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ENERGY PRODUCTION AND CARBON EMISSION ANALYSIS ON THE INSTALLATION OF RPPG TO ACHIEVE LOW-CARBON TRANSFORMATION IN RURAL RESIDENCES OF WEIZHOU ISLAND, SOUTHERN CHINA

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Abstract

Studies have revealed that buildings consume a significant amount of energy, with approximately 40% of total energy consumption being attributed to them. Rural residential buildings are responsible for roughly 23% of China's overall building energy consumption. Therefore, reducing energy consumption and carbon emissions from rural residential buildings is crucial in achieving the Chinese government's "carbon peak" and "carbon neutral" goals to combat global climate change and establish a new ecological balance. Case studies conducted in certain cities with high solar radiation have shown that installing rooftop photovoltaic power generation (RPPG) in urban residential areas has a noticeable effect on energy conservation and emission reduction of buildings. It is worth exploring whether RPPG can contribute to energy conservation and emission reduction in rural residential buildings, particularly on Weizhou Island, which faces energy shortages and has a fragile ecosystem. The article focused on studying the energy consumption of commonly found 2-story and 3-story rural residential houses on Weizhou Island. Using GBSWARE software, the energy consumption of these houses before and after installing RPPG was simulated and analysed. The results showed that installing RPPG could meet the building's energy consumption needs and provide additional electricity. Installing RPPG could reduce CO_2 emissions by 240,000 kg and 26,000 kg, respectively, over the 10-year service life of the RPPG. Installing RPPG on flat and pitched roofs could result in economic benefits of approximately 42,000 RMB and 59,000 RMB, respectively. The cost of installing RPPG on flat and pitched roofs could be recovered in the sixth and fifth years. The study concluded that installing RPPG in rural residences on Weizhou Island is a practical and effective path towards low-carbon transformation. This finding could support implementing RPPG in existing rural housing and serve as a reference for designing new buildings with low-carbon standards.

Keywords: GBSWARE software, Low-carbon transformation, Rooftop photovoltaic power generation (RPPG), Rural residence.

1. Introduction

1.1. Global carbon reduction and rural residences energy consumption and carbon emissions in China

Climate change is a significant challenge for sustainable development in the 21st century and affects the global community's shared future. To combat this issue, the United Nations Framework Convention on Climate Change has proposed a 50% reduction in global greenhouse gas emissions by 2050 [1]. Countries set their emission reduction targets before 2030 through NDC based on their specific national conditions and capabilities [2]. As the world's largest CO_2 emitter, China has established a national strategy to deal with climate change and aims to achieve a "carbon peak" by 2030 and "carbon neutrality" by 2060 [3]. Buildings are responsible for over 40% of global energy consumption, with their greenhouse gas emissions accounting for one-third of global energy consumption, according to the building energy consumption monitoring data platform [4]. Residential buildings contribute to over 60% of total energy consumption, making them significant energy users and a crucial focus of research worldwide in reducing energy consumption and carbon emissions.

Buildings are responsible for approximately 40% of global energy consumption and 36% of associated CO_2 emissions [5], significantly contributing to climate change in developed and developing countries. In China, the carbon emissions from the construction sector were estimated to be around 2.2 billion tons of CO_2 in 2019 [6], with rural residential buildings accounting for 23%, public buildings accounting for 30%, northern heating accounting for 26%, and urban residential buildings accounting for 21% [7]. The intensity of annual carbon emission per unit floor area is higher in rural residential buildings, at 23kg CO_2/m^2, compared to urban residential buildings, at 16kg CO_2/m^2 [8]. Studies have also found that the carbon emissions of residential buildings are 1.5-2.2 times higher than other non-residential buildings [9], emphasising the importance of reducing energy consumption and carbon emissions in rural residential buildings to achieve China's "carbon neutral" and "carbon peak" goals.

The building sector is a major contributor to global energy consumption and carbon emissions. China has set ambitious goals of achieving carbon peak and neutrality by 2030 and 2060, respectively [10]. Renewable energy sources such as wind, solar, and hydrogen are expected to achieve these goals significantly. However, the lack of data on building energy consumption and emissions across different regions in China poses a challenge to tracking progress towards these goals [11]. Therefore, research on building energy consumption and carbon emissions in different regions is necessary. It is essential to accurately assess the potential of photovoltaic power generation in the building sector [12], as this can contribute significantly to reducing carbon emissions and achieving carbon neutrality.

