1} \tag{5}$$

(4) Calculate the weights of the primary and secondary indicators respectively

(5) Calculate the Low Carbon Index (LCI). The scores of the second-level indicators are multiplied by the weights of the second-level indicators and added together to obtain the scores of the corresponding first-level indicators, and then the scores of the first-level indicators are weighted and added together to obtain the total score of the low-carbon evaluation of clean energy use, which is called the "Low Carbon Index", and the detailed calculation formula is as follows.

$$Q_i = \sum_{i=1}^{n} W_j Q_j \tag{6}$$

$$LCI = \sum_{i=1}^{6} W_i Q_i \tag{7}$$

Where Qj denotes the evaluation score of secondary indicators, Wj denotes the weight of secondary indicators, Qi denotes the sum of the scores of primary indicators, Wi denotes the weight of primary indicators, and LCI denotes the low carbon index.

(6) Based on the above calculation results, the low-carbon performance of rural residential buildings is judged, and for high-carbon residential buildings, this study hopes to achieve low carbonization through retrofitting.

3.2 Questionnaire design and data collection

Based on the in-depth analysis and survey, a total of 110 questionnaires were distributed to government departments, research institutions and universities in the fields of energy planning and construction, respectively, and 95 questionnaires were collected. Experts were invited to score each index in Table 1 as 9, 7, 5, 3 and 1, and add the adjacent median of 2, 4, 6 and 8. The data of the 95 questionnaires screened were averaged to obtain the AHP judgment matrix list.

Table 2 List of AHP judgment matrix

Judgment Matrix	Energy Use	Enclosures	Layout design	Construction Materials	Behavioral habits	Econom
Energy Use	1	3	4	6	5	3
Enclosures	1/3	1	3	4	4	2
Layout design	1/4	1/3	1	1	1/3	1/4
Construction Materials	1/6	1/4	1	1	1	1/3
Behavioral habits	1/5	1/4	3	2	1	1/3
Economic Factors	1/3	1/3	4	3	2	1

3.3 AHP analysis

The weights of the secondary indicators were calculated by (2), (3) and (4) above and integrated to form Table 3. The weights of "energy use", "envelope" and "economic factors" are larger, 0.364, 0.245 and 0.195 respectively, while the weights of "layout design", "building materials" and "behavior" are less. Among the secondary indicators, the top five ranked by weight are "clean energy utilization" (0.152), "external wall insulation system" (0.090) and "energy efficiency" (0.152). "(0.090), "window performance" (0.088), and "electricity consumption" (0.084), accounting for more than half of the total weight, which is an important influence on the clean energy use of rural residential buildings. The factors of clean energy use in rural residential buildings are important factors. Most of the indicators with lower weights are "behavior", "building materials" and "layout design", mainly because these influencing factors are influenced by the geographical environment and the original status of the building. For example, the "appropriateness of site selection" in the secondary index is determined at the beginning of building construction, so it is difficult to change it again during renovation, but it affects the energy source and its distribution during the operation and use of the building, which has a significant impact on the LCI. However, it affects the energy resources and their distribution during the operation phase of the building, and has a significant impact on LCI. From the above analysis, it is clear that "energy use", "envelope" and "economic factors" are important influencing factors in the assessment of clean and low carbon use of rural residential buildings [21].

Table 3 I and II index weights

Tier 1 Indicators	Weighting of primary indicators Wi	Secondary indicators	Weighti
Energy use (A)	0.364	Clean Energy Utilization (A1)	0.417
		Coal use (A2)	0.087
		Electricity consumption share (A3)	0.231
Envelope (B)	0.245	Window-to-wall ratio (B1)	0.179
		Window performance (B2)	0.359

