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Research on Carbon Emission Characteristics of Rural Buildings Based on LMDI-LEAP Model

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Abstract: Based on the emission factor method and LMDI-LEAP model, this paper systematically studies the current situation, influencing factors and changing trend of carbon emissions from rural buildings in a typical village located in southern China. The results showed that (1) the per capita carbon emissions generated by the energy consumption of rural buildings is 2.58 tCO_2/a. Carbon emissions from electricity consumption in buildings account for about 96.07%; (2) the per capita building area, building area energy intensity, population size, population structure and carbon emission coefficient affect rural building carbon emissions, with contribution rates of 70.13%, 31.27%, 0.61%, −1.21% and −0.80%, respectively; (3) from 2021 to 2060, the carbon emissions of rural buildings are expected to increase first and then decrease. In 2021, the base year, carbon emissions from buildings were 2755.49 tCO_2. The carbon emissions will peak at 5275.5 tCO_2. Measures such as controlling the scale of buildings and improving the utilization rate of clean energy can effectively reduce carbon emissions, in which case the peak can be reduced to 4830.06 tCO_2. Finally, the countermeasures and suggestions about rural building energy saving and emission reduction are proposed, including improving the construction management, raising energy efficiency standards in buildings, increasing the proportion of clean energy and raising residents' awareness of energy conservation.

Keywords: carbon emissions from rural buildings; influence factor; variation tendency; LMDI model; LEAP model

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1. Introduction

The emission of greenhouse gases (GHG), mainly carbon dioxide, has increased significantly, leading to frequent extreme climate events around the world, which seriously threatens the normal production and life order of human beings. In 2020, China proposed to increase its nationally determined contributions (INDCs) and strive to achieve carbon peaking by 2030 and carbon neutrality by 2060. In 2019, China's total carbon emissions were about 9.92 $GtCO_2$, accounting for 29.50% of the global total carbon emissions [1], which indicates that China's carbon emission situation is not optimistic, and the carbon emission reduction work has a long way to go. As an important energy consumption sector, the carbon emissions of civil buildings are about 4.997 billion tCO_2, accounting for 50.60% of the national carbon emissions [2], which indicates that carbon emission control in the construction sector will be the focus of China's energy conservation and emission reduction work. At present, there have been extensive studies on carbon emissions from energy consumption at the national or provincial level [3,4], the characteristics of carbon emissions from urban buildings and energy-saving renovation measures [5–8], etc., but there is a lack of research on rural carbon emissions. Under the background of China's policy of building a well-off society in an all-round way and rural revitalization, the rapid development of rural economy and the improvement of rural population and living standards will aggravate the energy consumption of rural buildings, resulting in the growth of carbon emissions [9–11]. Studies have also shown that rural areas are becoming the second largest source of GHG [12]. It is important and urgent to fully understand the problems of carbon emissions in rural buildings and explore the low-carbon development mode suitable for rural buildings.

In recent years, studies on rural carbon emissions (mitigation) mostly focus on biomass energy utilization, agricultural system carbon emissions, etc. Garniera J et al. [13] studied the changes in GHG emissions during the intensification and specialization of agriculture and animal husbandry in France. Zhou et al. [14] calculated the carbon emissions of 2.79×10^5 km^2 of cultivated land in northern China and calculated that the carbon emissions per unit of cultivated land area was about 7.60×10^{-4} tCO$_2$/m^2. Sen A et al. [15] and Catia Goncalves et al. [16] studied the GHG composition and emission characteristics of biomass fuels such as fuelwood, farm residues and dung cakes used in rural areas. Johnsona M et al. [17] took traditional open-fire stoves in rural areas as the research object, compared and analyzed the field measured value with the theoretical value in the carbon emission database, and found that the theoretical value was significantly lower than the measured value, and the carbon emission database may seriously underestimate open fire emissions. In addition, some scholars have discussed the carbon emission characteristics of production and life, such as residential life [18], rural roads [19] and energy consumption structure [20], and divided the sources of rural carbon emissions into five categories: lighting, heat, cooking, household appliances and transportation [21]. Shi et al. [22] took a rural residential building in northern China as a case study and calculated that its carbon emissions per unit building area were about 6.21 tCO$_2$/m^2, accounting for 89.92% of the carbon emissions during building operation. Carbon emissions from rural buildings are much higher than those from agriculture. However, there are few studies on carbon emissions based on rural buildings. At the same time, unlike large high-rise buildings in cities, which are built with advanced technologies or building standards, rural buildings are mostly self-built by residents using traditional building techniques, with low floors and lack of thermal insulation structure [23].

Therefore, it is necessary to conduct a comprehensive study on the current situation, influencing factors and changing trends of rural building carbon emissions. The village Y is located in the south of the Yangtze River and has a variety of building types, such as residential buildings, commercial buildings and public buildings. The average temperature is 25–30 °C in summer and 0–10 °C in winter. The average annual relative humidity is 70%–80%. The buildings here mainly rely on electricity to provide heating and cooling sources, which is representative. This paper takes the buildings in village Y as the research object and uses the emission factor method [24–26] usually adopted by the International Energy Research Agency to calculate the carbon emissions of buildings. The LMDI model is used to quantitatively calculate the driving effects of the emission factors, energy intensity, building area, population structure and population size of rural building carbon emissions. This model has the advantages of the independent analysis path, ease of use, no residual error, and good zero-value processing ability, and has been widely used in the research of carbon emission driver factorization in various countries and fields [27–31]. At the same time, based on the concept of scenario analysis, different development scenarios are set from the perspective of future changes in rural construction scale, low-carbon technology and energy use structure, and the LEAP model is constructed to predict the energy demand and carbon emissions of rural buildings [32]. Finally, the low-carbon development path of rural buildings is discussed to provide theoretical reference for rural energy conservation and emission reduction work.