As more countries strive to achieve carbon neutrality by mid-century to combat global climate change, they increasingly turn to clean energy sources to reduce CO_2 emissions [13]. Studies have shown that installing roof-mounted residential photovoltaic power generators (RPPG) in areas with ample sunlight can effectively conserve energy, reduce emissions, and be economically feasible in regions such as humid and hot climates, as well as in the central and northern parts of Africa, Poland, and other areas [14-17]. However, further research is needed to determine the potential energy conservation and emission reduction benefits of installing RPPG on Weizhou Island in southern China. If deemed feasible, this could help alleviate electricity shortages, reduce carbon emissions, and support the ecological development of the island by not occupying additional land.

1.2. Climate and solar radiation on Weizhou Island

Weizhou Island is situated in the Beibu Gulf in the southern region of China, with coordinates ranging from 20°54'- 21°10' N and 109°00-109°15 'E, covering a total area of 24.74 square kilometres. Weizhou Island has a tropical marine monsoon climate, which is warm and humid, with an average annual temperature of 22.6 ℃ (as indicated in Table 1) [18]. The island is abundant in solar energy resources, with an average total solar radiation of 4395 ($MJ/m^2/a$), reaching up to 5642 ($MJ/m^2/a$) [19, 20]. Based on the solar energy resource classification table (as displayed in Table 2), Weizhou Island falls under the category of resource-rich-richer level, making it suitable for photovoltaic power generation [21].

Table 1. The monthly temperature in Weizhou Island [18].

Item \ Month	1	2	3	4	5	6	7	8	9	10	11	12	annual
Average temperature (℃)	15.0	15.6	18.1	22.0	25.4	26.7	28.2	28.0	27.0	24.4	21.3	17.9	22.6
Average maximum temperature (℃)	18.1	18.3	22.1	25.2	28.0	30.1	30.7	30.6	30.5	28.7	25.0	22.1	25.7
Average minimum temperature (℃)	13.0	13.4	17.0	20.6	22.8	26.0	26.7	25.9	25.1	22.5	18.8	15.2	20.6

Table 2. Classification of solar radiation level [21].

Level	Richest	Richer	Rich	General
Annual solar radiation (MJ/m^2)	≥6300	5040～6300	3780～5040	<3780

1.3. Energy in Weizhou Island

Weizhou Island is facing an energy shortage as it lacks a connection to the mainland and can only rely on a thermal power plant for electricity. This issue is particularly acute during the summer and tourist season when hotel and guesthouse power consumption increases significantly [19]. The development plan for Weizhou Island prioritises ecological preservation, so finding sustainable solutions to the energy problem is crucial. As a clean and environmentally friendly energy source, solar photovoltaic power generation could potentially address the island's electricity shortage. However, its feasibility must be evaluated quantitatively before making a final decision.

2. Research Method

2.1. Software simulation method

The GBSWARE software is a Chinese-language energy consumption analysis software recognised by the Ministry of Construction of China. Its calculation principle is similar to DOE-2, which the National Laboratory of the United States developed. Currently, the energy consumption calculation results of GBSWARE are similar to those of DOE-2 [22]. The 2022 version of GBSWARE was used to conduct an energy consumption simulation analysis, quantify the energy conservation and emission reduction of RPPG, and determine whether it is feasible to use RPPG for the low-carbon transformation of rural buildings in Weizhou Island. Before conducting the software calculation, parameters such as building materials, floor height, number of floors, building area, and sunshade must be set based on the weather conditions of Weizhou Island, such as sunshine. After the parameters are set, the software can calculate the energy consumption and carbon reduction with and without the installed RPPG.

2.2. Selection of study cases

According to the land law of China and the Administrative Measures for the Approval of Rural Homesteads in Guangxi (2013) [23], the size of rural villagers' homesteads in plain areas and urban suburbs should not exceed 100 square meters per household. Weizhou Island falls under plain areas and urban suburbs, so the residential buildings selected for this study occupy an area of 100 square meters. According to the technical regulations on urban and rural planning management of Beihai City and the village planning guidelines of Weizhou Island, newly built residential buildings in the village cannot exceed 3 floors and a total construction area of 450 m^2. Currently, more than 90% of the completed and newly built residences are 2-story and 3-story houses with flat roofs or pitched roofs (as shown in Fig. 1), so these types of buildings were selected for the study.