Tier 1 Indicators	Weighting of primary indicators Wi	Secondary indicators	Weighti
		External wall insulation system (B3)	0.366
Layout design (C)	0.041	Building orientation arrangement (C1)	0.282
		Geographical distribution (C2)	0.072
		Living space per capita (C3)	0.192
Construction materials (D)	0.058	New building materials utilization rate (D1)	0.302
		Building material reuse rate (D2)	0.258
		Building material saving (D3)	0.332
Behavioral habits (E)	0.102	Energy saving appliance usage rate (E1)	0.177
		Low carbon behavior awareness (E2)	0.228
		Water conservation (E3)	0.158
		Domestic waste recycling treatment (E4)	0.199
Economic factors (F)	0.195	Annual per capita household income (F1)	0.383
		Clean Energy Consumption (F2)	0.412
		Clean Energy Prices (F3)	0.113
		Building renovation subsidy satisfaction (F4)	0.093

After the calculation, the LCI evaluation level division is further derived as shown in Table 4. the LCI is less than 3, indicating the urgent need for the low carbon evaluation index system to identify its own shortcomings and prioritize the optimization of the indexes with higher weight values in order to improve its low carbon performance under limited conditions. Meanwhile, due to the poor condition of existing rural residential buildings, their renovation work is relatively large. For buildings with LCI in [3, 4), the low-carbon evaluation situation is medium, and the buildings can be retrofitted according to different criteria, giving priority to indicators with good low-carbon performance. buildings with LCI in the range of [4, 5] can temporarily not be retrofitted because of good conditions in all aspects. buildings with LCI of high or medium carbon type, this paper hopes that through retrofitting, the LCI can reach a score of 4 or higher to achieve their low-carbon Transformation.

Table 4 Classification of evaluation levels

Grade	Low carbon type	Medium carbon type	High carbon type
Low Carbon Index LCI	$LCI \in [4,\ 5\ ]$	$LCI \in [3,\ 4)$	$LCI \in [0,\ 3)$

4 Low Carbon Assessment Case Studies

In order to apply the constructed evaluation system to the assessment of the low carbonization of rural residential buildings, this study selected village A in Zhejiang Province as the research object, and investigated a total of 227 rural households in the village by means of visits and surveys to obtain the basic overview of the research object and the required content of evaluation indexes in the village, and conducted a detailed survey of 6 rural residential buildings (3 each of unrenovated and renovated), and the unrenovated and renovated The numbers of unrenovated and renovated were recorded as M1-M3 and H1-H3, respectively, for analysis. The specific assessment results are shown in Table 5.

Table 5 Indicator evaluation results

Tier 1 Indicators	Secondary indicators	M1	M2	M3	H1	H2	H3	Weights
Energy Use	Clean Energy Utilization	3	4	1	4	5	5	0.152
	Coal use	3	3	1	2	5	4	0.032
	Share of electricity consumption	2	3	2	1	3	4	0.084
Enclosures	Window to wall ratio	3	3	2	5	5	5	0.044

Tier 1 Indicators	Secondary indicators	M1	M2	M3	H1	H2	H3	Weights
	Window Performance	1	2	1	3	4	5	0.088
	External wall insulation system	2	3	1	3	5	3	0.090
Layout design	Building orientation arrangement	5	5	5	5	5	5	0.012
	Geographical Distribution	4	4	4	4	4	4	0.003
	Living space per capita	2	3	1	3	3	3	0.020
Construction Materials	Utilization rate of new building materials	1	1	1	1	1	1	0.018
	Building material reuse	2	3	1	3	4	4	0.015
	Building material saving	4	3	1	5	5	5	0.019
Behavioral habits	Energy-saving appliance usage rate	5	4	4	4	5	4	0.018
	Low Carbon Behavior Awareness	5	3	3	3	3	3	0.023
	Water conservation	4	5	1	4	5	5	0.016
	Domestic waste recycling treatment	4	4	1	3	5	4	0.020
Economic Factors	Annual household income per capita	5	5	5	5	5	5	0.075
	Clean Energy Consumption	3	4	1	4	4	3	0.080
	Clean Energy Prices	1	3	3	3	4	3	0.022
	Building renovation subsidy satisfaction	5	3	1	3	3	5	0.018

According to the formula, the comprehensive evaluation results of LCI of 6 rural residential buildings are shown in Table 6. According to the LCI in Table 6, it can be seen that there are 2 high-carbon and 1 medium-carbon buildings in the unrenovated buildings (M1-M3) and 2 low-carbon and 1 medium-carbon buildings in the renovated buildings (H1-H3), which are better than the unrenovated buildings.

