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Historic Building Renovation with Solar System towards Zero-Energy Consumption: Feasibility Analysis and Case Optimization Practice in China

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Abstract: This paper aims to study the required solar panel tilt angle, area, and investment payback period for achieving zero-energy heating in historically significant courtyard-style residential buildings. The retrofitting approach involves positioning solar panels on the main building of the structure using four supports, each located at the corners, elevated from the ground and not in direct contact with the building. This approach does not alter the external envelope structure of the building, thereby preserving the authenticity of the cultural heritage. Using BESI software, we simulated the heating energy demand of the sample building. We integrated a solar heating system within the building and analyzed the optimal solar panel layout area, installation angle, and payback period for achieving zero-energy heating. This allowed the building to meet the zero-energy heating requirements. Taking the Hu Family Courtyard heritage conservation building as an example, we proposed the optimal layout plan for solar energy retrofitting.

Keywords: traditional building; solar energy; renovation; zero energy consumption; feasibility analysis

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1. Introduction

The process of urbanization has presented numerous challenges in the maintenance and development of traditional village heritage architecture. The coexistence of urban lifestyle and the preservation of ancestral architecture has become increasingly contradictory, necessitating the alignment of architectural heritage preservation with the demands of modernization [1–3]. To promote global sustainability and reduce energy consumption, countries worldwide are actively advocating and constructing nearly zero-energy buildings [4]. Currently, software is being used to analyze the carbon dioxide emissions before and after the implementation of solar energy systems in buildings. By installing renewable energy systems and harnessing renewable energy sources within buildings, traditional structures can decrease the combustion of fossil fuels, thereby reducing carbon dioxide emissions. This has been proven to be an effective measure for the retrofitting of traditional buildings [5,6].

The western region of Sichuan is located in a remote area with relatively limited traditional energy supply, making the development of solar energy crucial for energy security. The utilization of solar energy can alleviate local energy demands and provide robust support for the sustainable development of western Sichuan [7]. Furthermore, the western Sichuan region boasts high altitudes, significant diurnal temperature variations, and consistently low annual temperatures, making it rich in solar energy resources [8]. The traditional residences in this area typically feature wooden structures and sloped roofs, offering favorable conditions for the installation of solar water heaters, photovoltaic panels, and similar equipment. Solar energy not only meets household water heating requirements but also exhibits excellent heating and energy-saving effects.

Recently, researchers have successfully integrated conservative restoration and renewable technologies to transform historic buildings into nearly zero-energy buildings (NZEBs). Furthermore, Becchio et al. [9] addressed building and technical system solutions aimed at achieving NZEB targets and conducted a study on cost optimality. These studies collectively emphasize the potential role of solar energy in the sustainable transformation of traditional heritage conservation buildings. Recent studies have explored the intersection of traditional heritage conservation buildings with solar energy, low-carbon transformation, and near-zero-energy consumption. These studies highlight the potential for sustainable energy solutions in traditional buildings and emphasize the importance of careful planning and consideration of heritage values. Among them, Abrahamsen et al. [10] emphasizes the importance of considering the environmental impact of solar photovoltaic panels in the process of achieving NZEB standards. Lucchi [11] focuses on the need for clear rules and heritage-compatible technologies when applying renewable energy in architectural heritage. Jiang et al. [12] provides an example of a high-, medium-, and low-carbon transformation strategy, which includes the use of solar energy. Ramaneti et al. studied the problem of tilt angle optimization for solar panels [13]. Ninsawat et al. have analyzed the area and economics of solar panels [14]. Li et al. provide a comprehensive review of policies, technologies, and assessment methods for low-carbon buildings and communities, stressing the necessity of considering overall approaches that take into account economic, technical, environmental, and social benefits [15]. These studies highlight the key strategic role of integrating solar energy into traditional heritage conservation buildings for achieving low-carbon transformation and near-zero-energy consumption.

Chinese researchers have conducted in-depth research on the potential and challenges of integrating renewable energy into buildings. By comprehensively analyzing renewable energy in buildings, researchers have revealed its tremendous potential in reducing energy consumption and carbon emissions [16]. Although the application of renewable energy faces challenges in certain regions, these issues can be addressed through improved calculation methods, local design, and integrated renewable energy systems [17]. The studies by [18,19] emphasize the importance of achieving low-carbon buildings, with [19] specifically highlighting the role of solar power, ground source heat pump technology, and energy management systems. Tan et al. [20] discuss the suitability of different renewable energy sources in buildings, while Zhang et al. [21] predict the potential energy consumption substitution and the share of renewable energy in building energy consumption. Zhang et al. [22] further emphasizes China's rich and stable solar energy resources, using Xinjiang as an example of an optimal location. M. Shi et al. investigated a laboratory field-of-view inclination measurement system for a vibration monitoring device based on photovoltaic panel structures [23]; Zhao et al. analyzed solar panel area [24]; and Wang et al. analyzed the economics of air conditioning in the context of PV [25]. These studies together emphasize the current research status of solar energy in China's construction industry.

While existing research has offered numerous methods and approaches for the preservation of traditional heritage buildings, studies focusing on the utilization of renewable energy for the transformation of heritage preservation structures remain relatively limited, particularly within the context of China. Furthermore, such research often emphasizes the modernization of these buildings through passive or active means, sometimes neglecting the considerations of usage requirements, optimal solar panel area, optimal solar panel installation angles, and associated economic factors during the renovation process. How can solar panels be strategically positioned in building renovations to achieve both optimal functionality and cost-effectiveness?

Due to the majority of residences in Kejia Lane, Huili Ancient Town being in the form of traditional courtyard houses with adobe and wooden structures, the primary building materials consist of earth, wood, stone, bamboo, bricks, and tiles. Many of these houses are constructed with a column-reducing method on a pier-and-beam foundation, allowing for increased interior space. The roof pitch is approximately 25 degrees, and most residences feature front porches and eaves, with eaves extending about 0.5 m. The roofing is uniformly covered with gray-blue tiles, and the roof structure is relatively simple, with tiles directly laid on wooden beams. The doors and windows are made of wood, and the flooring is constructed using brick and stone materials. Drainage is designed with houses facing north and south, with water flowing towards the lower end, and drainage channels are typically installed beneath the south-facing eaves [26]. Based on these distinctive characteristics and field surveys, we chose the Hu Family Compound as a representative case for solar energy utilization and economic analysis. In the Regulations for the Protection of the Historical and Cultural City of Huili, Liangshan Yi Autonomous Prefecture [27], it is stated that ancient dwellings, historic buildings, and architectural components such as doors, windows, plaques, tablets, and lintels within the Huili Historical and Cultural City Protection Zone shall not be dismantled without authorization. Furthermore, any modifications or renovations to historical buildings that would affect the historical appearance and traditional layout are prohibited. Therefore, we have chosen to install solar panels using ground supports to ensure they do not come into direct contact with the buildings.