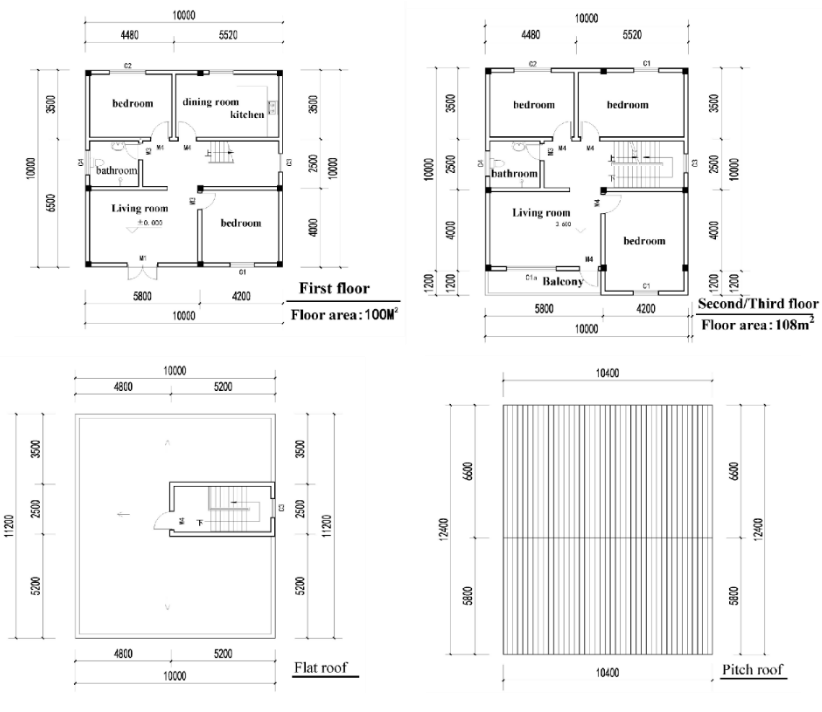

Fig. 1. Plan of each floor of the study cases (2-story and 3-story).

2.3. Parameters of study cases

Currently, most of the rural housing units on Weizhou Island consist of 2-3 story brick and concrete structures with a southwest orientation. The first floor has a height of 3.3 meters, while the second and third floors have a height of 3.0 meters. The materials used to construct the study cases are presented in Table 3. The climate on the island is generally hot from June to September, and air conditioning is used to enhance thermal comfort once the temperature rises above 26 ℃. Wall-mounted air conditioners are installed in bedrooms, while vertical air conditioners are installed in the living room and dining areas. The air conditioner in the bedroom is used for an average of 12 hours per day, while the living and dining room air conditioner is used for an average of 3 hours per day. Heating is not needed during any part of the year based on the local living customs.

Table 3. Building materials.

Item	Material and Construction
Wall	Hollow brick masonry, cement mortar plastering, levelling and white coating. The thickness is 240mm.
Roof	Cast-in-situ reinforced concrete, thickness: 110mm
Door	Solid wood door, thickness: 10mm
Window	Ordinary double glass, 1.5mm thick glass
Sunshade	The jumping part on the second floor is horizontal shading

According to the current statistics and calculations [24], 1 kWh of electricity equals 0.785kg of carbon emissions. For each 1 kWh of electricity saved, 0.4 kg of standard coal will be saved, and 0.272 kg of carbon and 0.785 kg of CO_2 will be reduced.

2.4. Selection of RPPG capacity

The flat and sloping roofs of 2-story and 3-story buildings in the study cases have different areas suitable for installing PV panels. The flat roof can accommodate 112m2panels, while the sloping roof can fit 132m^2. A market survey shows that household RPPG with capacities of 3KW, 5KW, 10KW, and 15KW are available in China, with their respective power generation capacities and costs listed in Table 4. Based on the area requirements and panel installation capabilities outlined in Table 4, the study building’s roof is best suited for a grid connected RPPG with an installed capacity of 10KW. This system has a power generation parameter per unit area of 0.2, a photovoltaic system efficiency of 0.8, a photovoltaic cell performance attenuation correction coefficient of 0.9, and a service life of 10 years as per design specifications.

