Early-Stage Design Parameters for Low-Energy Solar Rural Houses in Qinghai-Tibet Plateau

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Abstract. As an effective solution to achieve carbon neutrality, the development of low-energy solar houses is now in the ascendant in China. The Qinghai Tibet Plateau (QTP), which is rich in solar energy resources, is considered to be an important region for solar technologies studying. Rural houses are the main living form for residents in the QTP, early-stage design parameters play an important role in achieving low-energy consumption of rural houses. However, researches on the design method and parameters of low-energy solar rural house were relatively poor at present. This paper examined the influence of early-stage design parameters on the energy performance of low-energy solar rural houses incorporating building-integrated photovoltaic (BIPV) roof systems. A 2-storey 110 m2 rural house was studied as an archetype. Through simulation, a range of related building parameters, such as shape coefficient, window-to-wall ratio (WWR) and azimuth angle were analysed and compared. The impact of early-stage design parameters on energy consumption in winter, ventilation in summer and BIPV system annual energy yield were considered.

1 Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), human activity is the main cause of current global warming, we still have means to stabilize temperature increase to below 2 °C relative to the pre-industrial level, but it will require an urgent and fundamental departure from now [1]. Fossil energy consumption and greenhouse gas emissions have largely contributed to climate change. In response to the increasingly severe environmental issues and climate change. As the largest national emitter of greenhouse gases, China committed itself under the Paris Agreement to reach a carbon emissions peak by around 2030 [2] and, in the meanwhile, it announced the ambition to be carbon-neutral by 2060 [3]. The building sector consumes about 35% of the entire energy within China [4], so there is an urgency to take stringent measures to enhance building energy efficiency.

Qinghai-Tibet Plateau (QTP) is located in South-western China (78.3°–103.1° E, 26.5°–39.5° N) and situated at an average elevation of around 4,000 m above the sea level, which is known as the world's roof [5]. The QTP is considered to be an energy poverty area because of its high altitude, low temperature, undeveloped transportation and insufficient energy infrastructure construction[6]. Meanwhile, there are abundant solar energy resources in QTP show high potential to develop solar energy systems for buildings [7]. In addition, solar thermal and photovoltaic (PV) technologies have been used in buildings due to the significant development of technologies and the cost reduction of relevant equipment [8].

Xining region (101° 76' E, 36° 62' N) is located in the northeast corner of the QTP, which is the biggest population settlement of that region. The annual mean temperature of the Xining region is about 4.3 °C and shows a linear upward trend with 0.39 $°C \cdot (10\ a)^{-1}$. Mean annual rainfall is 394.3 mm ~ 535.6 mm, while more than 56% of the rainfall occurs in summer [9]. The heating period of the Xining region is from 15th, October to 15th, April of next year, last for 183 days [10]. Solar energy resources are rich in the Xining region, which provides a good basis for application for solar energy technologies. The annual duration of sunshine of this region is from 2,566.2h ~ 2,661.9h, there is a positive correlation between sunshine duration and solar radiation intensity. Annual solar global radiation is from 5,180 – 6,337 MJ/m^2.

Energy consumption of rural houses accounts for 23%~24% of total building energy consumption in China from 2000-2019, and the growth rate of energy consumption per unit building area (ECPUBA) is increasing [11]. China has promoted economic development and targeted poverty alleviation projects in rural areas in recent years. Residents' living standard has risen a lot, which lead energy consumption of rural houses increasing significantly. However, most rural houses were built without thermal insulation structures, resulting in great energy waste. Many studies have proposed strategies to improve the energy-saving performance of rural houses, such as energy-saving

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retrofit technologies [12-14], using energy-efficient appliances [15,16], improving rural energy policies[17] etc. With the efforts to achieve carbon peak and carbon neutrality of the Chinese government, the design and construction of low-energy solar rural houses will draw more attention to the building sector.

Previous studies have explored the impact patterns of some parameters on energy consumption, such as orientation, interior layout, aspect ratio etc. However, rarely studied the impact of design parameters on rural houses in the QTP. Thus, this study focused on the relationship between early-stage design parameters and building energy consumption along with the efficiency of the BIPV system for low-energy solar rural house design of the QTP region.

2 Methods

2.1 Rural houses and its archetype

One of the traditional rural houses in the QTP is called Zhuang-ke dwelling, which is built of thick rammed earth and characterized by warm in winter, cool in summer and windproof sand [18]. Zhuang-ke dwellings have good regional and climate adaptability, however, they need long construction time and take great manpower. It has been replaced gradually by modern construction in recent years. Rural houses are generally built into courtyard houses and a courtyard is enclosed by walls or the building itself.