2. Materials and Methods

Taking village Y as the research object, the statistical data of building, population and equipment were collected. LDMI model was established to analyze the main factors affecting building carbon emissions. Based on relevant national policies, three different energy development scenarios were established, and the energy consumption of village

Y from 2022 to 2060 was predicted in the LEAP model. Countermeasures and suggestions conducive to the sustainable development and emission reduction of village Y were proposed by comparing the results of each scenario.

2.1. Data Sources

2.1.1. Survey Data

In May 2022, a house-to-house survey was conducted on village Y to collect the basic data and energy consumption data of various buildings (Table 1). The planning data were obtained from the local government statistical yearbook, development plan and research report.

Table 1. Household survey contents.

The Research Project	Indicators
Population	Registered population
Building	Building type, building area, building age, building level, building structure, etc.
Equipment	Energy consumption type and consumption of cooking utensils and air conditioners

2.1.2. Carbon Emission Factor Data

Carbon emission factor data are mainly obtained from IPCC national GHG inventory guidelines, measured data and published literature [33,34]. The carbon emission coefficient adopted in this paper is shown in Table 2.

Table 2. Carbon emission factor data.

Energy	Carbon Emission Factor Value	Unit
Electricity	0.7035	$kgCO_2/kWh$
Water	0.30	$kgCO_2/t$
Liquefied petroleum gas (LPG)	2.98	tCO_2/t
Natural gas	21.6072	$tCO_2/10^4\ m^3$

2.2. Carbon Emission Calculation

Carbon emission calculation methods mainly include the emission factor method and the measurement method. Among them, the measured method is the continuous measurement of greenhouse gas emission concentration, which has a large workload and high equipment cost. The emission factor method mainly relies on calculation; that is, emissions are calculated through activity level data and related parameters. Now there are mature calculation formulas and complete data sources of various energy emission factors, which are widely used in various countries. In this paper, the emission factor method is chosen to calculate the carbon emissions of rural buildings. The specific formula is as follows:

$$E = \sum Q \times EF \quad (1)$$

where: E—carbon emissions;
Q—activity level;
EF—carbon emission factor.

$$E_{YX} = \sum_{i=1}^{n} F_i \times U_i \quad (2)$$

where: E_{YX}—carbon emissions during building operation;
U_i—energy consumption;
F_i—carbon emission factor.

2.3. Analysis Method of Influencing Factors

2.3.1. LMDI Model Construction

In this paper, the driving factors of building carbon emissions are decomposed into five factors: carbon emission coefficient effect (C/E), building area energy intensity effect (E/S), per capita building area effect (S/P), population structure effect (P/P) and population size effect (P). The calculation formula is as follows:

$$C = \sum_i \frac{C_i}{E_i}\frac{E_i}{S_i}\frac{S_i}{P_i}\frac{P_i}{P}P = \sum_i CE \cdot ES \cdot SP \cdot PP \cdot P \tag{3}$$

where: C—total carbon emissions;
P—total population;
C_i—carbon emissions, i =1, 2 and 3 correspond to rural residential buildings, commercial buildings and public buildings respectively;
E_i—energy consumption;
S_i—floor area;
P_i — population in buildings;
$CE = \frac{C_i}{E_i}$—the carbon emission coefficient effect;
$ES = \frac{E_i}{S_i}$—the energy intensity effect of building area;
$SP = \frac{S_i}{P_i}$—the effect of per capita building area;
$PP = \frac{P_i}{P}$—the effect of population structure.

2.3.2. LMDI Decomposition Model Construction

The sum decomposition formula of LMDI model to analyze the influencing factors of rural building carbon emissions is as follows:

$$\Delta C_{tot} = C^T - C^0 = \Delta C_{CE} + \Delta C_{ES} + \Delta C_{SP} + \Delta C_{PP} + \Delta C_P \tag{4}$$

where: ΔC_{tot}—the change of the total amount of rural buildings;
C^T—the carbon emissions of the building during the reporting period;
C^0—the carbon emissions of the building in the base period;
ΔC_{CE}—the contribution of the carbon emission coefficient effect to building carbon emissions;
ΔC_{ES}—the contribution of the energy intensity effect of building area to building carbon emissions;
ΔC_{SP}—the contribution of per capita living area effect to building carbon emissions;
ΔC_{PP}—the contribution of population structure effect to building carbon emissions;
ΔC_P—the contribution of population size effect to building carbon emissions.

$$\Delta C_{CE} = \sum_i w_{ci} \cdot \ln\left(\frac{CE_i^T}{CE_i^0}\right) \tag{5}$$

$$\Delta C_{ES} = \sum_i w_{ci} \cdot \ln\left(\frac{ES_i^T}{ES_i^0}\right) \tag{6}$$

$$\Delta C_{SP} = \sum_i w_{ci} \cdot \ln\left(\frac{SP_i^T}{SP_i^0}\right) \tag{7}$$

$$\Delta C_{PP} = \sum_i w_{ci} \cdot \ln\left(\frac{P_i^T}{P_i^0}\right) \tag{8}$$

$$\Delta C_P = \sum_i w_{ci} \cdot \ln\left(\frac{P^T}{P^0}\right) \tag{9}$$

$$w_{ci} = \begin{cases} L(C^T, C^0) = \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0}, C^T \neq C^0 \\ C^T, C^T = C^0 \end{cases} \tag{10}$$

The contribution rate of each effect to building carbon emissions can be expressed as follows:

$$\zeta(C_x) = \frac{\Delta C_x}{\Delta C} \tag{11}$$

where: $\zeta(C_x)$—the contribution rate of a single effect to rural building carbon emissions; ΔC_x—the contribution value of each effect to the total change of building carbon emissions; ΔC—the change in total carbon emissions from buildings.