Table 4. Household RPPG with different capacities.

Generation capacity	Supporting solar photovoltaic panel area(m^2)	Annual energy output (kWh)	Equipment purchases and installation costs (RMB)
3KW	30-50	4500	18600
5KW	50-70	7500	39800
10KW	100-120	15000	61500
15W	150-180	22500	92500

2.5. Criteria for the feasibility of RPPG

The cost-efficiency ratio is used as a criterion to determine whether installing a solar photovoltaic system on the roof for low-carbon transformation is economically viable. To simplify calculations, the following settings were made.

- The cost of installing the solar RPPG is represented as FI (in RMB), the power generation during the service life of the solar photovoltaic panel is EPV (in kW), the power generation is converted into the currency value of the same unit as the installed RPPG, represented as FPV. The local electricity price at that time is Pi (in RMB/kW).
- The carbon emissions reduced by using solar power generation are represented as Ce, the price of carbon trading as Pc, and the benefits of reducing carbon emissions as Fc. The cost-efficiency ratio of installing RPPG is F. The equation used to calculate F is F=FPV+Fc-FI. If F is greater than or equal to 0 and Ce is greater than or equal to 0, then the carbon reduction scheme of RPPG is feasible. On the other hand, if F is less than 0 and Ce is less than 0, then the carbon reduction scheme of roof photovoltaic power generation is not feasible.

3. Results and Discussion

3.1. RPPG effect and building energy consumption

The study building had an RPPG installed, and GBSWARE software was used to calculate the average annual power generation for the flat and sloping roofs, which were found to be 15238.5 kWh and 17905 kWh, respectively. Based on the 10-year design service life of the RPPG, the total power generation capacity for flat and sloping roofs is 152385 kWh and 179050 kWh, respectively (as shown in Table 5). If we calculate the power generation in terms of currency value using the electricity price of 0.59 RMB/kWh, 8990.715 RMB and 10563.950 RMB can be saved each year, respectively. Over the entire life cycle of the photovoltaic system, the electricity bill savings amount to 89907.15 RMB and 105639.5 RMB for the flat and sloping roofs, respectively.

Table 5. The capacity of RPPG.

Building	Area of installable photovoltaic panel (m^2)	Power generation parameters per unit area	Efficiency of photovoltaic power generation system	PV cell performance attenuation correction coefficient	Annual energy output (kWh)
2-story flat roof	120	0.2	0.8	0.9	15238.5
2-story pitched roof	141	0.2	0.8	0.9	17905
3-story flat roof	120	0.2	0.8	0.9	15238.5
3-story pitched roof	141	0.2	0.8	0.9	17905

The information from sections 2.2 and 2.3 was entered into the GBSWARE software to calculate the annual energy consumption of the building. The results are shown in Table 6. The 3-story pitched roof building has the highest annual energy consumption of 9558.00 kWh, while the 2-story pitched roof building with

RPPG has the lowest at 8781.04 kWh. The lowest energy consumption per unit area of the building is 27.04 KJ/m^2 in the 3-story pitched roof building with RPPG, and the highest is 44.62 KJ/m^2 in the 2-story flat roof building.

Table 6. Building energy consumption of the study cases.

Building	Built-up area (m^2)	Energy consumption per unit building area (KJ/m^2.Y)	Annual building energy consumption (kWh.Y)
2-story flat roof	212	44.62	9459.44
2-story flat roof with RPPG	212	41.42	8781.04
2-story pitched roof	212	44.54	9442.48
2-story pitched roof with RPPG	212	40.79	8647.48
3-story flat roof	324	29.53	9567.72
3-story flat roof with RPPG	324	27.42	8884.08
3-story pitched roof	324	29.50	9558.00
3-story pitched roof with RPPG	324	27.04	8760.96

3.2. Carbon reduction effect of installing RPPG

Since the energy consumption of buildings and RPPG are calculated by electricity, it is necessary to convert the reduced power generation into carbon emissions (CO_2 emissions). According to Weak current industry network (2022), 1 kWh is equivalent to 0.785kg of CO_2 emissions [19], the carbon emissions are equal to the sum of photovoltaic power generation and building energy consumption multiplied by 0.785, and the carbon emissions that can be reduced can be calculated.