In order to provide preliminary answers to the above academic questions, this paper takes the typical case of the Hu Family Compound located in Kejia Lane of Huili Ancient City, Huili County, Sichuan Province, China, as an example (Figure 1). Through software simulations and mathematical calculations, it determines the optimal installation angles, installation areas, and investment payback period during zero-energy consumption for heating. The objective is to address the conflict between the preservation of traditional heritage buildings and the demands of modern development.

Figure 1. Status of the Hu Family Compound site.

2. Materials and Methods

2.1. Building Parameter Settings

This study, based on the relevant literature regarding the Hu Family Compound [28], utilized AutoCAD software (2023) to construct an architectural model of the Hu Family Compound (Figure 2). Subsequently, this model was imported into the BESI (Building Energy Simulation, 2023) software within the Swire Green Building Simulation Suite for energy consumption simulation. The chosen geographical location for the simulation was Huili County in the Liangshan Yi Autonomous Prefecture, Sichuan Province, China, and relevant meteorological parameters were incorporated. The primary objective of this simulation was to calculate the building's heating demand energy consumption. The Simplified Correction Factor Method was employed to set the average heat transfer coefficient. The key parameters of the specific building model are shown in Table 1.

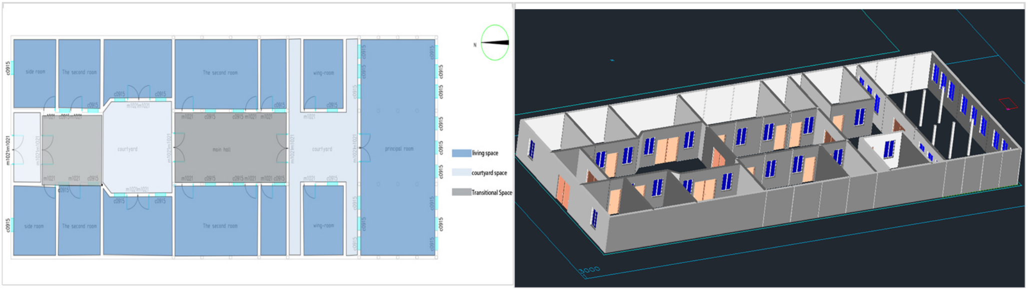


Figure 2. Model drawing of the Hu Family Compound.

Table 1. Building model parameterization.

Category	Detail
Total floor area	458 square meters (15.1 m^2·37.1 m^2)
Building height	3 m
Window-to-wall ratio	0.047
Building orientation	North–south orientation
Cooling period	2 May to 24 September
Angle of dip of roof	30°
Door and window opening method	Half-open

Throughout the simulation process, we considered these parameters and utilized the BESI tool to calculate the annual energy consumption of Hu Family Compound. This analysis aims to provide valuable insights into energy efficiency and sustainability in building management. The details of the structure and parameters of the building are shown in Table 2.

Table 2. Architectural modeling material setup.

(**a**) Building structural materials

Architectural parts	Structural measures
Wall construction	Adobe and cement mortar
Flooring	Wooden floorboards
Courtyard ground	Paved with asphalt slate
Roofing	Chinese-style tile
Doors and windows	Single-layer solid wood

(**b**) Nature of materials

Material Name	Thermal Conductivity Coefficient	Heat Storage Coefficient	Density	Specific Heat	Steam Penetration Coefficient	Thermal Inertia Index	Solar Heat Gain Coefficient
	W/(m·K)	W/(m^2·K)	kg/m^3	J/(kg·K)	g/(mh·kPa)		
Dry wooden boards	0.058	1.627	250.0	2510.0	0.000		
Plain soil	1.160	13.054	2000.0	1010.0	0.000		
Asphalt Slate	0.087	1.821	380.0	1380.0	0.000		
Chinese-style tile	0.930	10.583	1800.0	920.0	0.004		
Cement mortar	0.930	11.306	1800.0	1050.0	0.043		
Single-layer solid wood exterior doors		1.972				1.375	0.435
Single-layer wooden windows		4.7				1.375	0.566

2.2. Simulation of Solar Panel Parameters

Optimal mounting angle for solar panels: In this study, hourly solar radiation data from the DeST software (h) were utilized as a reference. The optimal installation angle of solar panels was calculated by Formulas (1)–(4), where H_T is the total radiation, W/m^2; H_{bT}

is the direct radiation, W/m^2; H_{dT} is the sky-scattered radiation, W/m^2; H_{rT} is the ground reflection radiation, W/m^2, H_{DN} is the normal radiation intensity, W/m^2; ε is the solar panel collector inclination; β is the solar azimuth; α is the solar azimuth angle; A is the solar panel collector azimuth; Hd is the scattered radiation intensity in the sky, W/m^2; ρ is the ground reflection coefficient; and H is the horizontal total radiation intensity, W/m^2. The chosen location for analysis was Huili County in Sichuan, with coordinates at a longitude of 100.27° and a latitude of 29.99°. The selected azimuth range encompassed −65° to 65°, covering east to west orientations. In terms of tilt angles, values from 0° to 90° (representing horizontal to vertical orientations) were considered. By exploring various combinations of tilt angles and azimuths, this study aimed to ascertain the patterns of solar energy capture in response to changes in installation angles. Subsequently, through optimization techniques, the optimal installation angles for the solar panels at Hu's Residence were determined. This analysis aimed to mitigate the impact of solar panel angles on both installation area requirements and investment payback periods.

$$H_T = H_{bT} + H_{dT} + H_{rT} \tag{1}$$

$$H_{bT} = H_{DN} \cdot (cos\varepsilon \cdot sin\beta + sin\varepsilon \cdot cos(A - \alpha)) \tag{2}$$

$$H_{dT} = H_d \cdot (1 + cos\varepsilon)/2 \tag{3}$$

$$H_{rT} = \rho \cdot H \cdot \left(1 - cos^2\varepsilon\right)/2 \tag{4}$$

Conversion and loss rates of solar panels: This study employs a novel ceramic-aluminum composite solar panel, which is composed primarily of aluminum alloy substrate, flow-collecting pipes, and a nanostructured absorptive coating. The main materials used in its development include black ceramic powder and a corrosion-resistant aluminum alloy. This solar panel exhibits an exceptional thermal conductivity efficiency of 0.98, a collector efficiency of 43.6%, and a sunlight absorption rate of 0.96% on its surface [29] The conversion efficiency is shown schematically in (Figure 3). With its high conversion rate and low loss rate, this solar panel is exceptionally well suited for use in heritage buildings.

