applied sciences

MDPI

Article

Analysis of Energy Performance and Integrated Optimization of Tubular Houses in Southern China Using Computational Simulation

Jing Wang [1,2], Weijun Gao [2,*], Zhu Wang [3] and Liting Zhang [4]

1 Zhejiang University Architectural Design and Research Institute Co., Ltd., Hangzhou 310007, China; wangjing.zju.edu@gmail.com
2 Faculty of Environmental Engineering, The University of Kitakyushu, Kitakyushu 8080135, Japan
3 Civil Engineering Institute, Zhejiang University, Hangzhou 310007, China; wlb-art@163.com
4 Energy and Environment Engineering Institute, Shanghai University of Electric Power, Shanghai 200090, China; zhangliting708@163.com
* Correspondence: weijun@kitakyu-u.ac.jp; Tel.: +86-137-5088-8856

Abstract: Chinese rural construction is currently booming, but faces considerable challenges in terms of energy performance. The objective of this research was to analyze the energy performance of tubular houses, which are a unique type of rural house in southern China, with a particular architectural form and environmental adaptations. Previous field measurements showed that there was much room for improvement, with both winter and summer cases requiring particular attention. Numerical simulations of the annual energy consumption were conducted using Open-Studio. The results show that various levels of reduction in energy consumption (varying from 1.6% to 30.5%) were achieved by combining different renovations. Among them, using solar energy with a sunroom was found to be the most effective approach, with an energy-saving rate of 28%, followed by the approach of attaching insulation to the walls and roof, with an energy-saving rate ranging from 13.2% to 30.5%. The integrated optimization measures had an energy-saving rate of 47.4% with a total renovation cost of CNY 41,143.1, and the payback period of investment was within five years. If a tubular house with improved thermal insulation can be inherited as a component in the process of urbanization, it will aid in energy conservation and natural ecosystem protection for southern China.

Keywords: tubular house; sustainability; energy performance; passive energy-saving technology; Open-Studio; integrated optimization

Citation: Wang, J.; Gao, W.; Wang, Z.; Zhang, L. Analysis of Energy Performance and Integrated Optimization of Tubular Houses in Southern China Using Computational Simulation. *Appl. Sci.* **2021**, *11*, 9371. https://doi.org/10.3390/app11209371

Academic Editor: Jürgen Reichardt

Received: 13 July 2021
Accepted: 26 September 2021
Published: 9 October 2021

1. Introduction

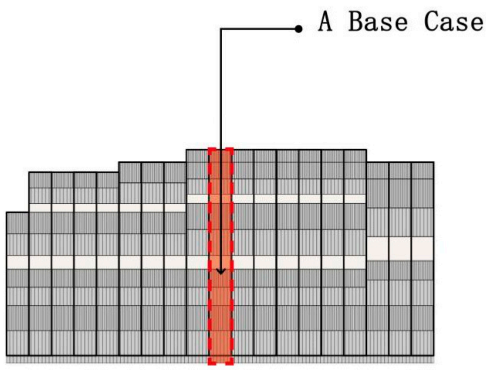
Globally, the construction industry today consumes 40% of the total energy production, generates between 30% and 40% of all solid waste, and emits 35–40% of total CO_2 emissions [1,2]. As the current situation is not satisfactory, a number of policies have been adopted worldwide. Examples include the Kyoto Protocol [3], Buildings Directive Energy Performance [4,5], and the Japanese low-carbon society plan [6], all of which have worked successfully as solutions for minimizing the environmental influence of buildings in order to make them sustainable [7].

However, China is a large country with a large agricultural sector, and the rural population accounts for 43.9% of the total population [8]. In China, the energy consumption of the construction industry accounts for 30% of the total energy production, with rural areas accounting for 37% of that value [9,10]. Numerous investigations of rural residences have shown that the poor thermal insulation properties of building envelopes, as a function of nonstandard traditional construction materials and methods, results in substantial energy consumption [11–14]. In addition, there is an increasing trend in annual energy consumption due to the generally improving living conditions in rural areas.

In view of the national situation, some attention has been given to this issue. In 2012, the "design standard for energy efficiency of rural residential buildings" was implemented by the Ministry of Housing and Urban–Rural Development, which provided a general national standard to address the issues of rural construction [15]. In an existing study, Hu and He researched a Trombe wall with Venetian blinds, which could increase the average indoor temperature by 5 °C during winter [16]. Zwanzig researched a transparent phase-change material to improve the utilization of solar radiation and promote heat storage and release ability [17]. Nayak had analyzed the state of solar cell devices based on performance and device stability in both organic and inorganic photovoltaics (PVs) [18]. Meysam had optimized the solar cell device integration of ultra-thin poly films via a single-step all-dry process [19]. All of these studies focused on the use of a single technology with a high economic cost. However, rural residents cannot afford this kind of investment because of their low income levels. In rural regions, integrated passive energy-saving technologies in combination with minimal input are most appropriate for improving the thermal performance of residences. The processes involved in this approach require a constant consideration of the building performance, including the building envelope, orientation, shading, and natural ventilation, together with the use of energy-efficient systems [20]. Currently, existing research is far from achieving this goal.

In addition, thermal performance research should be combined with local natural climatic conditions and regional architectural forms, especially in rural areas [21–24]. Chinese researchers have been paying close attention to existing rural residential dwellings, such as Yaodong dwellings located in the arid region of China [25] and Tibetan traditional dwellings located in the cold rural area of Gannan [26]. The tubular house is a typical form of traditional residential building that has a long history, as shown in Figure 1. It is abundant in southern China, where the summer is hot and humid, in regions such as Guangdong, Guangxi, Taiwan, and Zhejiang, and it is even widely found in India, analogously called a "tube house". Tubular houses, which are named for their narrow and long forms, are a good example of a regional building adapted to the local climate. The arrangement, involving a spatial structure connected by internal patios and long corridors, provides a characteristic regional architectural form for research. Since almost all the tubular houses are built in the form of townhouses, the shape factor can be decreased, and the heat loss from the external surfaces can be reduced. Furthermore, two yards enable a reduction in the heating load by introducing sunlight and a reduction in the cooling load by providing ventilation. Thus, it has a positive effect on the energy conservation. If the tubular house can be inherited as a component in the process of urbanization, it will aid in energy conservation and natural ecosystem protection in southern China.

(**a**)



(**b**)

Figure 1. *Cont.*

(**c**)

(**d**)

(**e**)

Figure 1. (**a**,**c**) Appearance of the traditional tubular houses; (**b**) a base case in a group arrangement of tubular houses; (**d**,**e**) Google map of the tubular houses (2021).

In the past decade, extensive work has been carried out to reveal the thermal mechanisms of tubular houses. A team from the South China Institute of Technology [27] studied the basic principles of insulation and ventilation of tubular houses in Guangzhou. Lin [28] studied the relationship between ventilation, wind pressure, and thermal compression in tubular houses. Gao [29] proposed that increasing the height of the yard could increase the ventilation effect of tubular houses. Ling [30] studied the relationship between the yard area and the energy consumption of tubular houses in Fujian. The famous Indian architect Correa [31] indicated that tubular houses should improve the wind effect of the atrium in the yard to promote indoor ventilation. However, considering the research methodology and technique strategy, numerous researchers have focused on the impact of architectural forms and ventilation. Unfortunately, the energy consumption of tubular houses has not been investigated in previous research, and there remains a lack of experimental validation and quantitative analysis.

Our group from Zhejiang University has studied tubular houses in northern Zhejiang Province for more than 10 years [32]. Active heating or cooling systems are generally in high demand for buildings in the northern Zhejiang Province due to the "hot in summer and cool in winter" climate of the region. Previous field measurements showed that there was much room for improvement with regard to thermal conditions in such dwellings, with both winter and summer cases requiring particular attention. Analyses of energy consumption and energy-saving potential based on field measurements and computer simulations for dwellings have been widely applied worldwide [25]. In this study, numerical simulations of the annual energy consumption were conducted using the tubular house model in Open-

Studio. Different energy efficiency measures were evaluated in terms of the decrease in the annual energy consumption. Subsequently, the results show that various levels of reduction in energy consumption (varying from 1.6% to 30.5%) were achieved by combining different renovations. Furthermore, the relationship between energy consumption and insulation material thickness was established using a highly fitting logarithmic curve. To facilitate the understanding of the research method framework, it is presented in Figure 2.