2.4. Carbon Emission Forecast

2.4.1. Scenario Setting

Considering that the carbon emissions of rural buildings are affected by many factors, this paper designs three scenarios according to the relevant policies and regulations issued by China and reasonable assumptions about the future development of village Y [35–38]. All scenarios, namely, baseline scenario, medium constraint scenario, and high constraint scenario, needed to meet the economic and social development needs of village Y (Energy, population and building size to ensure normal development). The carbon emission level of village Y from 2022 to 2060 is predicted, and 2030 and 2060 are the key prediction time nodes.

1. Baseline scenario

Carbon reduction mostly depends on conventional technological means, and the intensity of carbon reduction measures is low. In the building sector, building energy conservation, cooling and heating structures, energy equipment and system efficiency have been continued with existing policy efforts to steadily promote building energy conservation.

2. Medium constraint scenario

Carbon reduction efforts have been further improved. In the construction sector, policies have been strengthened in building energy conservation, cooling and heating structures, cooking structures, the proportion of clean and renewable energy applications and the efficiency of energy-using equipment and systems. For example, the government led to change the way of building cooking, accelerated the transition from LPG to natural gas and electricity and guided the public to raise the awareness of energy conservation, so as to replace the old and low-energy-efficiency electrical appliances inside buildings.

3. High constraint scenario

In addition to conventional technologies, emerging technologies, such as PSDF (photovoltaics, storage, direct current and flexibility) and biogas power generation technology, have been applied to buildings to further improve carbon-reduction efforts. In the construction sector, we will intensify policy efforts in all aspects, especially the long-term adoption of more breakthrough technologies to achieve greater energy conservation and carbon reduction, such as the promotion of rooftop photovoltaic systems, encouraging the use of air source heat pumps, the construction of biogas power generation demonstration projects, and the development of biomass energy.

2.4.2. Parameter Settings of the LEAP Model

In this paper, taking 2021 as the base period and 2022–2060 as the forecast period, the LEAP model parameters of the three scenarios are set considering the per capita building area, population size and terminal energy consumption.

1. Building area

The floor area per capita in rural residential buildings in China increased from 24.8 m^2 in 2000 to 47.3 m^2 in 2018 [39]. With the implementation of the Rural Revitalization issued by the Chinese government, before 2030, the architectural volumes of rural buildings will continue to increase [40]. The village Y government plans to attract more than 1 million visitors a year. Twenty B&Bs or hotels will be built, and 26,835 m^2 of new public buildings will be built within five years. The residential building volume changes with the population. The building volume will reach saturation around 2030, and the construction speed will slow down. Combined with the existing construction scale of village Y and the rural building planning policy [41–43], The data of floor area are shown in Table 3.

Table 3. LEAP model parameters of village Y in the benchmark scenario.

Indicator	Unit	Base Year	Baseline Scenario		Medium Constraint Scenario		High Constraint Scenario	
		2021	2030	2060	2030	2060	2030	2060
Building area/(m^2)	Residential building	70,200	81,328	83,803	77,965	80,338	74,605	74,829
	Commercial building	27,600	56,700	58,426	52,650	54,253	49,921	51,441
	Public building	23,446	65,316	67,304	63,064	64,983	62,453	64,354
Proportion of cooking energy/(%)	LPG	96	39.22	6.08	27.03	0.04	16.96	0.00
	Natural gas	0	50.65	36.40	56.09	34.00	57.72	15.60
	Electricity	4	10.13	57.52	16.88	65.96	25.32	84.40
Number of air conditioning/(set/household)	Residential building	4.73	5.03	5.23	4.93	5.15	4.83	5.08
	Commercial building	16.85	19.35	20.53	18.68	19.87	17.85	19.32
	Public building	1	1	1	1	1	1	1
Population/(person)	Registered population	1068	1140	1042	1140	1042	1140	1042

Note: Public buildings are considered to be cooled and heated by a central air conditioning system, so the number of air conditioning units will not be subdivided.

2. Village population

Affected by the policy of Rural Revitalization and Talent Introduction, the permanent population of village Y has increased year by year, with an average annual growth rate of about 7.79%. Many institutions and scholars at home and abroad have made predictions on the evolution of China's population by 2050, and all believe that China's population will peak in 2030 [44,45]. In particular, China's population aging shows urban-rural inversion; the aging level in rural areas is 1.24 percentage points higher than that in urban areas [46–48]. Village Y also faces the problem of rural population aging. This study assumes that the population of village Y will reach the peak in 2030 and maintain a low-growth trend before that. Meanwhile, due to the onset of the aging development stage, the proportion of the elderly population will continue to increase, and the total population will decline rapidly after the peak. The average annual population growth rate from 2030 to 2050 is set to be −0.30%.

3. Terminal energy consumption

The cooking structure will be greatly changed according to the introduction of energy-related policies. With the increase of living standards and indoor comfort requirements, the number of air conditioners will continue to grow. Combined with the scenario analysis of the cooking sector in China's Sustainable Energy Scenario in 2020 [49] and the forecast of air conditioning demand in China's Low-Carbon Development Pathways by 2050 [50], the proportion of cooking energy and air conditioning density under the three scenarios were set.