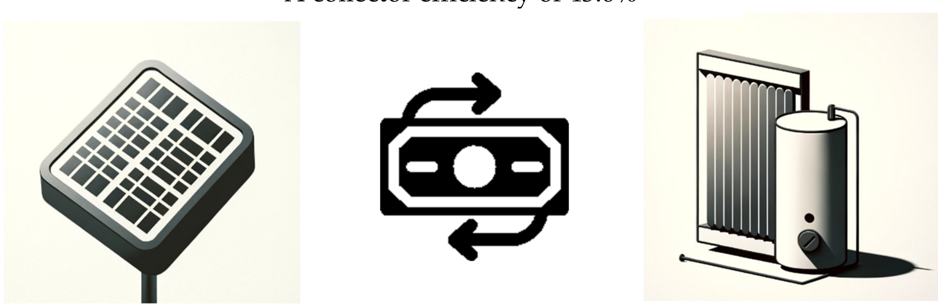


Figure 3. Solar panel conversion efficiency.

The optimal laying area for solar panels: H_0 in Formula (5) represents the monthly average solar radiation, and H_{11}–H_3 represent the solar radiation from November to March in KJ/m^2. Formula (6) represents the daily average solar radiation from November to March, also measured in KJ/m^2. Meanwhile, Formula (7) serves as the formula for calculating the heating energy consumption of the solar panels. In this equation, "E" denotes the energy produced by the solar panel in kWh; "H_W" denotes the average daily solar radiation in KJ/m^2; "S" denotes the area covered by the solar panel in m^2; "d" denotes the number of days that the solar panel has been in operation in d; "η" denotes the conversion efficiency of the solar panel in %; and "T" denotes the conversion loss rate of the solar panel in %. The optimal area for laying out the solar panels, ensuring minimal energy consumption for heating while achieving nearly zero-energy consumption, can be determined using the following equations.

$$H_0 = (H_{11} + H_{12} + H_1 + H_2 + H_3)/5 \quad (5)$$

$$H_W = H_0/30 \quad (6)$$

$$E = H{\cdot}S{\cdot}d{\cdot}\eta{\cdot}(1 - T)/3600 \quad (7)$$

Installation position of solar panels: Due to the utilization of the local sunlight conditions within the Huili region, the Hu Family Compound benefits from a significant amount of sunshine, totaling 2421.5 h per year. This abundance of sunlight is advantageous for the compound, particularly in the two courtyards located within the premises. Furthermore, the surrounding buildings in Kejia Lane are of the one-story courtyard type, resulting in minimal shading from adjacent structures. And the personnel mainly move around the main house. Considering these circumstances, a small area for laying solar panels was planned on the roof of the main house of the Hu Family Compound, which is about 115 square meters (Figure 4). By optimizing the utilization of these limited spaces, it is possible to maintain a regular cycle of operation for the split solar water heating system. This system will be located outside the main house in the courtyard, with an air layer established above the ground to accommodate the placement of heat-conducting mate-rials. The residual heat from the water in the solar panels will flow into the heat-conducting layer through gravity, thereby heating the indoor floor and enhancing the indoor thermal comfort. The functioning of this system involves the receipt of solar radiation by the solar panels and the placement of temperature sensors on the solar collector panels to observe variations in solar thermal energy. The liquid contained within the reservoir undergoes heating, while the variations in temperature are continuously observed by temperature sensors that are positioned within the reservoir. To guarantee the efficient flow and preservation of heat within the system, a safety valve is incorporated into the connecting pipeline, and a pressure relief valve is located within the reservoir. The bottom of the building is constructed as a heat-conductive layer, along with a filler layer, insulation layer, expansion joints, fixed clips, steel wire mesh, and tie-downs. Additionally, a heating coil made of high-temperature-resistant polyethylene (PE-RT) is selected for laying. An air layer is created between the ground and the floor, effectively preventing thermal loss and providing insulation for the building.

The design arranges a collector with efficiency of 0.436, heat loss coefficient of 0.02, length of 15 m, width of 7.6 m, and an area of 115 m^2 on the roof of the main room of Hujia courtyard. This ensures that the solar panel does not affect the overall lighting and ventilation of the building while still being able to absorb sufficient solar energy. Since the winter temperature in the Huili area is above 0 °C and there is no risk of water freezing, two split solar hot water systems will be installed on the exterior wall without occupying indoor space. This will maintain a high level of light-to-heat conversion efficiency and provide additional energy for users in daily use. The solar panels are positioned on the main building of the structure, with supports at all four corners elevated from the ground and not in direct contact with the building. The double-sloped roof of the main building will have solar panels on the side near the inner courtyard. The presence of the solar panels will only be felt by the residents living in the courtyard, and it will not affect the traditional heritage-protected building’s architectural style when viewed from different directions. To maintain the architectural style, the solar panels can be easily removed for events like exhibitions or receptions to meet the requirements of visitor tours.