Table 6 Integrated assessment results

Number	M1	M2	M3	H1	H2	H3
LCI	2.68	3.24	1.66	3.81	4.73	4.29
Grade	High carbon type	Medium carbon type	High carbon type	Medium carbon type	Low carbon type	Low c

As shown in Fig 2, the average low-carbon index of the unrenovated buildings is 2.53, and the average low-carbon index of the renovated buildings is 4.28. The low-carbon index of the renovated buildings is significantly higher than that of the unrenovated ones, and the level of low-carbonization is higher, indicating that renovation can effectively improve the low-carbonization level of residential buildings.

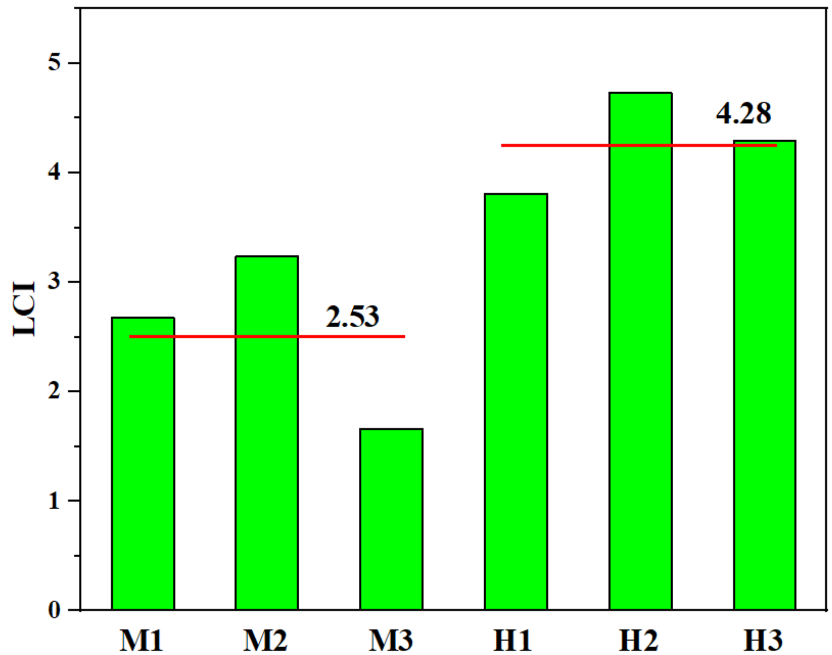

Fig. 2 Low carbon index and average of each farm household

As shown in Fig 3a, by comparing the scores of the six primary indicators of each farmer, it can be found that the area formed by the area connected by the dots of each indicator score is significantly higher in M1 than in M2 and M3, and the area size is M2 > M1 > M3, mainly because M2 has a greater advantage in "envelope structure" and "energy use". M2 > M1 > M3, mainly because M2 has greater advantages in "envelope" and "energy use". As can be seen from Fig 3b, the area of H2 formed by the connection of the dots of each index score is significantly higher than that of H1 and H3, and the size of the area is H2 > H3 > H1, although the advantage of H2 in "economic factors" and "behavioral habits" is not obvious. However, H2 has an outstanding performance in "energy use", and according to the previous section, "energy use" has a higher weighting factor.