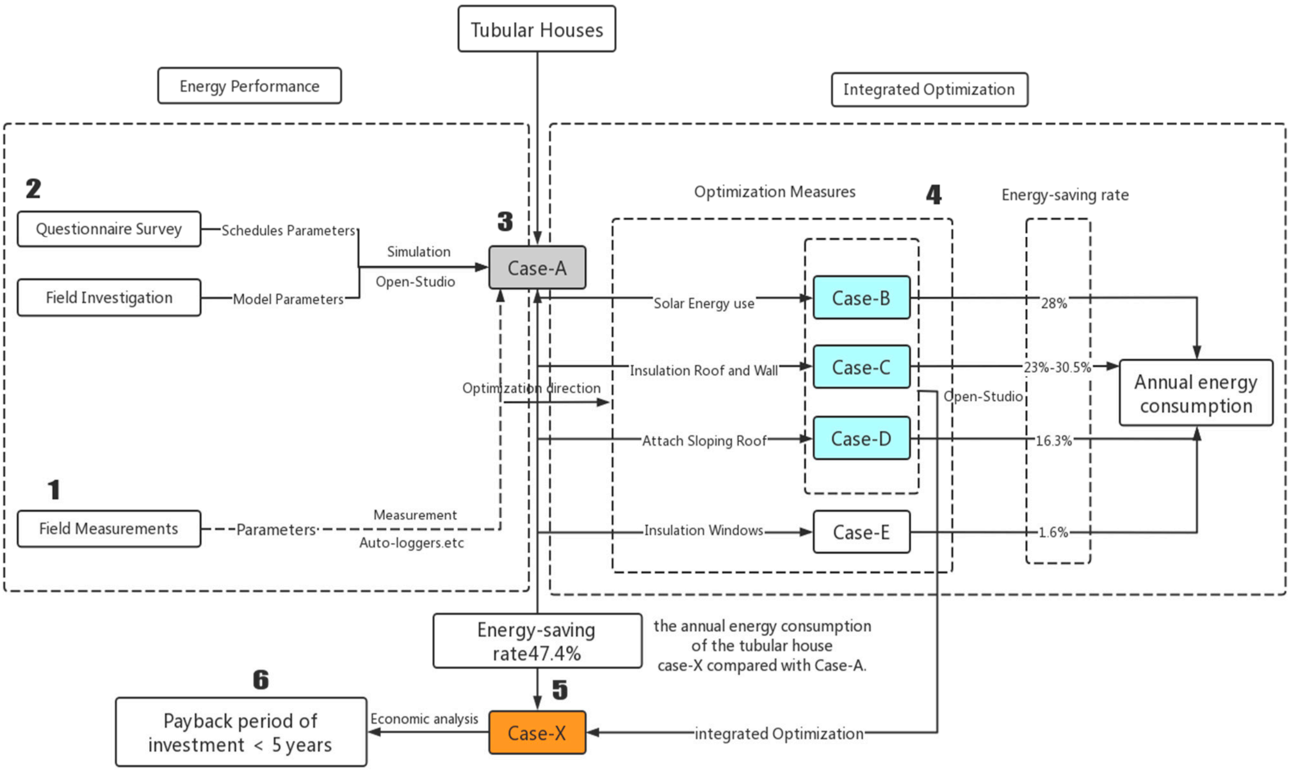


Figure 2. Research methods framework.

Step 1. Field Measurement: A series of experimental measurements were carried out, focusing on the characteristics of the tubular house and the current situation of the thermal comfort, to provide the basis for the study.

Step 2. Investigation: The field investigation about modeling parameters of tubular house and a questionnaire survey about living schedule of 121 households were conducted.

Step 3. Models Built: A typical tubular house was built in Open-Studio as CASE-A according to the parameters in steps 1 and 2.

Step 4. Simulation: Several energy consumption simulations were conducted throughout the winter and summer by combining different renovations to solve the problems found in steps 1 and 2.

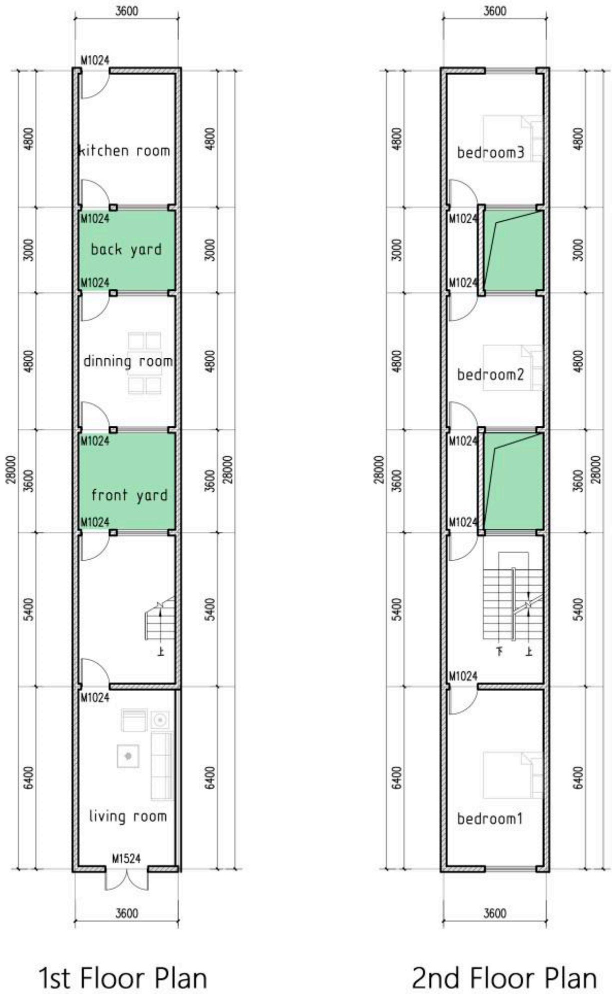
Step 5. Analysis: Analyze all the simulation results, taking CASE-X as the integrated optimization measure, with an energy-saving rate of 47.4%.

Step 6. Economic analysis: Take economic analysis of CASE-X with a total renovation cost of CNY 41,143.1, and the payback period of investment within five years.

2. Materials and Methods

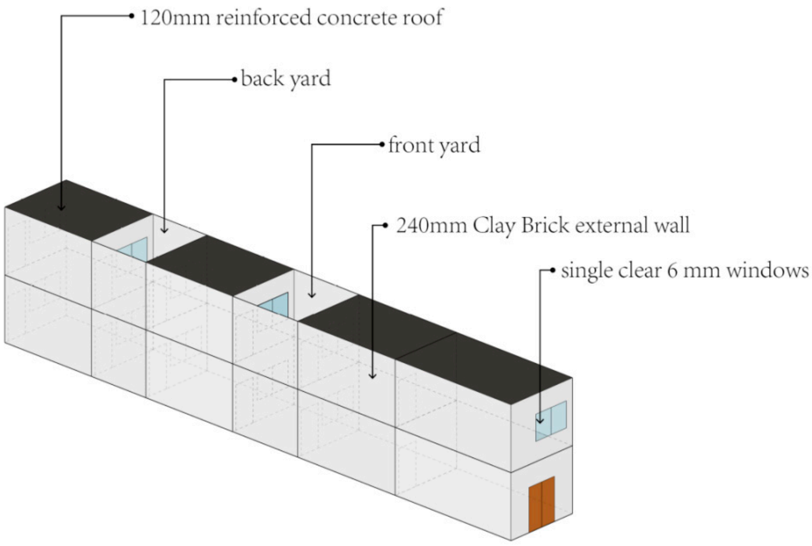
2.1. Research Object

The protection of traditional dwellings has received increasing attention. Energy consumption and indoor comfort are very important factors for their sustainable development [18]. The tubular houses located in Zhang Luwan village in northern Zhejiang Province were chosen as the study buildings. The village has a long history. Furthermore, considering that almost all the tubular houses are built in the form of townhouses rather than separate single houses, the research object of this study was a typical two-story tubular house located in the middle of a group of townhouses as Case-A, shown in Figures 1b, 3 and 4a. It faces south, with 3.6 m from east to west and 28 m from north to south, with proportions of 1:7.77, presenting a long and narrow form so as to meet the construction demands of high density at lower layers. Moreover, it can also be divided into three parts by internal yards: the front as the living room, the middle as the dining room, and the back as the kitchen on the first floor, while the second floor features three bedrooms. The height of both the floors is 3 m. The total building area is 154.08 m^2. Figure 3 shows a model diagram of a tubular house. This house was fit for a "hot in summer and cold in winter" climate, where active heating or cooling systems are generally in high demand, and it belongs to the highly focused residence group under a public social structure.



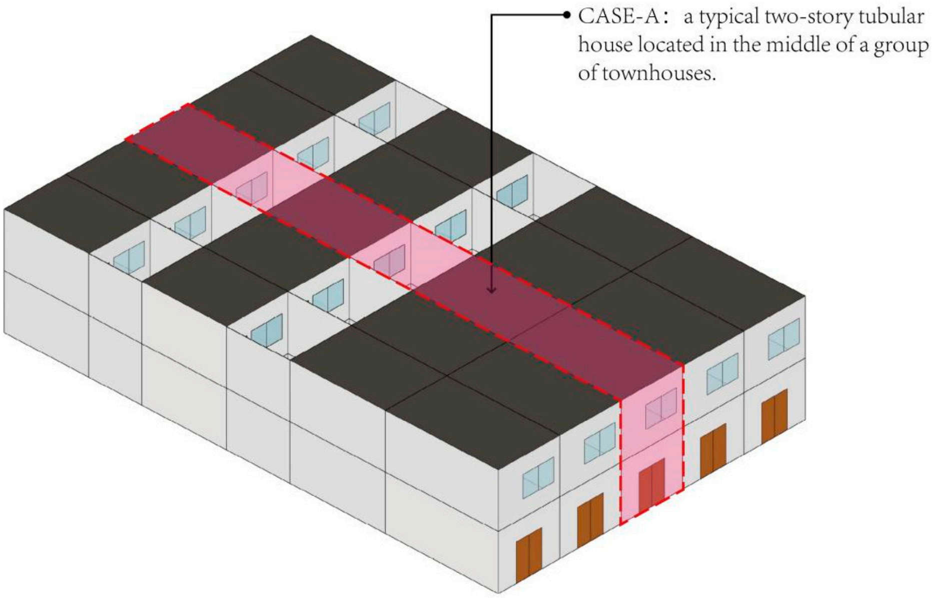
(**a**)