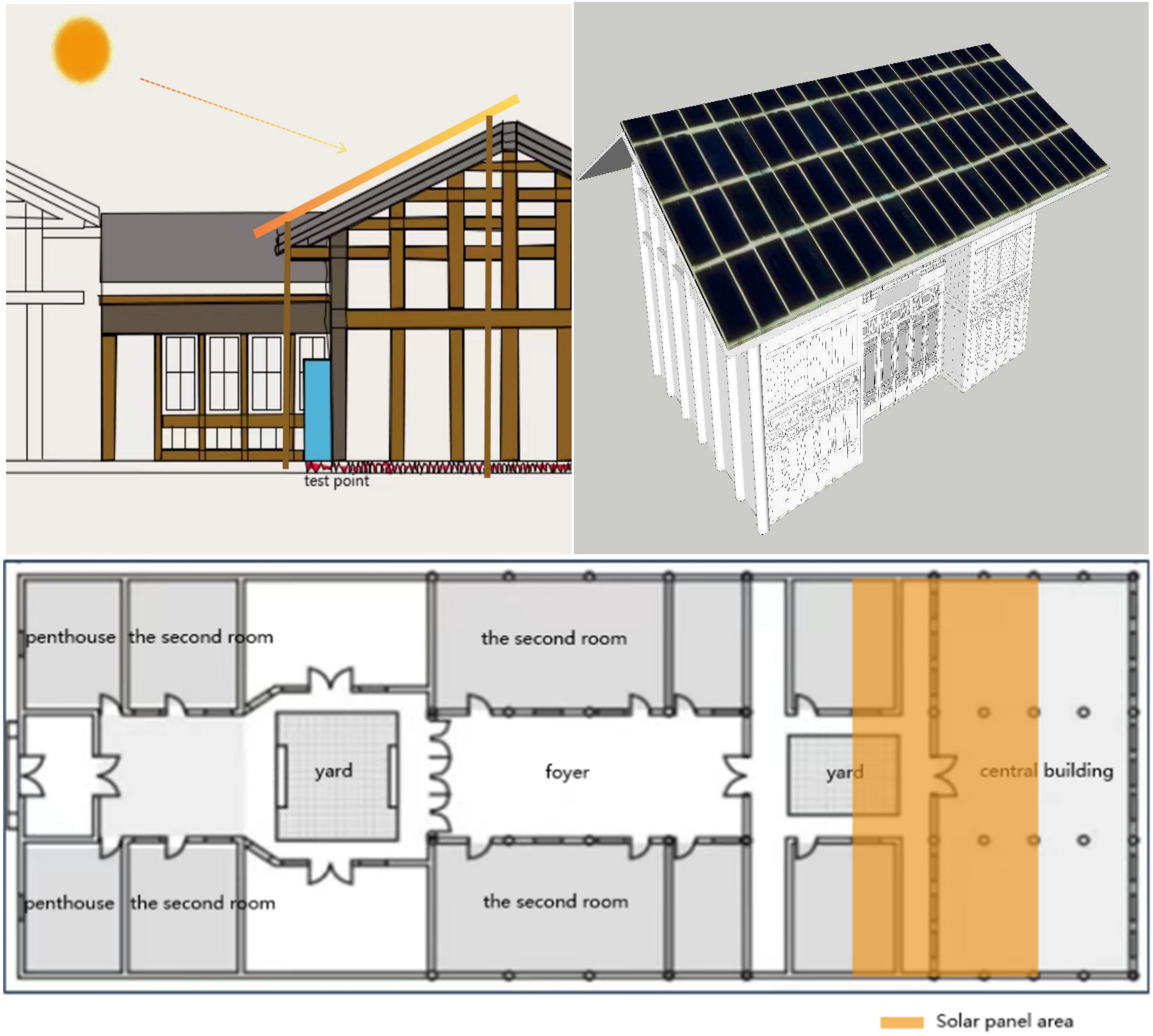


Figure 4. Split flat plate solar panel system layout.

2.3. Building Economics Model

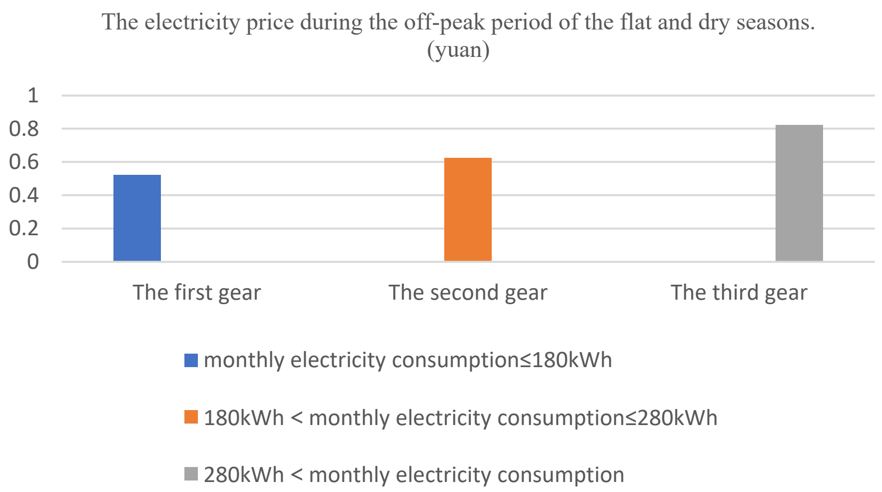
Through Formula (3), the optimal solar panel installation area for the Hu Family Compound was calculated. In Formula (8), a connection was established between the solar panel area and the investment payback period. Solar panel areas were set according to the parameters as shown in the diagram, while keeping other variables constant. This study aimed to explore the potential relationship between solar panel area and economic feasibility.

This research utilized the current market price of ceramic–aluminum composite solar panels, which is CNY 1500 per square meter [29]. Based on the calculated optimal solar panel installation area, the initial investment amount was determined. Formula (8) represents the investment payback period formula, where Pt represents the payback period, I represents the initial investment amount, and A denotes the annual net cash flow.

The economic viability of installing solar panels at the Hu Family Compound was assessed using the investment payback period. Figure 5 illustrates the stepped electricity pricing during peak and off-peak periods in the Huili region. Formula (9) calculates the monthly electricity cost savings achieved by the Hu Family Compound through the use of renewable energy, with "p_e" representing the monthly electricity consumption.

$$P_t = I/A \tag{8}$$

$$P = 180 \cdot 0.5224 + 100 \cdot 0.6224 + (p_e - 280) \cdot 0.8224 \quad (9)$$



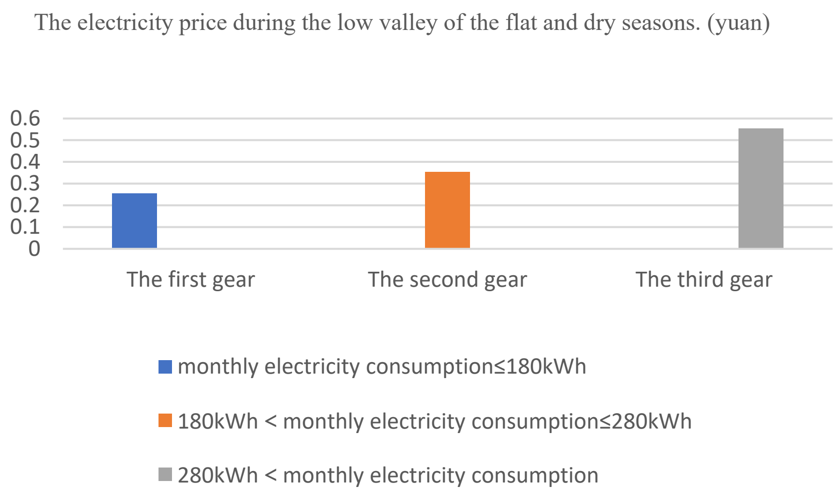


Figure 5. Sichuan province tiered electricity price (CNY).