3. Results and Discussion

3.1. Current Status of Carbon Emissions in Rural Construction

Buildings in village Y were generally built after 1980, with one to three floors and concrete or brick walls. The roof of the building is pitched or flat, and some of the building facades are damaged or moldy. The total construction area of village Y is about 121,246 m^2. Among them, residential buildings are used by villagers with a total construction area of about 70,200 m^2. The usage of LPG is about 15.21 t/a, the electricity consumption is about 16 kWh/(a·m^2), and the water consumption is about 6.89 t/(a·m^2). The commercial building includes catering and accommodation, with a total floor area of about 27,600 m^2. The total use of LPG is about 9.34 t/a, the average power consumption per unit floor area is 49 kWh/(a·m^2), and the water consumption per unit floor area is about 0.23 t/(a·m^2). Public buildings are mainly used for Party and government offices, science, education, culture and health, landscape and leisure, with a total construction area of 23,446 m^2. The power consumption per unit building area is about 54.88 kWh/(a·m^2), and the water consumption per unit building area is about 4.39 t/(a·m^2). The natural gas pipeline is under construction and is expected to be operational by 2024, so its carbon emissions are not considered for now.

In 2021, the total carbon emissions of buildings in village Y were 2755.49 tCO_2/a, and the total carbon emissions of per capita building energy re 2.58 tCO_2/a. From the perspective of building type, as shown in Figure 1a, the total carbon emissions of residential buildings were 837.71 tCO_2/a, commercial buildings were 981.17 tCO_2/a, and public buildings were 936.61 tCO_2/a. The contribution of commercial buildings, public buildings and residential buildings to the total carbon emissions of village Y were 35.61%, 33.99% and 30.40%, respectively. Carbon emissions per unit building area from high to low were public buildings, commercial buildings and residential buildings, which were 0.039 tCO_2/m^2, 0.036 tCO_2/m^2 and 0.012 tCO_2/m^2, respectively.

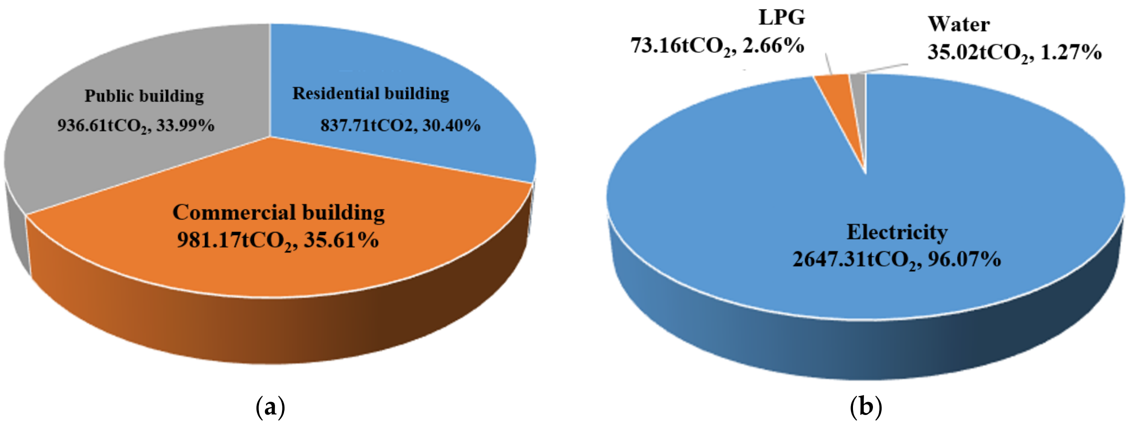

Figure 1. Statistics of building carbon emissions (**a**) and energy consumption (**b**) in village Y in 2021.

From the perspective of energy consumption, as shown in Figure 1b, the total carbon emissions of building electricity are 2647.31 tCO_2/a, accounting for 96.07% of the total carbon emissions of building energy; the carbon emissions of LPG consumption are 73.16 tCO_2/a, and the carbon emissions of building water are 35.02 tCO_2/a. Village Y is located in the hot-summer and cold-winter region of China, and the building shape coefficient is high. No thermal insulation measures are set for the external walls, and there are no sunshade facilities. The window frame is made of wood or aluminum alloy, with a single layer of transparent glass. The heat transfer coefficient is up to 4.8–6.2 W/(m^2·K), and the area ratio of window to wall is between 0.2 and 0.45. The lack of a thermal insulation system for the building envelope leads to the increase of energy consumption for cooling and heating in winter and summer. At the same time, there is a general lack of awareness of equipment management and maintenance, and some residents are still using three-level energy efficient air conditioners, which have long service times and low efficiency, resulting in a significant increase in electrical energy consumption.

3.2. Analysis of Influencing Factors of Rural Building Carbon Emissions Based on LDMI Model

3.2.1. Contribution Rate Analysis of Carbon Emissions

From 2019 to 2021, the total carbon emissions of village Y buildings increased year by year. As shown in Figure 2 and Table 4, the energy intensity effect of building area, per capita building area effect and population size effect were all positive. Among them, the contribution value and contribution degree of the effect of per capita building area were 1370.69 tCO_2 and 70.13%, the contribution value and contribution degree of the effect of energy intensity of building area were 611.09 tCO_2 and 31.27%, and the contribution value and contribution degree of the effect of population size were 11.88 tCO_2 and 0.61%, respectively. It shows that the positive driving effect brought by the growth of per capita building area is the most significant, followed by the energy intensity effect of building area. The comprehensive carbon emission factor effect and population structure effect were negative; the contribution value and contribution degree of the comprehensive carbon emission factor effect were −23.68 tCO_2 and −1.21%, respectively, and the contribution value and contribution degree of the population structure effect were −15.59 tCO_2 and −0.80%, respectively.