Figure 3. *Cont.*



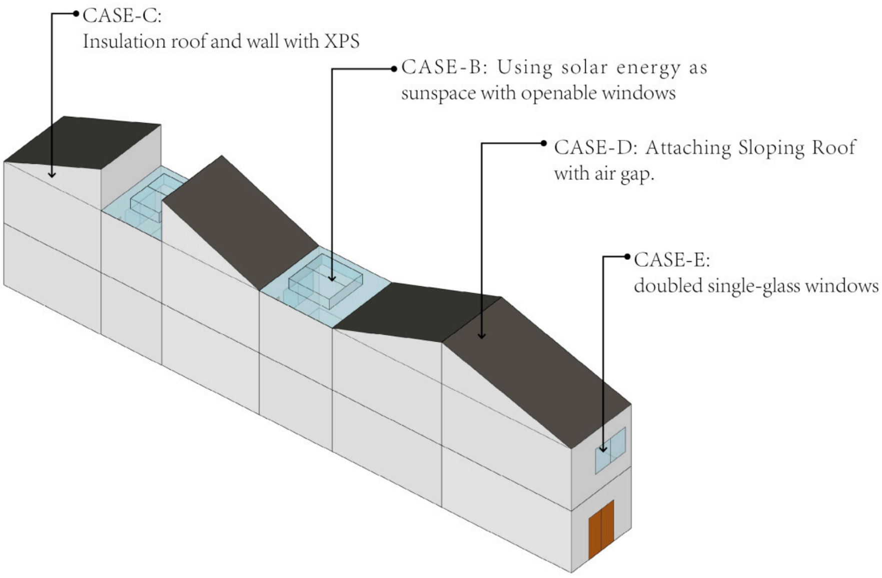
(**b**)

Figure 3. (**a**) Layout of a tubular house in CAD 2020, and (**b**) 3D model of a tubular house in Sketchup 2019.

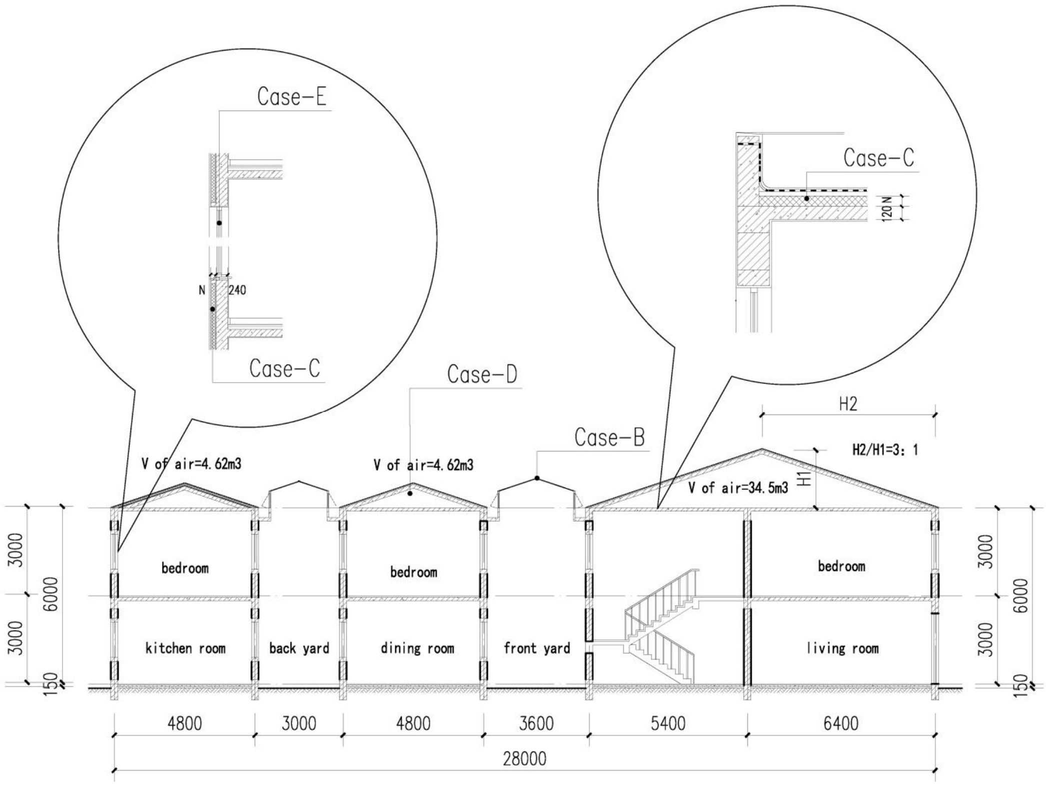


(**a**)

Figure 4. *Cont*.

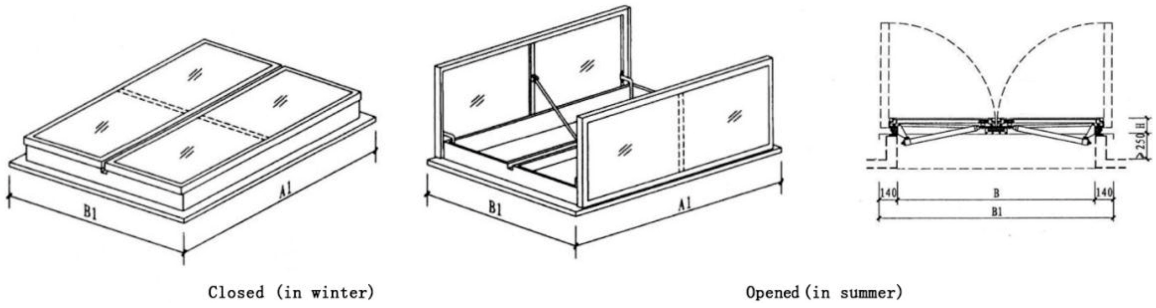


(**b**)



(**c**)

Figure 4. *Cont*.



(**d**)

Figure 4. (**a**) The Image of CASE-A, (**b**) image of new tubular houses with different energy efficiency measures in Sketchup 2019, (**c**) image of new tubular houses with different energy efficiency measures in Cad2021, and (**d**) image of the sun-space windows.

2.2. Field Measurements

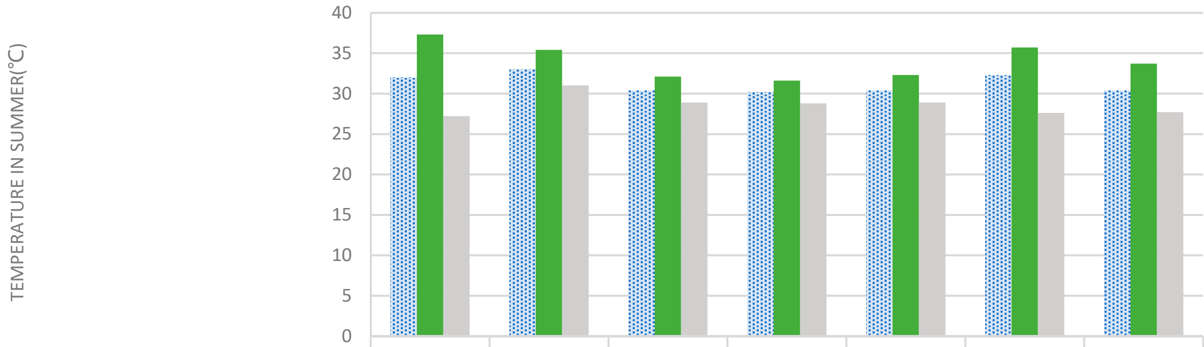
It is important to note that the thermal environment of a traditional tubular house is not always optimal. There is much room for improvement in terms of the thermal conditions in such dwellings, with both winter and summer cases requiring particular attention. The thermal properties of the building envelopes are the main reason for the poor thermal environment. A traditional tubular house is always covered by poor envelopes such as a 120 mm reinforced concrete roof, a 240 mm clay brick external wall, and single clear 6 mm windows, according to the field survey.

A series of experimental measurements were carried out, focusing on the characteristics of the tubular house and local climate in 2019 during winter and summer. Auto-loggers were used to simultaneously monitor the indoor and outdoor air temperatures and relative humidity. These instruments were placed at a height of 1.5 m in the middle of eight zones. There were no active systems in operation when the measurement was conducted. All the field measurements were carried out without active system used, focusing on the characteristics of the tubular house and the current situation of the thermal comfort to provide the basis for the study.

A general summary of the measurements revealed that traditional tubular houses have particular structural and thermal characteristics.