3. Geographical Information

The geographical coordinates of Huili City, Sichuan, range from approximately 26°5′ to 27°12′ north in latitude and from around 101°52′ to 102°38′ east in longitude. Huili City is situated at the southernmost tip of the Liangshan Yi Autonomous Prefecture in Sichuan Province, China, as depicted in Figure 6. This region benefits from abundant solar radiation, with the highest solar radiation occurring in May and June, reaching up to 600 MJ/m^2. Conversely, the lowest annual solar radiation is observed in October, though it still reaches a substantial level of around 350 MJ/m^2 (Figure 7). It is worth noting that the Hu Family Compound, located within the heritage-protected area of Huili Ancient Town, was selected as a case study to investigate the impact of various solar panel parameters on heating for heritage buildings.

As shown in Figure 7, December is the coldest month of the year in the Huili region, ith an average temperature of 8 °C. In contrast, July and August are considered the warmest months, with an average temperature of 23 °C. This suggests that during colder periods, the building can receive a significant amount of solar radiation. The region experiences concentrated rainfall, leading to distinct rainy and dry seasons. Although the annual temperature difference is relatively small, there is a significant fluctuation in day–night temperatures. Therefore, studying how to harness solar energy to enhance human thermal comfort is of paramount importance.

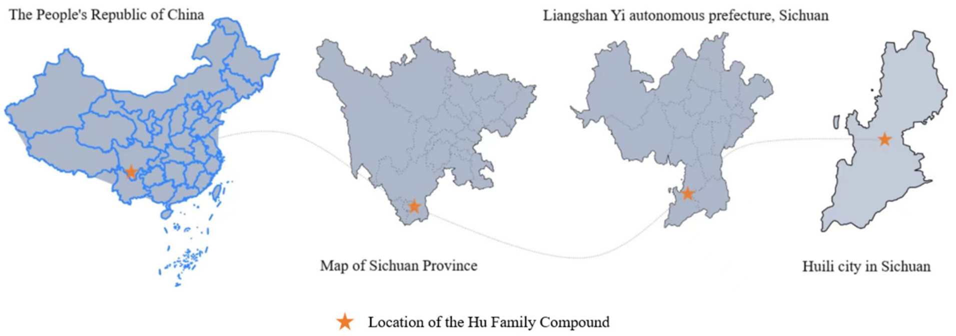


Figure 6. Location map of case city, Huili, in southern China.

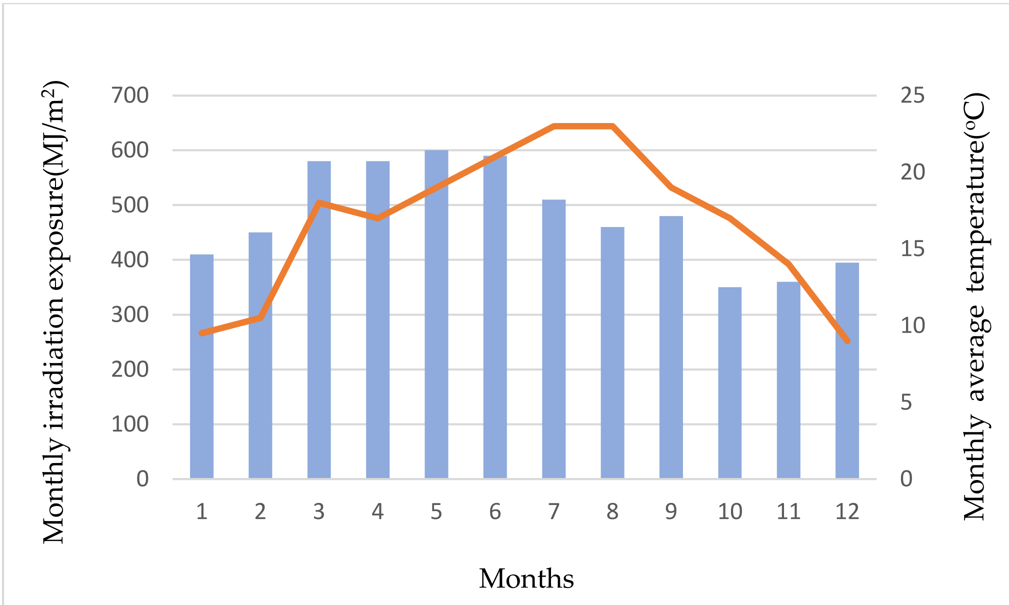


Figure 7. Key climatic parameters in Huili.

4. Results and Discussion

4.1. Optimal Mounting Angle for Solar Panels

Based on Figure 8, we were able to find that a solar panel at an azimuth angle of 0°, regardless of the value of the solar panel mounting tilt angle, will reach the maximum value under its own tilt angle. At an azimuth angle of 0° and a mounting tilt angle of 30°, the intensity of solar radiation per unit area reaches the maximum value. In order to verify that the optimal value of the mounting azimuth angle is 0°, we kept the tilt angle unchanged, and the changed the azimuth angle to −15°, 0°, and 15°, as shown in Figure 9. It is found that the intensity of solar radiation per unit area is maximum at 0° and reaches the maximum value when the inclination angle is 30°. So, the optimal installation tilt angle is about 30°, and the optimal azimuth angle is about 0. In order to further clarify the optimal tilt angle of solar panels on this basis, we obtained the annual pattern of the solar energy capture capacity of Huili County with the tilt angle and azimuth angle as shown in Figure 10 in the regression optimization calculations, and through the planning and solving, the optimum azimuth angle of 0.391 and the optimum mounting inclination of 30.037° could be derived.

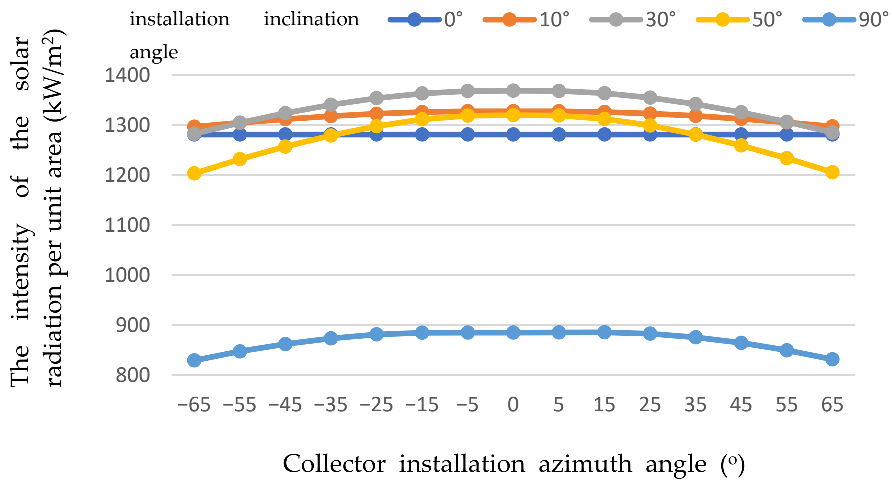


Figure 8. Effect of different azimuth angles on solar radiation capture under several inclination conditions in Huili County.