In rural houses in Xining as an example, residents now cover the courtyard by using aluminium frames and glass structure (AFGS) (Figure 1) to prevent cold wind, accept more sunlight, raise indoor temperature in winter, keep the yard clean and against burglars. This structure is applied widely by residents because of its low cost, easy construction and good flexibility. The temperature of the courtyard can be increased significantly when enclosed by AFGS, which provides a better environment for residents to carry out labour and living practices in winter.

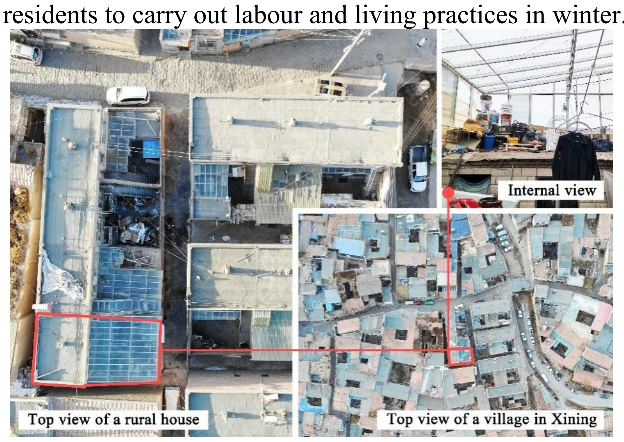

Fig. 1. Rural houses in Xining, QTP.

Martin and March 1972 first proposed a set of formal building archetypes as a method of building form analysis to simplify the analysis of urban building morphology and daylight access [19]. Rural houses were diverse in terms of materials, appearance and layout. However, there were also many similarities in the construction technology and living habits. A rural house archetype was built according to the common rural house form. This archetype oriented south and was composed of a living area and a courtyard. The living area was a 2-storeys building, and the courtyard was enclosed by a wall and covered with AFGS roof. The inclined surface of the AFGS roof was oriented south. Part of the AFGS area was replaced by BIPV modules to generate electric energy (Figure 2).

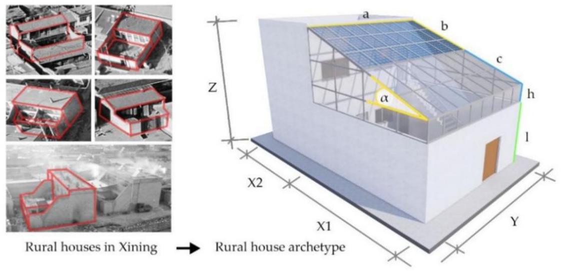

Fig. 2. Rural house archetype and its reference rural houses.

2.2 Related geometrical and parameters

The plan shapes were shown in Figure 3, where the total construction area was fixed as 110 m^2 (grey shading area) and the building floor height was defined as 3.3 m. Therefore, the volume of the living area was fixed, and the volume of the courtyard area was fixed. The length of side Y was increased from 6 m to 9.5 m, and sides X1 and X2 were shortened accordingly. With the change of side Y length, the area of the south exterior wall, the house aspect ratio and the shape coefficient also changed. The house aspect ratio was side Y divided by side X1 plus X2. The impact of shape change on building energy consumption was discussed, and PV modules were not applied in the simulation when using EnergyPlus software [20] to discuss building passive energy conservation strategies.

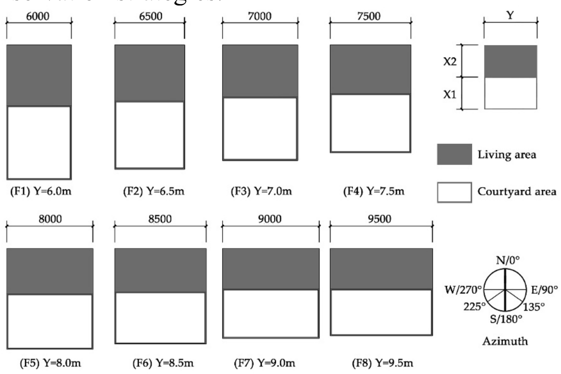

Fig. 3. Plan shapes of the rural house; grey shading indicates the living area, black frame indicates the courtyard area, linear measurement in millimetres (mm).

For the rural house courtyard with roof-integrated BIPV modules, the tilt angle of the roof and orientation of the building had a significant impact on the energy production of the PV system. The tilt angle of the roof was changed from 0° to 90°. Building azimuth is changed from 90° to 270° (north is 0) (Figure 4). A series of BIPV system options will be assessed in terms of the costs and energy production of BIPV systems through the

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renewable energy simulations modelling software RETScreen Expert [21].