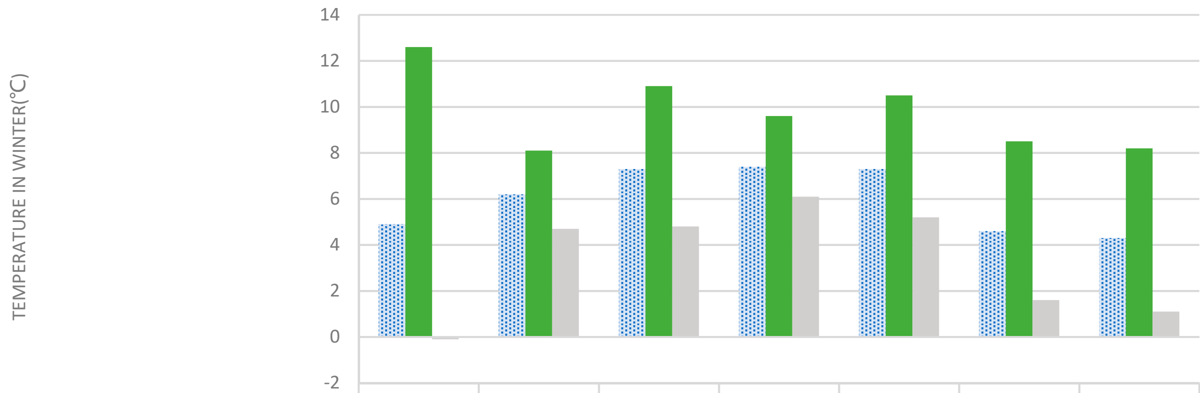
The results in Figure 5 show that the arrangement and spatial structure played important roles in making the indoor temperature lower than the outdoor temperature in summer; however, the temperature in some zones was still too high. In winter, the indoor temperature was higher than the outdoor temperature, reflecting the advantages of a tubular house. However, the average indoor temperature was approximately 4–7 °C; thus, inhabitants would feel cold without a heating method.

In summer, the indoor and courtyard temperatures of the tubular house increased with height. The temperature difference between indoors and outdoors on the second floor was 1.9 °C, while that on the first floor was 5–5.8 °C. In winter, the situation was the opposite. The analysis suggested that in summer, the higher indoor temperature of the second floor was due to insufficient heat insulation by the roof material. In winter, for the zones of the first floor, the heat loss was low because there was no direct heat transfer in the outdoor environment. The temperature of the front yard was slightly lower than that of the back yard because of the higher ratio of width to height of the yard and more sunlight in the former (the width of the front yard is 3600 mm and the back yard is 3000 mm, while they share the same height of 6000 mm). Furthermore, the indoor relative humidity in summer reached 70%. It can be clearly seen that there is much room for improvement in terms of the thermal conditions in such dwellings, with both winter and summer cases requiring particular attention. Thus, a search for feasible improvements is required.



	OUTDOOR	BEDROOM (2F)	DININGROOM (1F)	KITCHEN(1F)	LIVING ROOM (1F)	FRONT YARD	BACK YARD
Average temperature in summer(℃)	32	33	30.4	30.2	30.4	32.3	30.4
The highest temperature in summer(℃)	37.3	35.4	32.1	31.6	32.3	35.7	33.7
The lowest temperature in summer(℃)	27.2	31	28.9	28.8	28.9	27.6	27.7

(**a**)



	OUTDOOR	BEDROOM (2F)	DININGROOM (1F)	KITCHEN(1F)	LIVING ROOM (1F)	FRONT YARD	BACK YARD
Average temperature in winter(℃)	4.9	6.2	7.3	7.4	7.3	4.6	4.3
The highest temperature in winter(℃)	12.6	8.1	10.9	9.6	10.5	8.5	8.2
The lowest temperature in winter(℃)	-0.1	4.7	4.8	6.1	5.2	1.6	1.1

(**b**)

Figure 5. (**a**) Field measurement results of indoor and outdoor temperature in summer, and (**b**) field measurement results of indoor and outdoor temperature in summer and winter.

2.3. Computer Simulation

2.3.1. Open-Studio

The current study addressed this problem via simulation using the energy simulation program Open-Studio as the main analysis tool. Open-Studio is a cross-platform collection of software tools to support whole-building energy modeling using Energy-Plus and advanced daylight analysis using Radiance. Open-Studio includes graphical interfaces and a software development kit (SDK). Open-Studio features the same algorithms and data as Energy-Plus, which is a complete building design and environmental analysis tool that covers a broad range of simulation and analysis functions, covering thermal properties, energy, lighting, shading, and resources. As described by many researchers [33–35] who used this software to evaluate the required design configurations in their studies, it was chosen as the most suitable for the objectives of the current study because it is a highly visual building simulation tool. Using simulation methods through the works of EnergyPlus and Open-Studio for energy conservation purposes shows high applicability in many studies [36–41]. Models of the tubular house were built for comparative analysis, and energy consumption simulations were conducted throughout the winter and summer.

2.3.2. Simulation Parameters

The weather data file for Open-Studio was obtained from the EnergyPlus web page (Hangzhou city.epw), and the building materials were either chosen from the Energy-Plus library or created from the user library. Tables 1 and 2 display the zone and material properties of the tubular house model, respectively.

Table 1. Material descriptions of the tubular house model.

Component	Layers	Thickness (mm)	Thermal Conductivity (W/(m·K))	Density (kg/m^3)	Specific Heat (J/kg·K)	Heat Transfer Coefficient (W/(m^2·K))
CASE-A roof	Reinforced concrete	120	1.74	2500	920	
CASE-A external wall	240 clay brick	240	0.81	1800	1050	
CASE-A internal wall	120 clay brick	120	0.81	1800	1050	
CASE-A floor	Reinforced concrete	100	1.74	2500	920	
CASE-A windows	Single clear 6 mm	6				6.4
CASE-C insulation roof	XPS	10–100	0.03	27		
CASE-C insulation wall	XPS	10–100	0.03	27		
CASE-E double single-glazed windows						3.0

Table 2. Zone properties of the tubular house model.

Zone Properties	Description
Zone number	6
The type of active or passive system used	Electric heating coil system (in winter) Natural ventilation (in summer, when 12 °C < T outdoor < T inside) DX cooling coil system (in summer)
Comfort lower band	18 °C
Comfort upper band	26 °C
Occupants' metabolic rate	Sedentary activity: 70 W (6 persons)

2.3.3. Simulation Case Design: Winter Heating Case/Summer Mixed Cooling Case

Because the active system used for both cooling during summer and heating during winter for the internal spaces is AC in southern China, the electricity from the power grid was chosen as the energy supply pattern in the simulation throughout the year. The setting parameters in the simulation need to be adjusted considering the air-conditioned conditions and occupancy schedules for various rooms.

In this study, the energy performance of five buildings (CASE-A/CASE-B/CASE-C/CASE-D/CASE-E) was investigated as a function of two operational cases. In the winter heating case, the building was airtight, and air exchange between the inside and outside occurred solely via infiltration. The inside air temperature was controlled using a heating system (18 °C in this study). In the summer mixed cooling case, the buildings were operated in a mixed mode of active cooling and natural ventilation. More specifically, if the outside air temperature was lower than the inside temperature and higher than the natural ventilation set-point temperature (12 °C in this study), then natural ventilation was introduced to chill the indoor air. If the cooling capacity of the natural ventilation is insufficient, the active cooling system operates to maintain the indoor air set-point temperature (26 °C in this study).

The energy consumed by the system was in the form of electricity, and the COP of the cooling system was 1.67. The internal gains (including lighting and equipment) were designed to be 4 and 5 W/m^2. All interior spaces were heated or cooled, except for the yards.

According to a questionnaire survey of 121 households, there were six members in most families. Considering daily life and sleep habits, indoor occupancy reaches its maximum during mealtimes, at 7:00–8:00 a.m., 1:00–2:00 p.m., and 5:00–6:00 p.m. Outside of these times, an average low occupancy of two persons is typical. The sensible heat was quantified at 70 W for each person with light activity.

2.4. Energy Saving Using Different Measures

Optimizing rural residences with low economic inputs to minimize energy consumption is vital. Considering that the thermal properties of the building envelopes are the main reason for the poor thermal environment, energy efficiency measures could be introduced to address these aspects, such as decreasing the shape factor (CASE-A), using solar energy with a sunroom (CASE-B), introducing a thermal insulation layer into the external wall and roof (CASE-C), attaching a sloping roof with an air gap (CASE-D), and installing double single-glazed windows (CASE-E), as shown in Figure 4.

3. Results and Discussion

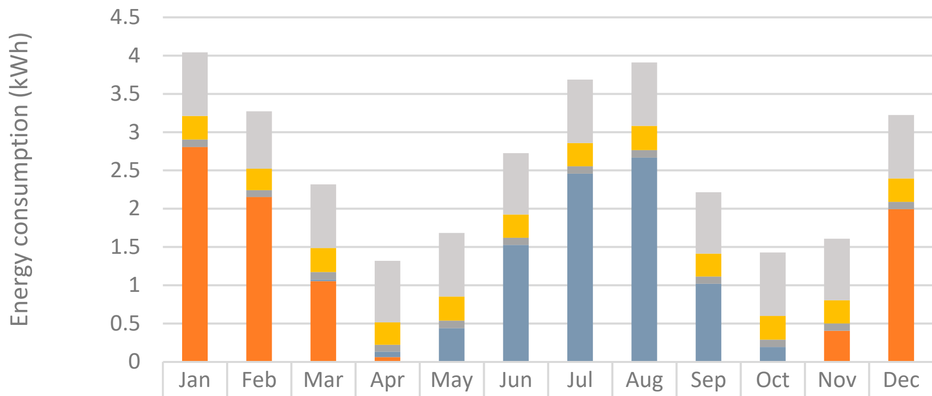
3.1. Simulation Results of CASE-A

Most tubular houses are built in the form of townhouses rather than separate single houses. Hence, the shape factor can be decreased, and the heat loss from the external surfaces can be reduced.