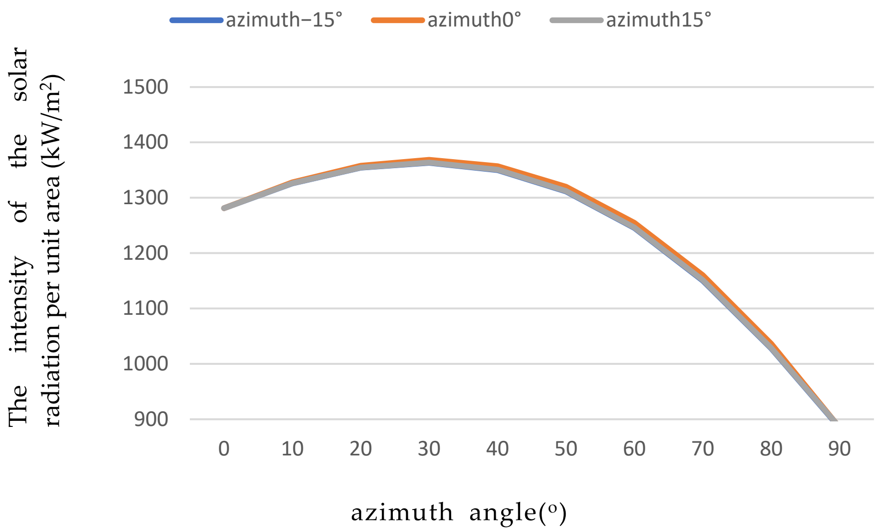


Figure 9. The influence of different inclination angles on the solar radiation capture under several azimuth conditions in Huili County.

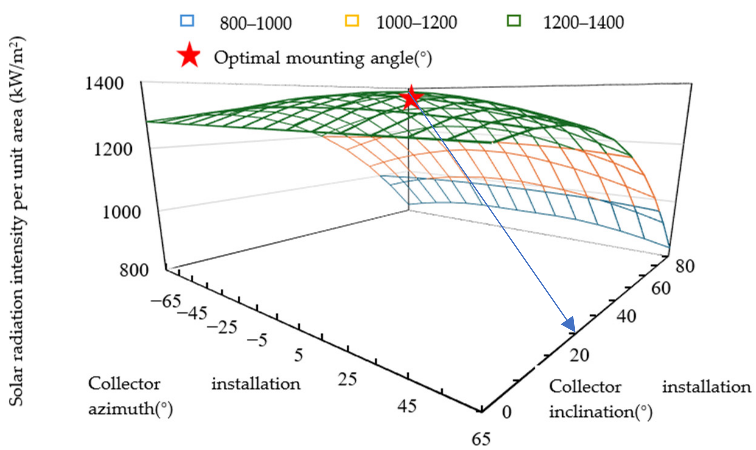


Figure 10. The annual law of solar energy capture capacity in Huili County changes with inclination angle and azimuth angle.

4.2. Optimum Area for Laying Solar Panels

The current residence at the Hu Family Courtyard houses five people, and the installation of the aforementioned split solar hot water system can effectively reduce the use of traditional energy and meet the requirements for the utilization of renewable energy. The solar water system in the Hu Family Courtyard operates from November to March the following year, spanning a total of five months, during which the building has a substantial heating demand and experiences high tourist traffic. According to Figure 11, it can be seen that the winter heating energy consumption of the Hu Family Compound from November to March of the following year is 29,700 kWh. According to Formula (5), the average monthly solar radiation (H0) for these five months is 5940 kWh. Based on the data from Figure 6 (monthly solar radiation) and Formula (5), the average solar radiation during the period from November to March is 73,165 KJ/m^2 per month. According to Formula (6), the daily average solar radiation (H) is 14,633 KJ/m^2. According to the solar energy calculation formula (Formula (7)), it is known that in order to provide 29,700 kWh of energy to heat a building in winter using a solar energy system, it is necessary to arrange solar energy equipment with higher collection efficiency and lower heat loss efficiency within a reasonable land area. Traditional solar panels have relatively low collection efficiency, with most ranging from 15% to 25%. In this case, if ordinary solar panels are used, the collection area must be expanded to meet the energy consumption requirements within a period of 5 months. Taking a collection efficiency of 25% as an example, calculations based on Formula (7) indicate that approximately 200 m^2 of solar panels would be needed to meet the requirements. Considering that the Hu Family Compound is a heritage-protected building, efforts should be made to minimize external factors that could cause damage during operation. Therefore, this study considers the use of solar energy equipment with high collection efficiency and low heat loss efficiency. After the research, it was found that using a new and efficient ceramic–aluminum composite solar panel system can effectively meet these two requirements. The collection efficiency of this ceramic–aluminum composite solar panel can reach 0.436, while the heat loss efficiency is only 0.02. Therefore, by installing a solar energy system with an area of 115 m^2, operating for 150 days, with a collection efficiency (η) of 0.436 and a heat loss efficiency (T) of 0.02, in a building with a daily average solar radiation (H) of 14,633 KJ/m^2, the calculated solar energy production would be 29,959 kWh. At the same time, the heating energy consumption of the Hu Family Compound during this period is approximately 29,700 kWh. This means that the heating demand of the building is fully supplied by solar energy, indicating that the building is now heated entirely by renewable energy and achieves near-zero-energy consumption in terms of heating. This greatly extends the lifespan of the heritage-protected building.

Based on software simulation analysis, under the condition that the Hu Family Compound adopts a solar energy system with a collection area of 115 m^2, a collection efficiency of 0.436, and a heat loss efficiency of 0.02, while operating for 150 days per year, and continues to operate under these conditions for 100 years, it will generate annual CO_2 emissions of 65.651 (tCO_2/a). This results in total CO_2 emissions of 6565.101 (tCO_2/a) over the entire lifespan. In comparison, if a solar energy system is not used, the annual CO_2 emissions over the entire lifespan would be 77.773 (tCO_2/a), with total CO_2 emissions of 7777.353 (tCO_2/a). From (Figure 12), it can be seen that installing a solar energy system can reduce CO_2 emissions by 15.6% annually, effectively enhancing the sustainability of the building.