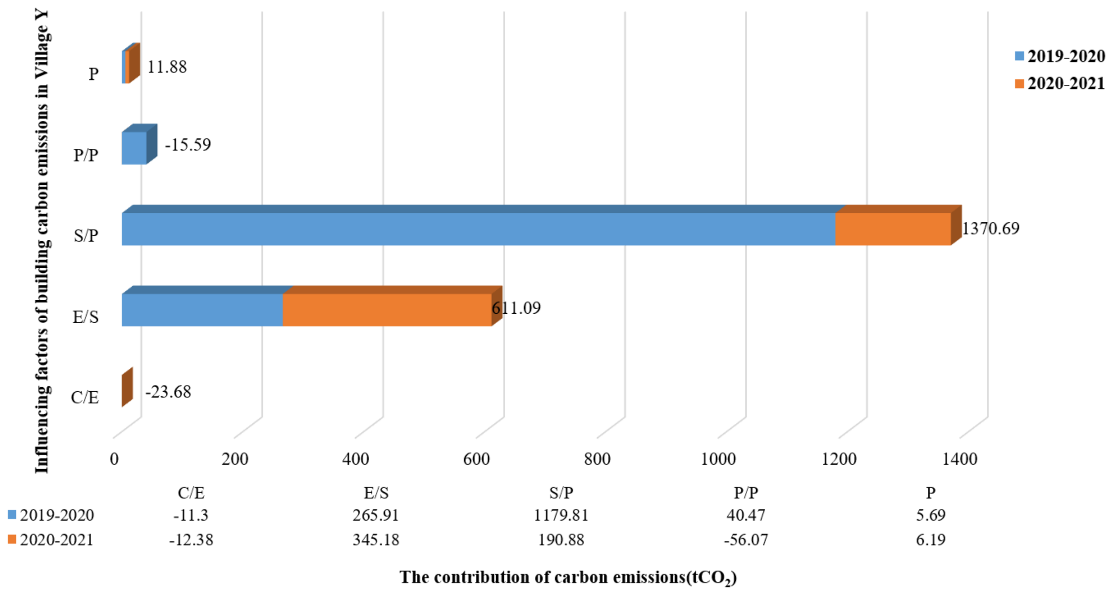

Figure 2. The contribution of building carbon emissions in village Y from 2019 to 2021. P: population size effect. P/P: population structure effect. S/P: per capita building area effect. E/S: building area energy intensity effect. C/E: carbon emission coefficient effect.

Table 4. Results of LMDI decomposition of building carbon emissions in village Y from 2019 to 2021 (contribution rate, unit: %).

Year	Carbon Emission Coefficient Effect	Building Area Energy Intensity Effect	Per Capita Building Area Effect	Population Structure Effect	Population Size Effect	The Total Effect
	$\zeta(\Delta C_{CE})$	$\zeta(\Delta C_{ES})$	$\zeta(\Delta C_{SP})$	$\zeta(\Delta C_{PP})$	$\zeta(\Delta C_{P})$	$\zeta(\Delta C_{tot})$
2019–2020	−0.76%	17.96%	79.69%	2.73%	0.38%	100.00%
2020–2021	−2.61%	72.85%	40.29%	−11.83%	1.31%	100.00%
2019–2021	−1.21%	31.27%	70.13%	−0.80%	0.61%	100.00%

3.2.2. Analysis of Influencing Factors of Rural Building Carbon Emissions

1. Per capita building area effect

The per capita building area is the main factor driving the energy consumption and carbon emissions of rural buildings. This effect is always positive, and the contribution value increases year by year, indicating that the larger the per capita building area, the higher the building energy consumption and carbon emissions. From 2019 to 2021, it contributed 70.13% to the growth of rural building carbon emissions. Per capita building area reflects the service level provided by construction products, which tends to change with the change of people's needs. For residential buildings, per capita building area is often affected by the residents' living standards. For commercial buildings and public buildings, the per capita building area is often closely related to the development level of the tertiary industry. With the continuous rise of the residents' income and the further development of the tertiary industry, the effect of per capita building area will continue to promote the continuous rise of rural building energy consumption and total carbon emissions in the future.

2. Building area energy intensity effect

Energy intensity of building area is a comprehensive reflection of the residents' living standard, the residents' energy consumption behavior and the building technology level and is an important index to characterize the progress of energy technology [51,52]. According to the decomposition results, the positive driving effect of the energy intensity of building area on rural building energy consumption and carbon emissions is second only to the effect of per capita building area, and the contribution rate to the growth of rural building carbon emissions from 2019 to 2021 is 31.27%.

The new building area was about 22,061 m^2 in 2019–2020 and about 5277m^2 in 2020–2021. While the growth of building area slows down, the impact of energy intensity effect of building area on carbon emissions of rural buildings increases, from 2.73% in 2019–2020 to 72.85% in 2020–2021. This indicates that in this research stage, rural energy technology has not made a great breakthrough, and residents may lack the awareness of energy management.

3. Population size effect

This part reflects the impact of the permanent resident population on building carbon emissions in village Y. It showed a small promotion effect on building carbon emissions, with slight growth from 0.38% in 2019 to 1.31% in 2021. This is mainly due to increasingly prominent structural problems, such as the declining proportion of the labor force and the increasing proportion of aging people in village Y during the research stage. Although the growth of population will cause the increase of building energy consumption and carbon emissions, its positive effect will continue to be at a low level.