CASE-A is a typical two-story tubular house located in the middle of a group of townhouses with an area of 154.08 m^2, while the modified building area was 115.20 m^2. According to the CASE-A analysis in Open-Studio, the annual energy consumption of the tubular house was 21,603 kWh in total, and 187.53 kWh/m^2 in the building area. The heat load was 55.05 W/m^2, while the cooling load was 54.04 kWh/m^2.

As shown in Figures 6–8, it is evident that both the cooling and heating loads accounted for approximately 27% of the total energy consumption. The energy-saving renovation of the tubular house should focus on both winter and summer, especially in July (average outdoor temperature of 27.6 °C), August (average outdoor temperature of 28.2 °C), January (average outdoor temperature of 5.2 °C), and February (average outdoor temperature of 6.6 °C). On the other hand, April and October represent the most comfortable seasons, with average outdoor temperatures of 16.2 °C and 19.2 °C, respectively, and the energy consumption during these seasons is almost zero.

Figure 9 shows the peak loads for each space. This suggests that both the cooling and heating peak loads of the second floor are much higher than those of the first floor because of insufficient roof insulation. Furthermore, the peak loads of the rooms beside the courtyard are lower than those of the other rooms, suggesting that the courtyard enables a reduction in the heating load by introducing sunlight and a reduction in the cooling load by providing ventilation. Thus, it has a positive effect on the energy conservation.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Fans	829.86	749.55	829.86	803.09	829.86	803.09	829.86	829.86	803.09	829.86	803.09	829.86
Interior Equipment	308.93	280.27	314.94	292.56	314.94	303.38	304.12	314.94	298.57	308.93	303.38	304.12
Interior Lighting	95.65	87.52	98.61	90.91	98.61	94.91	94.61	98.61	93.87	95.65	94.91	94.61
Cooling	0.51	0.41	19.6	70.12	437.52	1524.1	2457.6	2666.6	1018.5	182.83	2.88	0.66
Heating	2805.9	2153.5	1052.8	60.25	0.28	0.09	0.1	0.03	0.22	9.54	402.24	1993.8

Figure 6. Energy consumption of various equipment of CASE-A.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Outdoor Air Dry Bulb (C)	5.2	6.6	10.8	16.3	21.2	24.9	27.6	28.2	24.1	19.2	12.7	6.5
Cooling Load (kWh)	0.51	0.41	19.6	70.12	437.52	1524.11	2457.64	2666.56	1018.53	182.83	2.88	0.66
Heating Load (kWh)	2805.86	2153.51	1052.75	60.25	0.28	0.09	0.1	0.03	0.22	9.54	402.24	1993.83

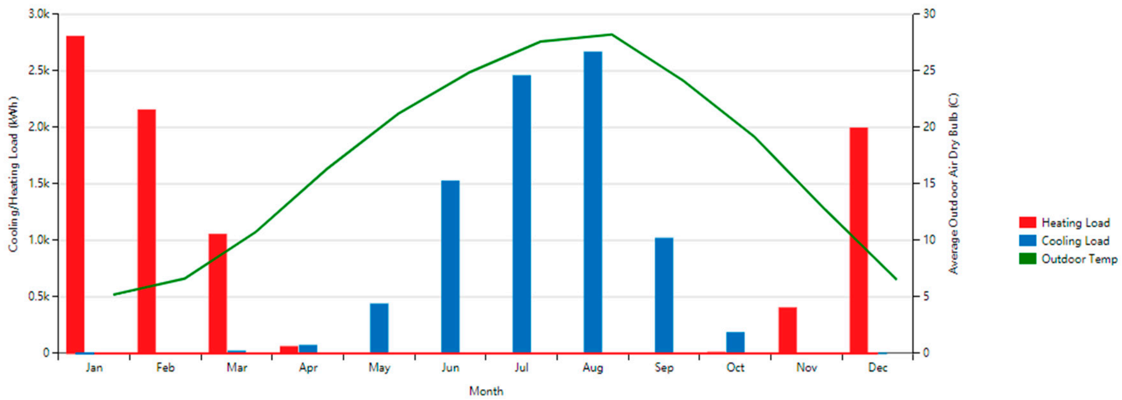


Figure 7. Monthly cooling load and heating load (kWh), as well as the monthly average outdoor temperature (°C).

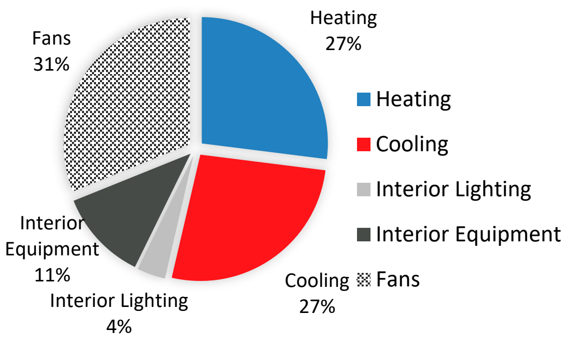


Figure 8. Energy consumption of various equipment.

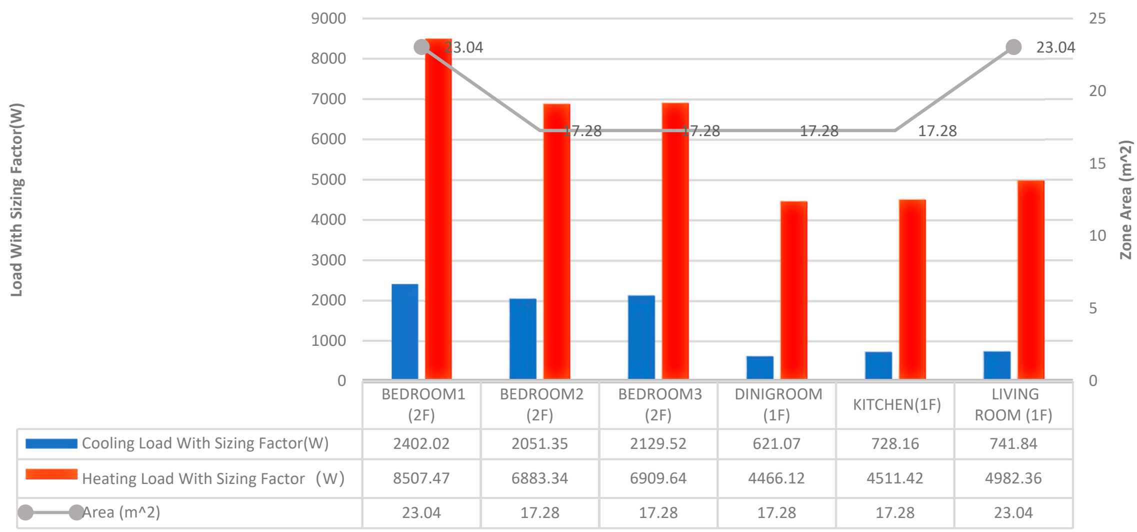


Figure 9. Cooling peak load and heating peak load of each zone, along with the sizing factor (W).

3.2. *Simulation Results of Using Solar Energy and Sunroom*

CASE-B: Two yards were transformed into sunrooms with openable windows added to the roof. These windows were closed in winter for indoor heat storage and opened in summer to increase ventilation, thereby reducing energy consumption.

As shown in Figures 10 and 11, in CASE-B, the annual consumption decreased from 187.85 to 134.98 kWh/m^2, with an energy-saving rate of 28%, providing the most effective energy-saving measures.

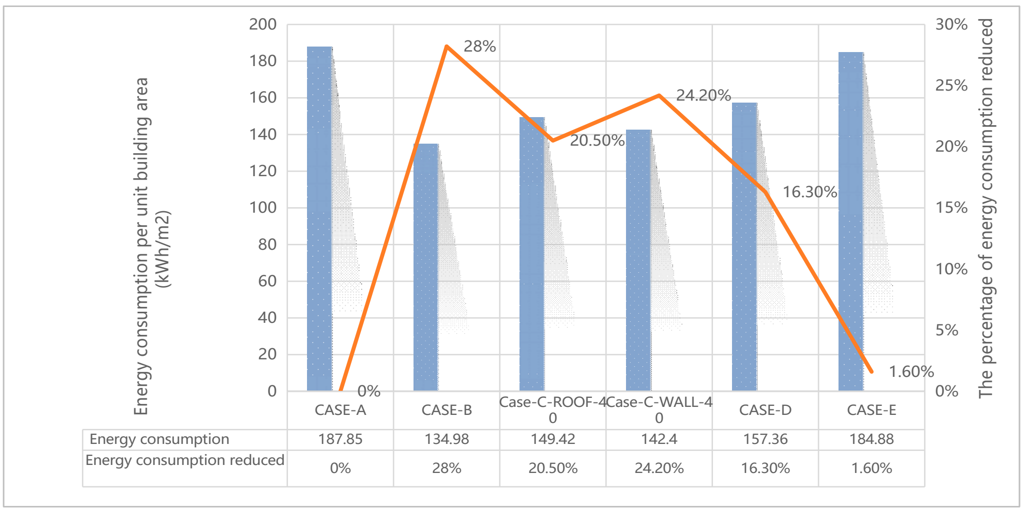
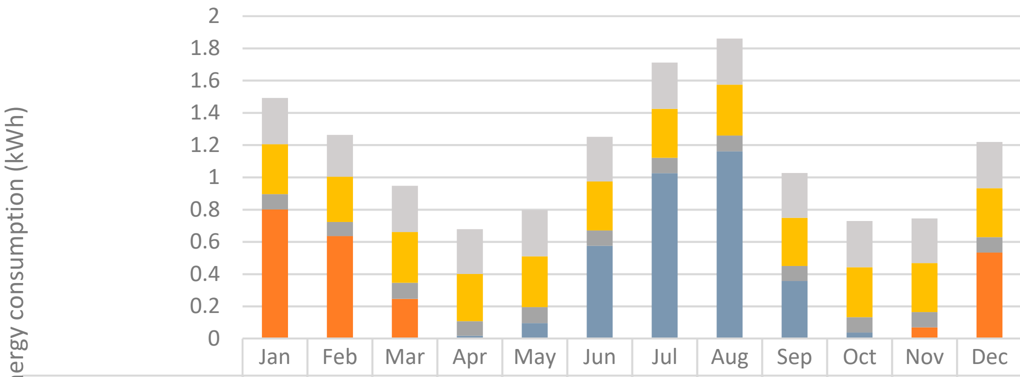