According to the calculations presented in Table 7, the installation of RPPG has the potential to significantly reduce CO_2 emissions in both 2-story flat roofs and pitched roofs. Specifically, the use of RPPG can result in annual CO_2 emission reductions of 11,962.23 kg and 14,055.43 kg for the 2-story flat roof and pitched roof, respectively. Furthermore, apart from the energy consumption for the building itself, there are additional surplus emissions of 5,069.11 kg and 7,267.15 kg of CO_2 annually, which can be utilized to offset carbon emissions elsewhere. Similarly, for a 3-story flat roof and a pitched roof, the installation of RPPG can lead to yearly reductions of 11,962.23 kg and 14,055.43 kg in CO_2 emissions, respectively.

In addition to the energy consumption of the building itself, there are 4988.22 kg and 7178.07 kg of CO_2 surplus that can be used to balance the carbon emissions of other places each year（as shown in Table. 7）. Since the total annual energy consumption of the 2-story building is less than that of the 3-story building, the remaining electricity of RPPG installed in the 2-story building is relatively large, and the carbon emissions can be used to balance other places are also relatively large. The 2-story flat roof and pitched roof are 80.89kg and 89.08kg more than the 3-story flat roof and pitched roof, respectively.

Table 7. Carbon emissions of the study cases.

Building	Annual building energy consumption (kWh.Y)	Annual energy output (kWh)	Annual surplus power generation (kWh)	Annual CO_2 emission of building energy consumption (kg)	Total annual CO_2 emission can be reduced (kg)	Annual CO_2 emissions that can be traded (kg)	Total CO_2 emission reduced in 10 years (kg)
2-story flat roof	9459.44	——	——	7425.66	——	——	
2-story flat roof with RPPG	8781.04	15238.5	6457.46	6893.12	11962.22	5069.11	240195.4
2-story pitched roof	9442.48	——	——	7412.35	——	——	
2-story pitched roof with RPPG	8647.48	17905.0	9257.52	6788.27	14055.43	7267.15	265524.8
3-story flat roof	9567.72	——	——	7510.66	——	——	
3-story flat roof with RPPG	8884.08	15238.5	6354.42	6974.00	11962.22	4988.22	241225.8
3-story pitched roof	9558.00	——	——	7503.03	——	——	
3-story pitched roof with RPPG	8760.96	17905.0	9144.04	6877.35	14055.43	7178.07	266659.6

3.3. Cost-effectiveness ratio

The cost-effectiveness of installing RPPG on roofs was evaluated for all scenarios using the formula F = FPV + Fc - FI described in section 2.4 and substituting the data from Tables 3 to 6. The results are presented in Table 8.

The cost-efficiency ratio for RPPG on the flat roof and sloping roof of the 2-story building was 42098.15 RMB and 59274.5 RMB, respectively. Similarly, for the 3-story building, the cost-efficiency ratio for RPPG on the flat and sloping roofs was 42157.15 RMB and 59339.5 RMB, respectively. It can be concluded that for buildings with the same number of floors, the cost-efficiency ratio of the RPPG installed on the sloping roof is significantly higher than that installed on the flat roof. In the second and third-floor buildings, the difference between the cost and efficiency ratio of installing RPPG on the flat roof and the sloping roof is about 17176.35 RMB and 17182.35 RMB, respectively, in 10 years. In other words, for buildings with the same number of floors, the income from installing RPPG on the sloping roof is about 1700 RMB per year, more than that on the flat roof.(kWh)

Table 8. Cost efficiency ratio of study buildings.