4. Population structure effect

Population structure includes permanent population and floating population. Village Y has a well-developed tourism industry; the floating population is mainly tourists. Due to the impact of the pandemic, the number of tourists decreased from 900,000 person-times per year in 2019–2020 to 800,000 person-times per year in 2021, resulting in a decrease in the contribution rate of population structure to the carbon emissions of rural buildings from 2.73% in 2019–2020 to −11.83% in 2020–2021, showing a negative effect. Wang et al. found that the increase of carbon emissions in Beijing from 1997 to 2010 was mainly driven by changes in production structure and floating population growth [53].

Therefore, the improvement of rural tourism represented by the population structure effect will promote the growth of rural building energy consumption and carbon emissions to a certain extent. The development of rural tourism is a process in which people from all over the country continue to gather in the countryside, which has the profound significance of improving people's quality of life and population quality. The contribution rate of population structure to rural building carbon emissions fluctuates, but fundamentally, it still has the potential to promote the growth of rural building carbon emissions.

5. Carbon emission coefficient effect

The carbon emission coefficient is a retrogressive factor between building carbon emissions and energy consumption. From 2019 to 2021, the carbon emission coefficient effect mainly inhibited the change of building energy consumption and carbon emissions. This is mainly because electric energy is the main source of energy consumption in rural buildings. I In recent years, energy conservation and emission reduction efforts at the level of electric power policy have been continuously increased, which has significantly improved energy efficiency, and the overall carbon emission factor of electric power has decreased year by year, thus reducing the carbon emissions of rural buildings. At the same time, it also highlights the important role of technological progress in controlling building energy consumption and carbon emissions.

3.3. Rural Building Carbon Emissions Prediction Based on LEAP Model

3.3.1. Energy Demand Forecast

The electricity consumption of buildings in village Y includes the total terminal electricity consumption of air conditioning and lighting, TV, washing machines, baths and cooking, etc. The changes of electricity demand under three different scenarios are shown in Figure 3. It can be found that before 2030, the electricity demand of buildings in village Y will increase rapidly. The electricity consumption of commercial buildings will increase from 135.24 $\times$ 10^4 kWh to 277.83 $\times$ 10^4 kWh, and the electricity consumption of public buildings will increase from 128.67 $\times$ 10^4 kWh to 358.45 $\times$ 10^4 kWh. With the rapid growth of rural economy, more and more people go to rural areas for tourism, leisure and entertainment, which promotes the development of public industries. The volume of commercial and public buildings will increase, showing a rigid growth trend, and the demand for all kinds of energy will also rise. From 2030 to 2060, the change range is significantly smaller, and the proportion of electricity consumption in residential buildings is always within 20%. In addition to the saturation of building increment, the upgrading of building energy-saving technology and the optimization of energy consumption structure, the reduction of energy consumption demand caused by the aging population is also an important reason.

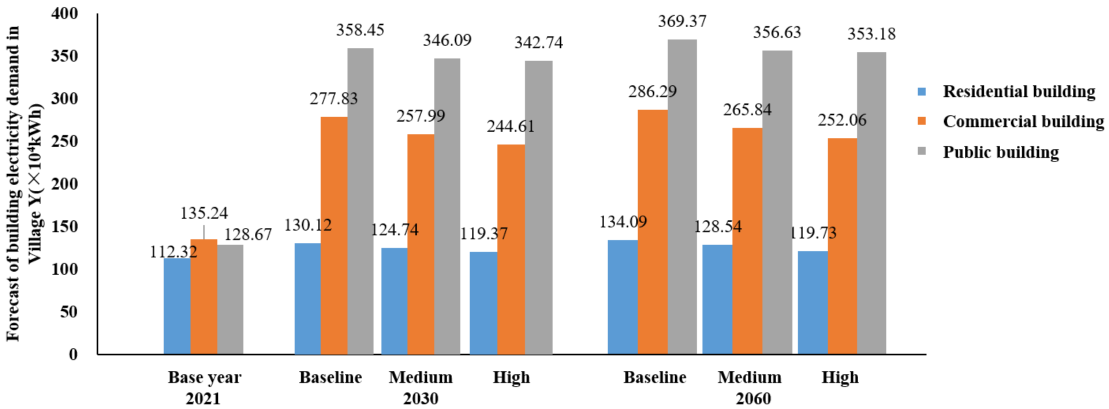

Figure 3. Forecast of building electricity demand in village Y from 2021 to 2060.

In civil buildings, fossil fuels such as liquefied petroleum gas and natural gas are mainly used for cooking activities. With the continuous improvement of natural gas supply and electrification levels, the cooking energy structure in village Y buildings will change accordingly. The use of LPG decreased from 24.55 t in 2021 to 0.01 t in 2060 under the medium constraint scenario, while the use of natural gas increased from 0 m^3 in 2021 to 1.34 $\times$ 10^4 m^3 in 2060. The water consumption of residential buildings is related to the population size and is not affected by different energy development scenarios. In 2021, the water consumption of 1068 people was about 7359.3 t. In 2030, when the population of village Y reaches 1140 people, the water consumption is expected to be 7854.6 t, and in 2060, the water consumption is expected to be 7179.38 t for 1042 people. The water demand of commercial buildings and public buildings increases with the increase of building area. The estimated total water consumption of village Y buildings under the three scenarios is listed in Table 5.

Table 5. Other energy forecasts for buildings in village Y.