Figure 10. Energy-saving rates of different measures. CASE-A: a traditional tubular house built in the form of townhouses; CASE-B: solar energy use with sunroom; CASE-C-ROOF-40: insulation roof with 40 mm XPS; CASE-C-WALL-40: insulation wall with 40 mm XPS; CASE-D: sloping roof with air gap; CASE-E: double single-glazed windows.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Fans	286.65	258.91	286.65	277.41	286.65	277.41	286.65	286.65	277.41	286.65	277.41	286.65
Interior Equipment	308.93	280.27	314.94	292.56	314.94	303.38	304.12	314.94	298.57	308.93	303.38	304.12
Interior Lighting	95.65	87.52	98.61	90.91	98.61	94.91	94.61	98.61	93.87	95.65	94.91	94.61
Cooling	0.18	0.24	1.22	10.19	95.87	575.53	1026	1160.7	356.53	37.15	0.47	0.28
Heating	800.48	635.68	245.98	7.05	0.3	0.1	0.14	0.07	0.2	0.32	69.25	533.79

Figure 11. Energy consumption of various equipment of the CASE-X.

The original tubular houses feature a narrow patio to extract wind and accelerate indoor air circulation. After the renovation, as shown in Figure 12, in summer, the high windows were opened, and the glass roof was heated by solar radiation, which enhanced the effect of wind extraction and discharged the indoor heat. In winter, the windows were closed to form a greenhouse effect, which helped to maintain indoor heat. In this way, tubular houses can have a better energy-saving effect and become more economical.

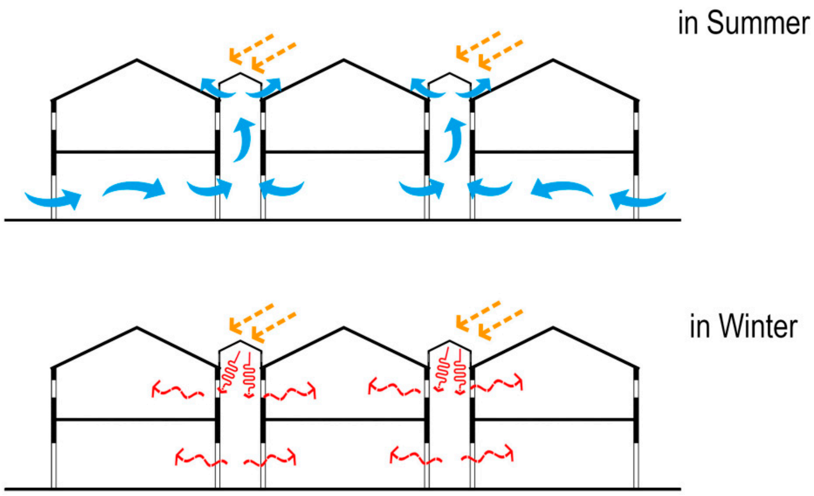


Figure 12. Working diagram of using solar energy and a sunroom in summer and winter.

3.3. Simulation Results of Insulation Roof and Wall

CASE-C: Thermal insulation in external walls and roofs has become a widespread energy-saving measure for village buildings in China. Extruded polystyrene and expansion polystyrene boards, commonly known as XPS and EPS boards, are generally used as insulation materials. An extruded polystyrene board was selected as the insulation material for the simulation because of its superior adhesive properties. Insulation materials (XPS) with different thickness (10–100 mm) were added to the roof (CASE-C roof) or walls (CASE-C wall) to assess their effect on annual energy consumption.

As shown in Figure 13, thickening the insulation materials of the roof from 0 to 100 mm led to a decrease in winter energy requirements to 144.95 kWh/m^2, with an energy-saving rate of 23%. Accordingly, thickening the insulation materials of the walls from 0 to 100 mm could also decrease the winter energy requirement to 130.58 kWh/m^2, for an energy-saving rate of 30.5%. It is evident that the insulation material of the walls was more effective because the exterior wall area was larger than that of the roof. More importantly, the energy-saving rate decreased slowly when the thickness of the insulation materials was increased beyond 30 mm, according to the trend shown in Figure 13. Considering the economic factors, it is recommended to choose 30 mm XPS, which was found to be the most efficient.

By simulating the impact of different XPS thicknesses on the energy consumption of tubular houses, a curve regression simulation was performed on the data. The relationship between energy consumption and XPS material thickness was established using a highly fitting logarithmic curve. The specific energy consumption (EIR) and thickness of the roof insulation material XPS (N) were fitted to the following logarithmic function: EIR = 177.469 − 7.317 × ln(N), where N = 10, 20, 30, . . . , 90, 100 (see Equation (1) and Table 3), with a fitting index R^2 = 0.969 and a Pearson correlation coefficient p < 0.0001, much lower than the limit of 0.01, indicating a high degree of fitness, as shown in Figure 14. The specific energy consumption (EIW) and thickness of the wall insulation material XPS (N) were fitted to the following logarithmic function: EIW = 194.114 − 14.173 × ln(N), where N = 10, 20, 30, . . . , 90, 100 (see Equation (2) and Table 4), with a fitting index R^2 = 0.986 and a Pearson correlation coefficient p < 0.0001, much lower than the limit of 0.01, indicating a high degree of fitness, as shown in Figure 15. A highly fitting logarithmic curve may rigorously guide the choice of insulation material thickness in the energy-saving renovation of other tubular houses.

Table 3. Parameter Estimates of EIR and N.

Parameter Estimates of EIR and N					
	Unstandardized Coefficients		Standardized Coefficients	t	p
	B	Standard Error	Beta		
Constant	177.469	1.798	-	98.679	0.000 **
ln(N)	−7.317	0.464	−0.984	−15.77	0.000 **

$p < 0.05$, ** $p < 0.01$.

Table 4. Parameter Estimates of EIW and N.

Parameter Estimates of EIW and N					
	Unstandardized Coefficients		Standardized Coefficients	t	p
	B	Standard Error	Beta		
Constant	194.114	2.152	-	90.21	0.000 **
In(N)	−14.173	0.555	−0.994	−25.528	0.000 **

$p < 0.05$, ** $p < 0.01$.

3.4. *Simulation Results of Attaching Sloping Roof with Air Gap*

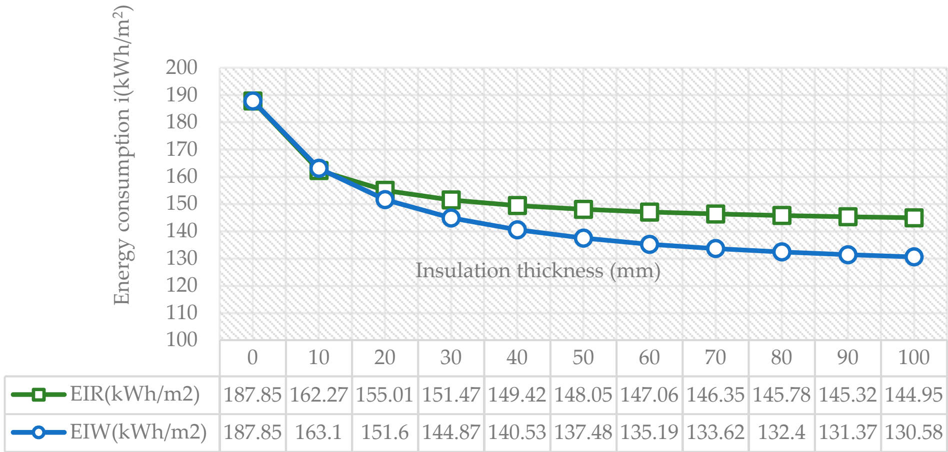
CASE-D: The traditional tubular house has a flat roof without any insulation measures. CASE-D involved adding a sloping roof with an air gap to the top of the house, thereby not only adapting to the architectural features of this area, but also contributing to roof insulation (see Figure 4).