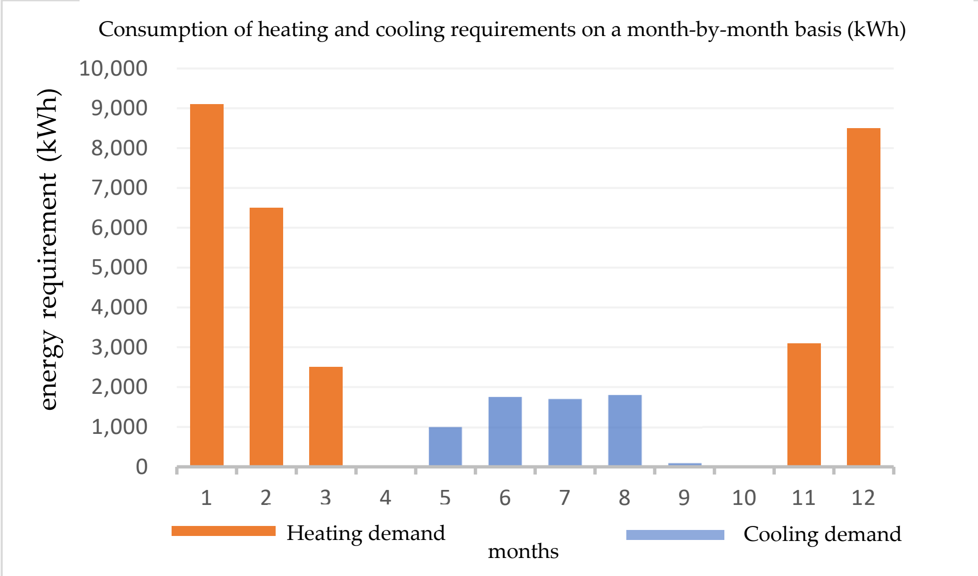


Figure 11. Building energy demand.

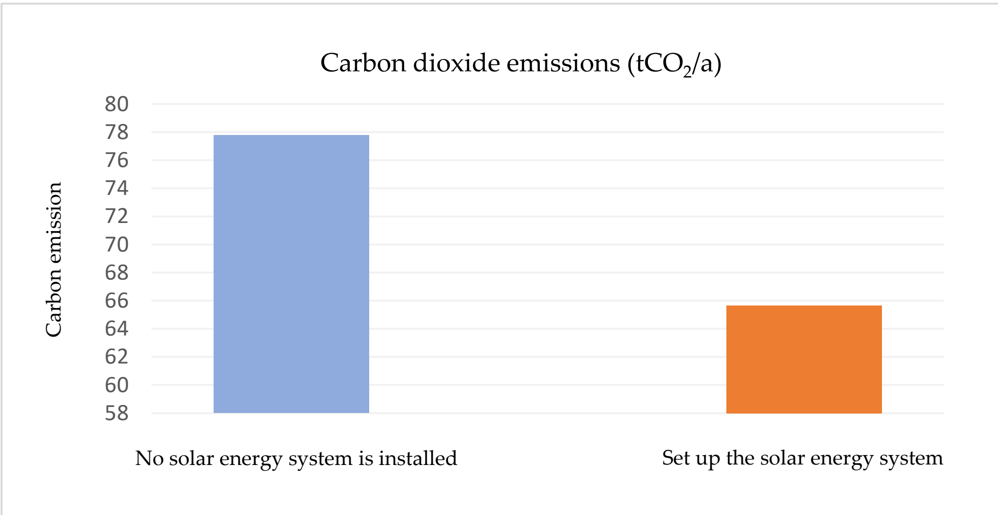


Figure 12. Annual carbon emissions of buildings.

4.3. Economic Feasibility Analysis

Currently, the average market price for ceramic–aluminum composite solar panels is CNY 1500 per square meter, and their lifespan is greater than 10 years. With relatively low costs, it has been calculated that the purchase of equipment for the Hu Family Compound will cost approximately CNY 175,000. To fully meet the heating energy demands, the solar energy system needs to provide approximately 5940 kWh of energy per month. Taking into account the differences in electricity prices during the dry season, rainy season, peak hours, and non-peak hours, sensitivity analysis was conducted to ensure the universality of the conclusions. The peak hours are from 7 a.m. to 11 p.m., while non-peak hours are from 11 p.m. to the following morning at 7 a.m. Based on the above conditions, during the flat and dry seasons from November to March of the following year, if it is assumed that the electricity consumption remains the same in the peak hours, the local electricity price can be determined (Figure 5). According to Formula (9) and the monthly electricity consumption (W) calculation, renewable energy can save an average of approximately CNY 4811.06 per month. If it is assumed that the electricity consumption remains in the non-peak hours, the savings from renewable energy can be estimated at around CNY

3213.79 per month, using the local electricity price (Figure 5). Assuming a monthly savings of CNY 4811.06, the payback period can be calculated using the formula for payback period (Formula (8)): payback period (pt) = initial investment amount (I)/annual net cash flow (A). The calculation shows that the cost can be recovered after the equipment has been operating for 36 months. If the monthly savings are CNY 3213.79, it would take approximately 54 months of equipment operation to recoup the cost.

In order to better illustrate the impact of the area of solar panel installation on the investment payback period, this study set a range of solar panel areas from 20 m^2 to 140 m^2 while keeping other conditions unchanged. The investment payback period was calculated for each area, and the results are shown in Table 3. From Figure 13, it can be observed that as the area of solar panel installation increases, regardless of whether it is during peak or off-peak electricity consumption periods, the investment payback period shows a convergence phenomenon. This means that with increasing investment, the decrease in the investment payback period becomes slower. Therefore, in the case of Hu family compound, where the solar panels should meet the heating energy consumption demand, the appropriate area is determined to be 115 m^2. At this point, there is no need to further increase the area of the solar panels, as it would result in relatively lower economic benefits.

Table 3. Payback period for placing solar panels (months).

Solar Panel Area (m^2)	Equipment Price (CNY)	Monthly Energy Generated by Solar Equipment (kWh)	Peak and Level Electricity Price (CNY)	Payback Period (Months)	Valley Floor Electricity Price (CNY)	Payback Period (Months)
20	30,000	1042.064	782.993	38.314	502.782	59.668
40	60,000	2084.130	1639.989	36.586	1079.566	55.578
60	90,000	3126.194	2496.982	36.044	1656.348	54.336
80	120,000	4168.258	3353.975	35.778	2233.131	53.736
100	150,000	5210.322	4210.969	35.621	2809.913	53.382
120	180,000	6252.388	5067.964	35.517	3386.697	53.149
140	210,000	7294.452	5924.957	35.443	3963.479	52.984