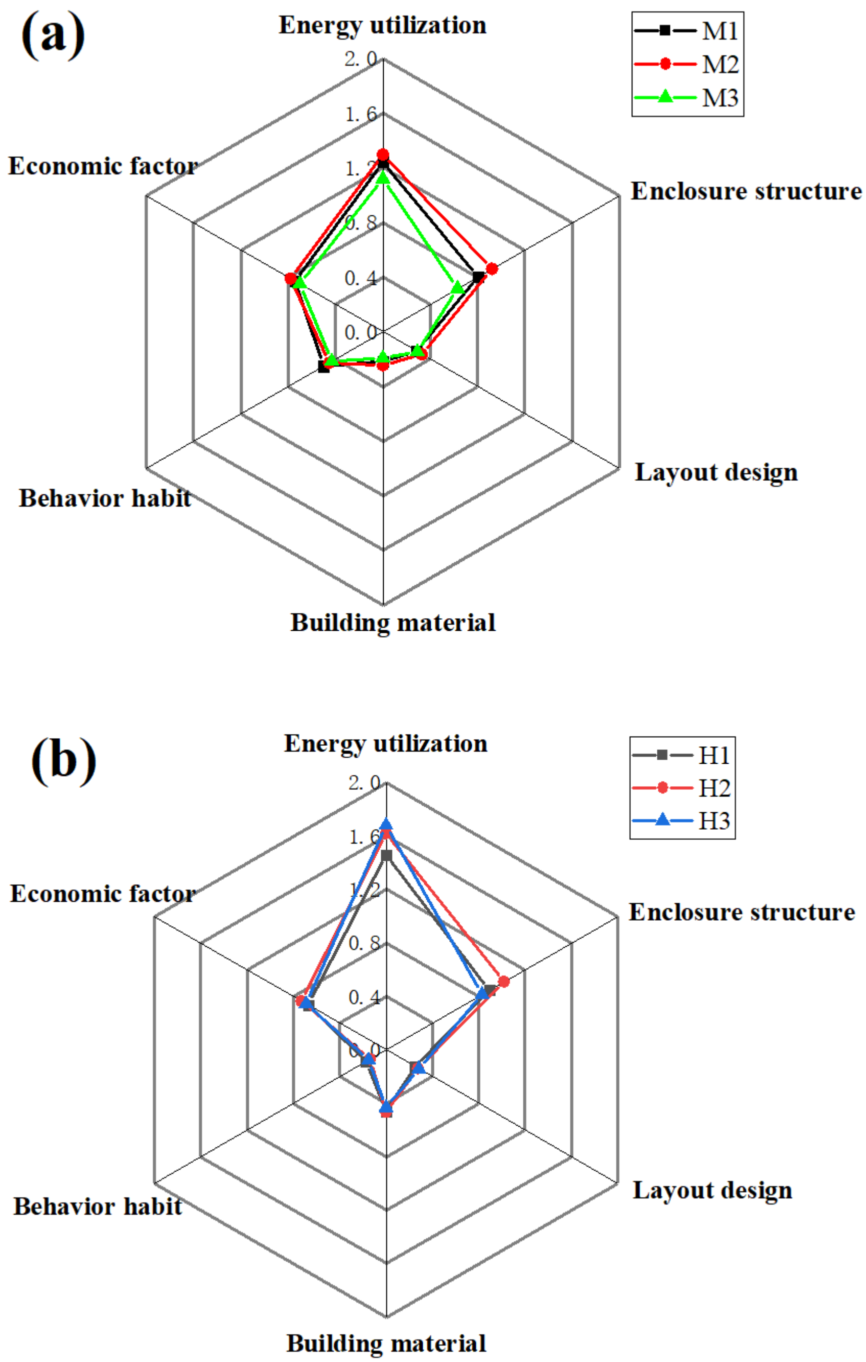

Fig. 3 Comparative analysis of primary indicators (a) M1, M2, M3, (b) H1, H2, H3

In order to further evaluate the level of low carbonization of each household, this study analyzed the secondary indicators of each household, as shown in Fig 4a, a total of eight secondary indicators in M2 have a weighted evaluation score greater than M1 and M3, which all contribute to the assessment of low carbonization. Checking the research situation of M2, we found that the windows used in the building are aluminum windows, which have very good heat insulation effect and play a good role in reducing heat loss, and the exterior wall construction is made of Sanchi wall, which is better than both M1 and M3, so the building has higher heat insulation effect and plays an important role in LCI. In the case of energy use, M2 uses more biomass, mainly tree branches, and biomass has an important role in low carbon, and these two indicators also show the importance of "energy use" and "envelope", which have a significant impact on improving LCI [22]. M3 is a "high-carbon" case with the lowest evaluation score, and the analysis of its score can help to improve the level of low carbonization in the future. Generally, because M3 did not carry out envelope renovation and energy renovation, the energy used is mainly bulk coal and cellular coal, which is used a lot and causes relatively serious pollution. For M3, the indicators with good weighted scores are "per capita annual household income" and "window-to-wall ratio", which shows that M3 has a good per capita annual income level and has the economic ability to use clean energy. The "window-to-wall ratio" also lays a certain foundation for future envelope renovation and does not require too many changes in windows and doors.