As shown in Figure 10, in CASE-D, the annual energy requirement decreased from 187.85 to 157.36 kWh/m^2, with an energy-saving rate of 16.3%, thus exhibiting a significant result.

3.5. Simulation Results of Insulation Windows

CASE-E: The insulating level of windows in traditional tubular houses is also relatively poor. All single clear windows with an aluminum window frame commonly used in traditional tubular houses were replaced with double single-glazed windows.

As shown in Figure 10, in CASE-E, the annual energy requirement decreased from 187.85 to 184.88 kWh/m^2, with an energy-saving rate of only 1.6%, thus providing little reduction in energy consumption. This is because the external window area of tubular houses is quite small, and simple double-glazing would not have much of an effect.



	0	10	20	30	40	50	60	70	80	90	100
EIR(kWh/m2)	187.85	162.27	155.01	151.47	149.42	148.05	147.06	146.35	145.78	145.32	144.95
EIW(kWh/m2)	187.85	163.1	151.6	144.87	140.53	137.48	135.19	133.62	132.4	131.37	130.58

Figure 13. Energy consumption for insulation materials (XPS) of different thickness (kWh/m^2).

$$EIR = 177.469 - 7.317 \times \ln(N),\ N = 10, 20, 30, \ldots, 90, 100;\ R^2 = 0.969, \quad (1)$$

where EIR is the energy consumption in the case of the insulation roof (kWh/m^2) and N is the insulation thickness of XPS.

$$EIW = 194.114 - 14.173 \times \ln(N),\ N = 10, 20, 30, \ldots, 90, 100;\ R^2 = 0.986, \quad (2)$$

where EIR is the energy consumption in the case of the insulation wall (kWh/m^2) and N is the insulation thickness of XPS.

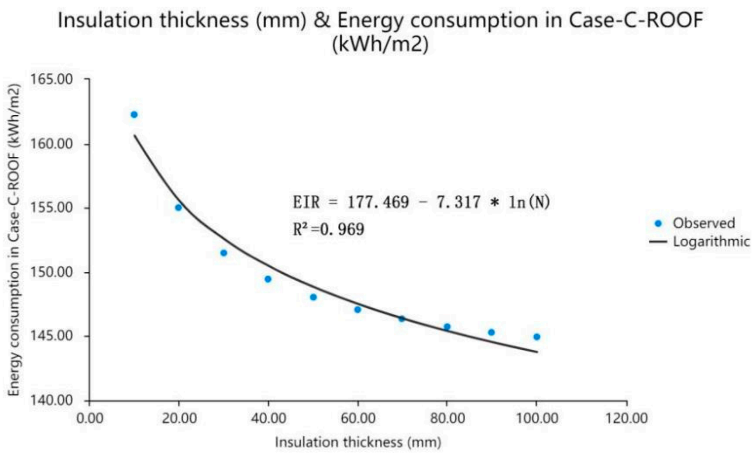


Figure 14. Logarithmic curve of EIR and N.

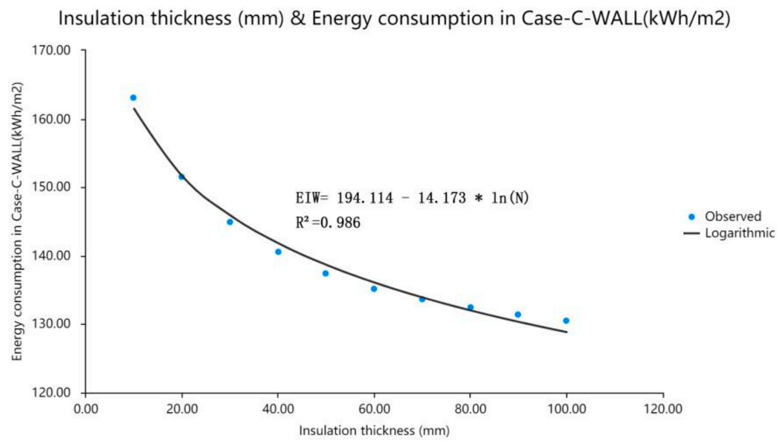


Figure 15. Logarithmic curve of EIW and N.

3.6. Simulation Results of Integrated Optimization

Based on all the simulation results above, considering the economic factors, the best integrated optimization measures for tubular houses in northern Zhejiang should be conducted as follows: CASE-B + CASE-C (30 mm) + CASE-D = CASE-X. The optimal measures were determined by all the simulation results of CASE-B to E. As shown in Figure 10, CASE-B, CASE-C, and CASE-D all provided significant results in terms of energy consumption, while CASE-E provided little reduction, with an energy-saving rate of only 1.6%. According to the CASE-X analysis in Open-Studio, the annual energy consumption of the tubular house was 13,719 kWh in total, and 86.83 kWh/m^2 in the building area, with an energy-saving rate of 47.4% compared with CASE-A. The heat load was 14.52 kWh/m^2, while the cooling load was 20.66 kWh/m^2, and the heat load was more optimized than the cooling load.

According to the National Bureau of Statistics of China, the consumption of 1 kWh of electrical power requires the burning of 0.404 kg of standard coal, which results in CO_2 emissions of 0.872 kg. The CO_2 emissions corresponding to CASE-A and CASE-X were 18,838.21 kg (21,603 kWh) and 11,962.9 kg (13,719 kWh), respectively, with a total difference of 6875 kg.

3.7. Economic Analysis of Renovation

Economic efficiency is an important factor restricting building renovations. Among insulation materials [8], the expansion of polystyrene board (EPS) and extruded polystyrene board (XPS) insulation are widely used. The XPS boards were chosen as exterior wall insulation and priced at 80 CNY/m^2. Subjected to geographical and technological limitations, existing solar rooms mainly use aluminum–plastic materials with an average price of 120 CNY/m^2.

According to the simulation results, the annual accumulated heat load of the building was 7884 kW h before rebuilding. Converting the saved heat load of renovation measures into electricity priced at CNY 1.1, the total energy-saving benefit is CNY 8672.4.

As shown in Table 5, the sunroom costs CNY 4752, accounting for only 11.5% of the total cost of energy-saving renovation, with the most effective energy-saving rate of 28%. Attaching a sloping roof accounted for 46.6% of the total cost, with the most effective energy-saving rate of 16.3%. The total renovation cost is CNY 41,143.1, and the payback period of investment is within 5 years (4.75).

Table 5. Energy-saving renovation costs.

Component	Energy-Saving Materials	Price (CNY/m^2)	Area (m^2)	Labor Cost (CNY/per)	Total Cost (CNY)
Insulation roof	30-XPS	80	77.04	80	12,326.4
Insulation wall	30-XPS	80	30.56	80	4889.6
Sunroom	Aluminum frame window	120	23.76	80	4752
Sloping roof	Reinforced concrete	150	83.376	80	19,175.1
Total cost					41,143.1

4. Conclusions

Tubular houses, named for their narrow and long forms, are common in southern China. They are a good example of a regional building that is adapted to the local climate. According to the results of field measurements, the thermal environment of traditional tubular houses is not always optimal, whereby both the cooling and heating loads account for approximately 27% of the total energy consumption. Thus, energy-saving renovations of tubular houses should focus on both winter and summer, especially in the months of July, August, January, and February. On the other hand, April and October are the most comfortable seasons, with average outdoor temperatures of 16.2 °C and 19.2 °C; as such, the energy consumption during these seasons is almost zero.

In the CASE-B to E simulation, different energy efficiency measures were evaluated in terms of their effects on annual energy consumption. The results show that various levels of reduction in energy consumption (varying from 1.6% to 30.5%) were achieved by combining different renovations. Among them, using solar energy with a sunroom was found to be the most effective approach, with an energy-saving rate of 28%, followed by the approach of attaching insulation to the walls and roof, with an energy-saving rate ranging from 13.2% to 30.5%. Furthermore, it was found that the energy-saving rate decreased slowly when the thickness of insulation materials was increased beyond 30 mm, according to the trend of the logarithmic curve. Thus, considering the economic factors, it is recommended to choose 30 mm XPS, which was found to be the most efficient. Additionally, attaching a sloping roof with an air gap to the top of the house was also successful, with an energy-saving rate of 16.3%; however, double single-glazed windows provided little reduction in energy consumption, with an energy-saving rate of only 1.6%, owing to the small external window area of tubular houses.

The relationship between energy consumption and XPS material thickness was also established using a highly fitting logarithmic curve. The specific energy consumption (EIR) and thickness of the roof insulation material XPS (N) were fitted to the following logarithmic function: EIR = 177.469 − 7.317 × ln(N), with a fitting index R^2 = 0.969 and a Pearson correlation coefficient $p < 0.0001$. The specific energy consumption (EIW) and thickness of the wall insulation material XPS (N) were fitted to the following logarithmic function: EIW = 194.114 − 14.173 × ln(N), with a fitting index R^2 = 0.986 and a Pearson correlation coefficient $p < 0.0001$. This conclusion can effectively guide the choice of insulation material thickness in the energy-saving renovation of tubular houses.

The best integrated optimization measures for tubular houses in northern Zhejiang should be conducted as follows: CASE-B + CASE-C (30 mm) + CASE-D = CASE-X, with an energy-saving rate of 47.4% compared with CASE-A. The total renovation cost is CNY 41,143.1, and the payback period of investment is within 5 years (4.75).