Building	Annual energy output (kWh)	Monetary value of PV power generation in10 years	Total CO_2 emissions can be reduced in 10 years (kg)	Monetary value of Total CO_2 emissions reduced +in 10 years	Installation cost of RPPG (RMB)	Cost efficiency ratio
2-story flat roof	——			——	——	
2-story flat roof with RPPG	15238.5	89907.15	240195.40	13691	61500	42098.15
2-story pitched roof	——			——		
2-story pitched roof with RPPG	17905	105639.5	265524.8	15135	61500	59274.5
3-story flat roof	——			——		
3-story flat roof with RPPG	15238.5	89907.15	241225.8	13750	61500	42157.15
3-story pitched roof	——			——		
3-story pitched roof with RPPG	17905	105639.5	266659.6	15200	61500	59339.5

3.4. Discussion

The results of the study are consistent with the view of Qiu et al. [12], Dehwah et al. [14], Alrawi et al. [15], Gernaat et al. [16], and Jurasz [17] stated above. The installation of RPPG on residential building roofs in Weizhou Island has proven effective in meeting daily electricity needs and providing additional benefits to residents.

These positive outcomes suggest that implementing low-carbon or even zero-carbon transformations in similar buildings is feasible. However, it should be noted that this conclusion was drawn based on the study case buildings alone. To fully understand the potential impact of RPPG on Weizhou Island, it is necessary to determine how many roofs on the entire island can be installed with RPPG, what the electricity production potential of RPPG is, and whether it can meet the power demand of the entire island. Such information would be of great significance for the low-carbon transformation, economic development, and ecological construction of Weizhou Island and should be studied in further detail. The development and ecological construction of Weizhou Island should be studied in further detail.

4. Conclusion

Based on the software simulation results, it can be concluded that installing RPPG on 2-story and 3-story rural residential buildings on flat and sloping roofs has a positive cost-efficiency ratio. Specifically, the cost-efficiency ratio of RPPG installed on the flat and sloping roofs of 2-story buildings is 42098.15 RMB and 59274.5 RMB, respectively, with a difference of 17176.35 RMB. Similarly, for 3-story buildings, the cost-efficiency ratio for RPPG installed on flat and sloping roofs are 42157.15 RMB and 59339.5 RMB, respectively, with a difference of 17182.35 RMB. This suggests that installing RPPG on 2 or 3-story buildings with flat or sloping roofs can generate economic benefits over its 10-year service cycle, with potential savings of around 42000 RMB and 59000 RMB for flat and sloping roofs, respectively. Therefore, it can be concluded that installing RPPG on roofs is a viable low-carbon transformation strategy.

Based on the data presented in Table 7, it can be inferred that the installation of RPPG on the roof of a 2-story building can yield an annual income of 10,359.82 RMB on a flat roof and 12,077.45 RMB on a sloping roof, including both power generation currency value and carbon neutral income. The cost of purchasing the RPPG system can be recovered in approximately 6 years on a flat roof and 5 years on a sloping roof. For a 3-story building, installing RPPG can yield an annual income of 10,365.72RMB on a flat roof and 12,083.95 RMB on a sloping roof, with a cost recovery period of approximately 6 years on a flat roof and 5 years on a sloping roof. These results indicate that installing RPPG on roofs of 2 or 3-story buildings is a feasible and cost-effective low-carbon transformation method.

5. Recommendation

Installing photovoltaic power generation systems on residential buildings' rooftops in Weizhou Island can significantly reduce carbon emissions and contribute to Weizhou Island's development as an eco-tourism destination. Moreover, it can help address the current power shortage. To enhance the benefits of photovoltaic power generation, efforts should be made to improve its efficiency, promote its use, and encourage villagers to install it. The government should also increase awareness and conduct surveys to understand villagers' willingness to install photovoltaic systems and introduce incentive policies to promote their use. While the study focused on the most common rural building types, other building types exist in Guangxi and China, and further research is needed to determine the suitable areas and conditions for installing rooftop photovoltaic systems to achieve low-carbon transformation.

If there is a limited budget for installing photovoltaic power generation and it is not possible to integrate the power generation into the grid, installing a 5KW photovoltaic power generation system for each household is recommended. This will ensure sufficient use without causing any waste. Since there is currently no cable connection between Weizhou Island and the mainland, any excess electricity generated from rooftop photovoltaic power generation will mainly be consumed on the island, in addition to the user's consumption. Selling excess electricity to nearby hotels that consume more power is a viable option. Additionally, using electric vehicles and ships powered by excess energy is recommended to store the energy.

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