Through the study of the renovated H1-H3, it was found that before the renovation as M1-M3, the walls of the buildings did not have good insulation materials, and they could only rely on burning large amounts of coal for heating and as a source of energy consumption such as domestic hot water and cooking in winter. However, in recent years, through the transformation of the envelope structure and the change of energy utilization, the insulation layer has been added to the exterior walls of residential buildings, and the insulation material is mainly of the polystyrene board type, which has a good thermal insulation effect and guarantees an effective improvement of the indoor thermal environment [23]. The energy used is also cleaner and low-carbon, and the reduction in the amount of coal combustion has improved the indoor air quality and changed the original "dirty, messy, and poor" situation. In terms of "energy use", biomass energy resources are abundant in the study village, and the renovated buildings have increased the use of new biomass stoves and solid-formed biomass pellets, and in recent years have increased the use of solar photovoltaic power generation, which can supplement household electricity and reduce the use of coal compared with no energy renovation. In terms of "envelope", the addition of wall insulation systems has improved indoor temperatures, and windows have been replaced with aluminum and plastic windows from the original wooden windows or old-fashioned steel windows. The "layout design" aspect, as an indicator with limited changes during renovation, was also selected with different regional conditions in mind, and although it did not change much in the case study, it will play its importance in a broader range of uses in the future [24]; the research site selected for this paper was Zhejiang Province, so "site rationality", "building orientation arrangement", and "geographic location distribution" have not changed, and "living area per capita " had some changes before and after the renovation, but this paper only focuses on residential buildings, and the renovation did not have an impact.