	Year	LPG/t	Natural Gas/$\times 10^4$ m^3	Water/$\times 10^4$ t
Base year	2021	24.55	0.00	11.67
Baseline scenario	2030	14.10	2.00	30.76
	2060	2.19	1.44	31.61
Medium constraint scenario	2030	9.72	2.22	29.68
	2060	0.01	1.34	30.49
High constraint scenario	2030	6.10	2.28	29.35
	2060	0.00	0.62	30.15

3.3.2. Carbon Emission Forecast

The forecast results of building electricity carbon emissions in village Y from 2021 to 2060 are shown in Figure 4. Under the three scenarios, the total carbon emissions of building electricity in village Y is expected to increase first and then decrease, reaching the peak around 2030. In the benchmark scenario, the peak carbon emissions of building electricity are 5153.86 tCO_2, which is 1.95 times of the total carbon emissions of building electricity in the base year 2021. The carbon emissions in 2060 is 4569.27 tCO_2, which is 1.73 times of the total carbon emissions of building electricity in the base year 2021. In the constrained scenario, the peak carbon emissions of building electricity are 4901.1 tCO_2, which is 1.85 times the total carbon emissions of building electricity in the base year 2021. The carbon emissions in 2060 are 4345.19 tCO_2, which is 1.64 times the total carbon emissions of building electricity in the base year 2021. Under the high constraint scenario, the peak carbon emissions of building electricity are 4752.49 tCO_2, which is 1.80 times the total carbon emissions of building electricity in the base year 2021. The carbon emissions in 2060 are 4194.48 tCO_2, which is 1.58 times the total carbon emissions of building electricity in the base year 2021. With the continuous economic development of village Y, the energy intensity effect of the building area and the per capita building area effect are dominant, and the power consumption and carbon emissions of buildings in village Y are increasing before 2030 under the positive drive. After 2030, the building volume reaches saturation. With the continuous improvement of energy saving and carbon reduction technology, the building electricity carbon emissions in village Y start to decrease year by year. The promotion of clean energy, such as natural gas and electricity, is conducive to energy conservation and emission reduction. The carbon emissions generated by fossil energy consumption in cooking activities decreased. Replacing coal with natural gas and renewables in Suzhou has reduced the annual growth rate of the total energy demand from 3.6% to 2.22% [54]. Ningbo designs strategic policies from the perspective of energy structural adjustment. By increasing the share of natural gas to 95% and generating more electricity from clean sources like wind, solar and water, carbon emissions will decrease from 651.83 MtCO_2 to 589.17 MtCO_2 [55].

As shown in Table 6, the baseline scenario is based on existing policies and measures in 2021. The growth rate of per capita building area and tertiary industry is high, and the energy structure adjustment and energy utilization efficiency are at a low level. Therefore, the peak value of carbon emissions in this scenario is the largest, which is 5331.45 tCO_2. In the medium constraint scenario, the per capita building area is adjusted, and the tertiary industry develops at a medium speed. While meeting the needs of social development, the implementation of energy conservation and emission reduction is further enhanced, the energy structure is further adjusted, and the energy utilization efficiency is improved. Therefore, the peak carbon emissions were reduced to a certain extent, and the carbon emissions in 2030 were reduced by 264.41 tCO_2 compared with the baseline scenario. In the high-constraint scenario, the construction scale is further regulated, and the growth rates of residential buildings, commercial buildings and public buildings are no more than 6.59%, 86.38% and 174.48% by 2060, respectively. At the same time, the energy structure of cooking was optimized. Clean energy, such as natural gas and electricity, completely replaced LPG, and electricity was used as much as possible, accounting for 84.4% of the total. Under this development scenario, carbon emissions are expected to be 4908.04 tCO_2 in 2030 and 4298.27 tCO_2 in 2060.

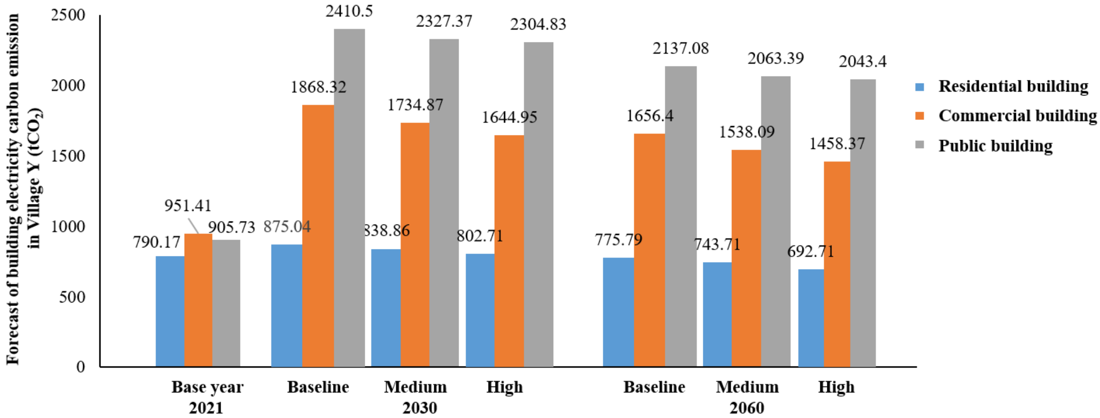

Figure 4. Forecast of building electricity carbon emissions in village Y from 2021 to 2060.

Table 6. Total Carbon Emissions forecast of buildings in village Y (Unit: tCO_2).