This study showed that the application of environmental adaptations to tubular houses, along with improved thermal insulation, can drastically reduce energy consumption. If this is inherited as a component in the process of urbanization, it will aid in energy conservation and natural ecosystem protection in southern China.

Author Contributions: Conceptualization, J.W., W.G.; data curation, J.W.; formal analysis, J.W.; funding acquisition, Z.W.; investigation, J.W.; methodology, J.W., W.G., Z.W.; project administration, Z.W.; resources, L.Z.; software, J.W.; supervision, W.G.; validation, W.G.; visualization, W.G.; writing—original draft, J.W.; writing—review and editing, L.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Science Foundation of China (Grant No. 51238011).

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: Not Applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Berardi, U. Clarifying the new interpretations of the concept of sustainable building. *Sustain. Cities Soc.* **2013**, *8*, 72–78. [CrossRef]
2. Son, H.; Kim, C.; Chong, W.K.; Chou, J.S. Implementing sustainable development in the construction industry: Constructors' perspectives in the us and korea. *Sustain. Dev.* **2011**, *19*, 337–347. [CrossRef]
3. The United Nations Framework Convention on Climate Change. 2008. Available online: http://unfccc.int/essential_background/kyoto_protocol/items/1678.php (accessed on 22 March 2016).
4. European Commission. *Energy Performance of Buildings Directive 2002/91/EC(EPBD)*; European Commission: Brussels, Belgium; Luxembourg, 2002.
5. Rodriguez-Ubinas, E.; Montero, C.; Porteros, M.; Vega, S.; Navarro, I.; Castillo-Cagigal, M. Passive design strategies and performance of Net Energy Plus Houses. *Energy Build.* **2014**, *83*, 10. [CrossRef]
6. Lau, L.C.; Tan, K.T.; Lee, K.T.; Mohamed, A.R. A comparative study on the energy policies in Japan and Malaysia in fulfilling their nations' obligations towards the Kyoto Protocol. *Energy Policy.* **2009**, *37*, 4771–4778. [CrossRef]
7. Kibert, C.J. Green Building Design and Delivery. *Sustain. Constr.* **2012**, *4*, 53.
8. Sadafi, N.; Salleh, E.; Haw, L.C.; Jaafar, Z. Evaluating thermal effects of internal courtyard in a tropical terrace house by computational simulation. *Energy Build.* **2011**, *43*, 887–893. [CrossRef]
9. Zou, Y.; Song, B.; Liu, J. An interpretation of the national standards for energy efficiency design of rural residential buildings. *Heat. Vent. Air Cond.* **2013**, *43*, 77–81.
10. He, B.J. Building energy efficiency in China rural areas: Situation, drawbacks, challenges, corresponding measures and policies. *Sustain. Cities Soc.* **2014**, *11*, 7–15. [CrossRef]
11. Building Energy Conservation Research Center TU. *Chinese Residential Energy Annual Development Report in 2013*; China Architecture and Building Press: Beijing, China, 2013. (In Chinese)
12. Building Energy Conservation Research Center TU. *China Building Energy Efficiency Annual Development Report in 2012*; China Architecture and Building Press: Beijing, China, 2012. (In Chinese)
13. Mohsen, M.; Akasha, B. Some prospects of energy savings in buildings. *Energy Convers. Manag.* **2001**, *42*, 1307–1315. [CrossRef]
14. Gowreesunker, B.L.; Tassou, S.A. Effectiveness of CFD simulation for the performance prediction of phase change building boards in the thermal environment control of indoor spaces. *Build. Environ.* **2013**, *59*, 612–625. [CrossRef]
15. Lee, J.W.; Jung, H.J.; Park, J.Y.; Lee, J.B.; Yoon, Y. Optimization of building window system in Asian regions by analyzing solar heat gain and day-lighting elements. *Renew. Energy.* **2013**, *50*, 522–531. [CrossRef]
16. He, W.; Hu, Z.; Luo, B.; Hong, X.; Sun, W.; Ji, J. The thermal behavior of Trombe wall system with venetian blind: An experimental and numerical study. *Energy Build.* **2015**, *104*, 395–404. [CrossRef]
17. Jacobs, J. *The Death and Life of Great American Cities*; Random House: New York, NY, USA, 2016.
18. Nayak, P.K.; Mahesh, S.; Snaith, H.J.; Cahen, D. Photovoltaic solar cell technologies: Analysing the state of the art. *Nat. Rev. Mater.* **2019**, *4*, 269–285. [CrossRef]
19. Heydari Gharahcheshmeh, M.; Tavakoli, M.M.; Gleason, E.F.; Robinson, M.T.; Kong, J.; Gleason, K.K. Tuning, optimization, and perovskite solar cell device integration of ultrathin poly (3,4-ethylene dioxythiophene) films via a single-step all-dry process. *Sci. Adv.* **2019**, *5*, eaay0414. [CrossRef]
20. Oropeza-Perez, I.; Østergaard, P.A. Potential of natural ventilation in temperate countries—A case study of Denmark. *Appl. Energy* **2014**, *114*, 520–530. [CrossRef]
21. Maestre, I.R.; Cubillas, P. Influence of selected solar positions for shading device calculations in building energy performance simulations. *Energy Build.* **2015**, *101*, 144–152. [CrossRef]
22. Badescu, V.; Laaser, N.; Crutescu, R. Warm season cooling requirements for passive buildings in Southeastern Europe (Romania). *Energy* **2010**, *35*, 3284–3300. [CrossRef]
23. Badescu, V.; Laaser, N.; Crutescu, R.; Crutescu, M.; Dobrovicescu, A.; Tsatsaronis, G. Modeling, validation and time-dependent simulation of the first large passive building in Romania. *Renew. Energy* **2011**, *36*, 142–157. [CrossRef]

24. Ma, C.; Liu, Y.; Wang, D. Analysis of thermal performance and energy saving strategy of rural residential buildings in Northwest China. *J. Xi'an Univ. Arch. Technol.* **2015**, *47*, 427–432.
25. Zhu, X.R.; Liu, J.P.; Yang, L. Energy performance of a new Yaodong dwelling in the Loess Plateau of China. *Energy Build.* **2014**, *70*, 159–166. [CrossRef]
26. Sun, H.; Leng, M. Analysis on building energy performance of Tibetan traditional dwelling in cold rural area of Gannan. *Energy Build.* **2015**, *96*, 251–260. [CrossRef]
27. Jin, Z.S. Energy saving treatment of Guangzhou old residential. *South China Inst. Technol.* **1965**, *4*, 48–49.
28. Lin, H.K. Study on Guangzhou Tubular House Model Space Adapting to Hot and humid Climate. *South China Univ. Technol.* **2012**, *25*, 105–106.
29. Gao, N. Numerical Simulation of Natural Ventilation of Traditional Residential Buildings in Lingnan Area. *Build. Energy Environ.* **2015**, *34*, 76–79.
30. Lin, S.D. Preliminary study on spatial design of tubular houses in Zhangzhou. *Chin. Foreign Build.* **2013**, *8*, 75–77.
31. Wang, X.L. Study on the regional sexuality of living space. *Hebei Univ. Technol.* **2008**, *3*, 45–48.
32. Deng, X.R. Influence of structure of tubular houses on ventilation in Northern Zhejiang Province. *Zhejiang Univ.* **2020**, *11*, 223–225. Available online: http://qikan.cqvip.com/Qikan/Article/Detail?id=7103257422 (accessed on 1 October 2021).
33. Al-Sallal, K.A. Testing glare in universal space design studios in Al-Ain. UAE desert climate and proposed improvements. *Renew. Energy* **2007**, *32*, 1033–1044. [CrossRef]
34. Krüger, E.L.; Dorigo, A.L. Daylighting analysis in a public school in Curitiba, Brazil. *Renew. Energy* **2008**, *33*, 1695–1702. [CrossRef]
35. Kharrufa, S.N.; Adil, Y. Roof pond cooling of buildings in hot arid climates. *Build. Environ.* **2008**, *43*, 82–89. [CrossRef]
36. Yi, H.; Braham, W.W. Uncertainty characterization of building energy analysis (BEmA). *Build. Environ.* **2015**, *92*, 538–558. [CrossRef]
37. Mastrucci, A.; Rao, N.D. Decent housing in the developing world: Reducing lifecycle energy requirements. *Energy Build.* **2017**, *152*, 629–642. [CrossRef]
38. Bui, D.K.; Nguyen, T.N.; Ghazlan, A. Enhancing building energy efficiency by adaptive façade: A computational optimization approach. *Appl. Energy* **2020**, *265*, 114797. [CrossRef]
39. Shan, X.; Luo, N.; Sun, K.; Hong, Y. Coupling CFD and building energy modelling to optimize the operation of a large open office space for occupant comfort. *Sustain. Cities Soc.* **2020**, *60*, 102257. [CrossRef]
40. EnergyPlus TM Version 9.1.0 Documentation—Engineering Reference. U.S. Department of Energy. 2019. Available online: https://bigladdersoftware.com/epx/docs/9-1/engineering-reference/ (accessed on 18 April 2019).
41. EnergyPlus, U.S. Department of Energy's (DOE) Building Technologies Office (BTO). Available online: https://energyplus.net/ (accessed on 18 April 2019).