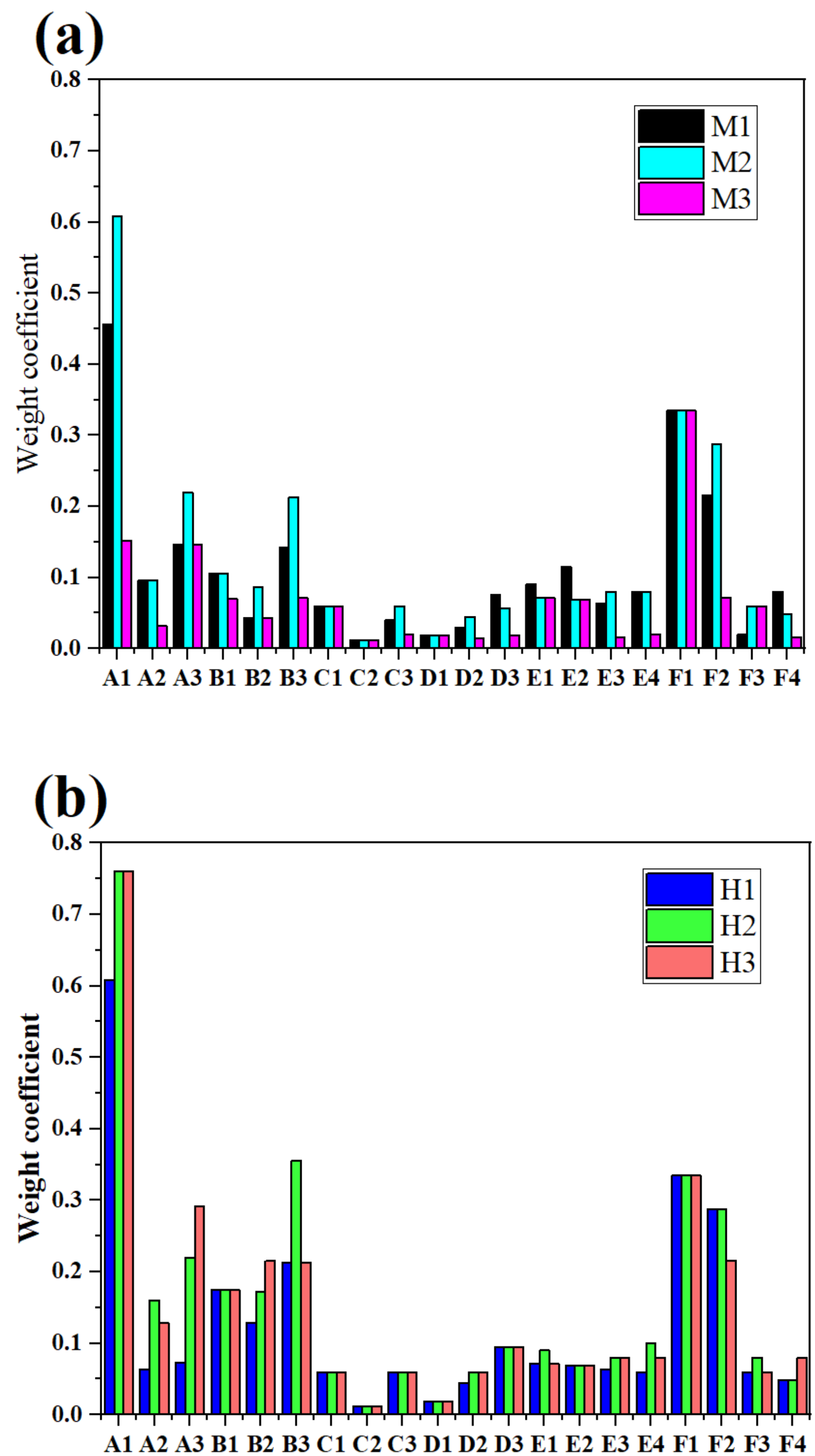

Fig. 4 Comparative analysis of secondary indicators (a) M1, M2, M3; (b) H1, H2, H3

5 Conclusion

This paper takes the assessment of the low carbonization of clean energy use in rural residential buildings as the research direction, constructs a conceptual framework for low carbonization assessment and an evaluation index system, selects a rural residential building as a research case of the evaluation index system, and applies the index system constructed in the previous paper to assess its low carbonization. The main findings are as follows.

(1) From the perspective of the assessment indicators for the low carbonization of clean energy use in rural residential buildings, the indicator system involves a number of aspects, which have a great deal to do with envelope structure and economic factors in addition to energy utilization, and also have an influence on layout design, building materials and behavioral habits. The weighting of the primary indicators is set at 36.4% for energy utilization, 24.5% for envelope structure, 4.1% for layout design, 5.8% for building materials, 10.2% for behavioral habits and 19.5% for economic factors.

(2) From the case studies, the main reason for the higher level of decarbonization of clean energy use in retrofitted rural residential buildings is the increased use of renewable energy sources such as electricity, biomass and solar energy through both energy utilization and building envelope modifications. In terms of key influencing factors, "clean energy utilization", "share of electricity consumption", "external wall insulation system" and "window performance " are key influencing factors for the level of decarbonization of clean energy use in a rural residential building.

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Conflict of Interest

The authors declare no potential conflict of interest.

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