	Year	Electricity	LPG	Natural Gas	Water	The Total
Base year	2021	2647.31	73.16	0.00	35.02	2755.49
Baseline scenario	2030	5153.86	42.02	43.28	92.29	5331.45
	2060	4569.27	6.53	31.09	94.82	4701.71
Medium constraint scenario	2030	4901.1	28.97	47.93	89.04	5067.04
	2060	4345.19	0.03	29.04	91.48	4465.74
High constraint scenario	2030	4752.49	18.18	49.32	88.05	4908.04
	2060	4194.48	0.00	13.33	90.46	4298.27

3.4. Discussion on Carbon Emission Reduction Strategies

1. Improving the construction management

With the acceleration of rural revitalization processes, the building stock (total floor area) has been increasing, further aggravating the terminal energy consumption and carbon emissions of the building sector [56,57]. The result shows that the contribution rate of per capita building area to building carbon emissions in village Y is up to 70.13%. The government should strictly control the scale of new construction according to the current level of economic development and the future population size. For residential buildings, the whole process of building construction (planning, design, construction and use) is guided, and the use of passive technical measures is encouraged to improve the quality of residential buildings according to the characteristics of local resources. For public buildings, the scale of buildings should be reasonably guided according to functional requirements. For commercial buildings, we should pay attention to the rise of the farmhouse industry and prevent the excess of related buildings.

2. Raising energy efficiency standards in buildings

The establishment and effective implementation of building energy efficiency standards will have a significant impact on building energy consumption and carbon emissions. The research results of this paper show that public buildings will still be the building type with the largest proportion of energy consumption and carbon emissions in rural buildings in the future and have great potential for emission reduction. Governments can take the lead in implementing green building standards and demonstrating low-carbon buildings when investing in public buildings. Studies have shown that green building in rural areas can improve energy efficiency and decrease carbon emissions [58,59]. At the same time, we will actively formulate plans for low-carbon building construction, encourage the use of green building materials, high-performance envelope structures and high-efficiency energy-using equipment, and introduce relevant subsidy policies. Existing literature has also shown that financial incentives, construction standards, and policies are the crucial factors influencing building energy conservation [60,61].

3. Increasing the proportion of clean energy

In view of the current rural energy consumption still dominated by coal and LPG, the traditional energy consumption is not sufficient [62,63], which is disadvantageous to carbon emission reduction. The education and popularization of low-carbon knowledge should be strengthened, and villagers should be guided to use high-efficiency and low-emission clean energy to change their way of life. The application of these measures is conducive to reducing carbon emissions [64]. We can increase the supporting supply of renewable and clean energy, such as solar energy, air energy and biomass energy, and adjust the energy supply structure of rural buildings. For example, the construction of natural gas pipelines should be encouraged to replace bottled LPG, and biomass energy conversion technologies, such as biogas power generation, should be considered.

4. Raising residents' awareness of energy conservation

From the perspective of energy conservation behavior, attitudes toward energy conservation and personal cognition are the crucial factors influencing energy use behavior [65–67]. Both the popularization of efficient energy-using equipment and the cultivation of rational energy-using habits require the active participation and cooperation of the general public. It is necessary to strengthen residents' understanding of the necessity, measures and benefits of building energy conservation and emission reduction, and gradually cultivate and improve public awareness of energy conservation. Therefore, the government can organize energy conservation publicity week, low-carbon activity day, green building lectures and other activities to popularize the concept of low-carbon development, scientifically guide low-carbon lifestyles, and promote green energy-saving products and technologies.

4. Conclusions

1. Taking village Y as the research object, the paper analyzes the carbon emission level of rural buildings located in southern China. The building area of village Y is about 121,246 m^2, and the total building carbon emissions were 2755.49 tCO_2 in 2021. The carbon emissions per unit building area were 0.039 $tCO_2/(a \cdot m^2)$ for public buildings, 0.036 $tCO_2/(a \cdot m^2)$ for commercial buildings and 0.012 $tCO_2/(a \cdot m^2)$ for residential buildings, respectively. In the climate of hot summer and cold winter, the lack of thermal insulation measures results in large building energy consumption. The buildings here mainly rely on electricity to provide heating and cooling sources, and the carbon emissions of electricity account for 96.07%. Residential cooking mainly consumes LPG, which produces carbon emissions of 73.16 tCO_2.
2. The per capita building area, energy intensity of building area and population size have a positive driving effect on building carbon emissions in village Y. The per capita building area effect has the largest promoting effect on carbon emissions, with its contribution value and contribution degree reaching 1370.69 tCO_2 and 70.13%, respectively. Population structure and comprehensive carbon emission factors have a negative driving effect.
3. In the baseline scenario, medium constraint scenario and high constraint scenario, the building carbon emissions in village Y during 2021–2060 showed a trend of increasing first and then decreasing. Under the three scenarios, the predicted values of building carbon emissions in village Y in 2030 are 5331.45 tCO_2, 5067.04 tCO_2 and 4908.04 tCO_2, respectively. The predicted values of building carbon emissions in village Y in 2060 are 4701.71 tCO_2, 4465.74 tCO_2 and 4298.27 tCO_2, respectively. This indicates that the control of building area growth scale and energy structure under the medium high

constraint scenario will be conducive to energy conservation and emission reduction in the rural building field.

4. The situation of village Y reflects the lack of thermal insulation systems in the envelope of rural buildings and the lack of awareness of equipment management and maintenance among residents. The low-carbon development path of rural buildings can be further explored by strengthening the planning and management of energy conservation in rural construction, adjusting the energy structure and the proportion of clean energy application, and improving the public's awareness of energy conservation.

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