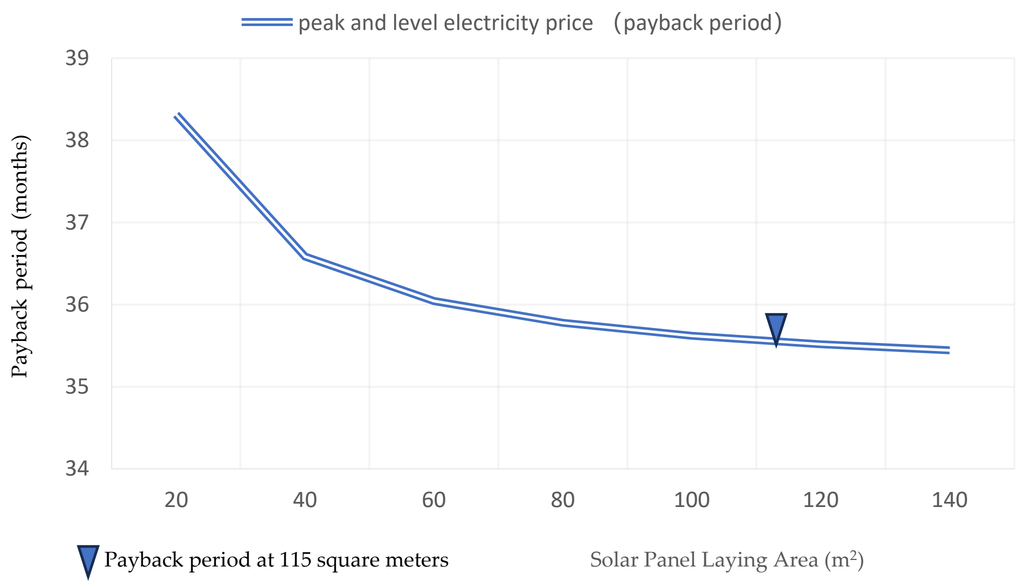


Figure 13. *Cont.*

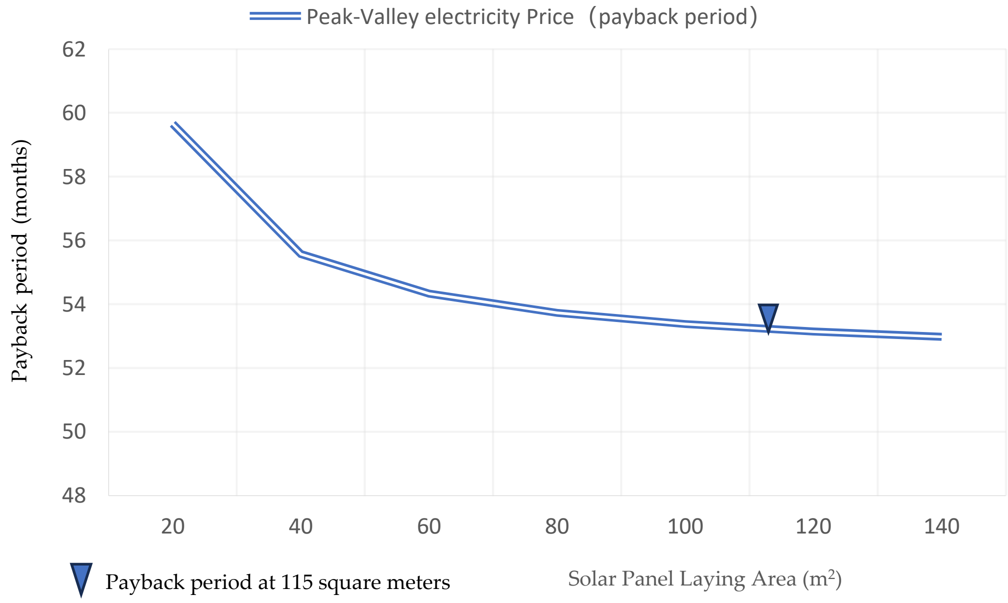


Figure 13. Relationship between payback period and area of solar panel placement.

4.4. In-Depth Analysis Based on the above Results

There is an intrinsic link between the area of solar panels laid on heritage buildings and the installation angle, as well as parameters such as the conversion rate of the equipment and the economics. How to determine the optimal installation angle of solar panels, select the conversion rate of the solar system, and obtain the optimal laying area when the area of solar panels increases with the demand for energy supply are subjected to the requirements of heritage protection, i.e., the area should be relatively small, and negatively correlate with the economy of the building. In this paper, a solar energy system is designed to meet the heating needs of a heritage building while minimizing the impact on the building and obtaining the best economic results. This study only presents a typical case and analyzes the design methods and application strategies of renewable energy in traditional heritage conservation architecture. The specific design details proposed may not be applicable to other situations because the performance and energy-saving potential of solar energy systems largely depend on the actual engineering conditions, including the building location, size, energy usage demands, economic conditions, and local climate conditions, among others. Further research in the future is also necessitated by these limitations. However, the solar energy system design method used in this article focuses on a traditional courtyard-style residential building, and variations may occur in different regions due to differences in solar radiation and economic analysis. In similar situations, this research can be applied and adapted to regional conditions. This study provides design references for the sustainable renovation of traditional heritage conservation buildings as follows:

(1) The use of solar energy for the renovation of traditional heritage buildings needs to ensure the optimal mounting inclination of the solar panels. The best azimuth angle of the solar panels in the Hu Family Compound was found to be 0.391 and the optimal mounting inclination was found to be 30.037. Researchers need to analyze them accordingly for different buildings.

(2) The area of solar panels is also crucial for solar retrofitting of heritage buildings. The optimal laying area of the Hu Family Compound is 115 m^2, and researchers should analyze the optimal laying area of specific case buildings by combining various factors.

(3) In this study, the best payback periods for heating with zero-energy consumption was 36 months and 54 months, respectively. Researchers should conduct a comprehensive analysis of multiple factors to determine the most appropriate investment cost, so

as to promote a virtuous cycle of renewable energy utilization and the sustainable transformation of heritage buildings.

5. Conclusions

Traditional heritage conservation buildings are currently facing the challenge of balancing heritage conservation with meeting the needs of contemporary lifestyles. Utilizing renewable energy sources to reduce traditional energy consumption, reduce carbon emissions, and achieve optimal functionality and cost-effectiveness while preserving cultural heritage buildings has become an effective way to achieve sustainable development in architectural heritage conservation. This paper takes a typical traditional courtyard house in Southwest China as an example, and investigates the optimal solution for retrofitting it with solar energy, including an optimal solar panel mounting azimuth angle of 0.391°, a mounting tilt angle of 30.037°, an optimal solar panel laying area of 115 m^2, and an optimal payback period of 37 months for peak electricity consumption and 54 months for non-peak electricity consumption. The optimal method of utilizing renewable energy for renovation in the conservation process of traditional heritage buildings is proposed. It provides methods and ideas for the sustainable transformation of traditional heritage buildings in the future.

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