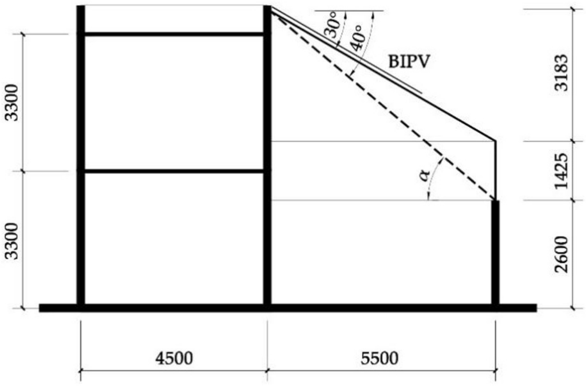

Fig. 4. Section of rural house and tilt angle of AFGS roof.

The insulation performance of walls and roofs was selected based on the TSNZEB (GB/T 51350-2019) standard [22]. This study focused on the relationship between building design parameters and energy efficiency, so that, the insulation performance of walls, roof and windows were fixed and its value were shown in Table 1.

Table 1. The insulation performance of construction in the simulation model.

Construction	Unites	Simulation model	Standard requirement
Exterior wall	$W/m^2{\cdot}K$	0.14	0.1 ~ 0.15
Exterior roof	$W/m^2{\cdot}K$	0.14	0.1 ~ 0.15
Ground floor	$W/m^2{\cdot}K$	0.27	0.2 ~ 0.3
Exterior window	$W/m^2{\cdot}K$	1.6	≤ 1
SHGC of window	-	0.65 in winter	≥ 0.45 in winter

Table 2. Simulation variables.

Variable	Initial value	Variation range
Plan shape	4	1, 2, 3, 4, 5, 6, 7, 8
House azimuth (°)	180	120~240; 9 levels
Floor height	3	2.7~3.9; 9 levels
WWR; south	0.24	0.1 ~ 0.5; 9levels
WWR; north	0.12	0.1~0.5; 9 levels
Window aspect ratio; south	4.1	1 ~ 7; 7 levels
Windowsill height; south	0.9	0.1 ~ 1.5; 8 levels
BIPV azimuth (°)	180	90~270; 13levels

A separate WWR was calculated for the south and north walls. The WWR of the south wall has a great impact on daylighting effectiveness and solar thermal gains. The WWR of the north wall has a great influence on heat loss. Effects of south window aspect ratio and windowsill height on energy consumption were simulated. The windows structure referred to appendix D of the TSNZEB (GB/T 51350-2019) standard [22], which is the aluminium-wood composite window (5+12 A+5+12 A+5 Low-E). Simulation variables were shown in Table 2.

3 Results

3.1. Form parameters affecting energy-saving performance

3.1.1 House form

When the building area remained a fixed value and the side length of the south exterior wall (side Y) was increased from 6 m to 9.5 m, the area of the south wall was increased, and meanwhile, the house aspect ratio (Y/(X1+X2)) was decreased, and the shape coefficient of the house was decreased at first and then increased. The shape coefficient is the ratio of the surface area of the building in contact with the outdoor atmosphere to the volume surrounding it. The relationship between annual energy consumption per unit building area (ECPUBA) with the increase of side Y was shown in Figure 5. The results showed that the change in energy consumption was nonlinear as first decreased then increased with the increase of side Y length, and energy consumption had a certain regularity with the change of shape coefficient. The results proved that a reasonable design for the width and depth of a rural house could significantly reduce energy consumption. There was an optimal shape coefficient for a small rural house, which needed to be discussed in the early-stage design.

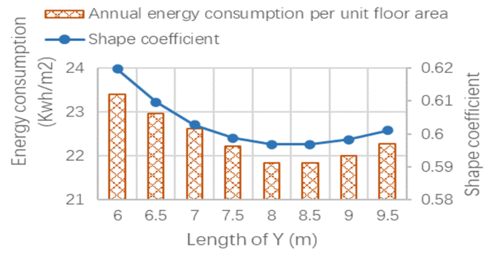

Fig. 5. The diagram of annual ECPUBA with length of side Y.

3.1.2 Window-to-wall ratio

The window-to-wall ratio (WWR), which was the measure of the percentage area of a building's exterior envelope that was made up of glazing, such as window, was an important parameter that could be controlled in the early-stage design. The influence of both WWR at the south and north on annual ECPUBA was simulated, and the results were shown below (Figure 6).

The result showed that energy consumption was significantly increased with the enlargement of WWR of the north external window in this simulation. However, energy consumption changed much less with the enlargement of WWR of the south, which was because the south window was not in contact with the outdoor environment directly but with air in the closed courtyard. WWR for the south window of 0.3 ~ 0.35 was considered an ideal value to save energy consumption in this simulation. Energy consumption could be increased when the south windows were too small or too large, this was because a small window could cause insufficient indoor solar radiation, and a large window could increase heat loss. Thus, it could be seen that it was necessary to weigh up the solar heat gain and indoor heat loss to find the best WWR of the south window. Meanwhile, the smaller the north window was, the more beneficial it was for energy saving when the north window was satisfied with the requirement of daylighting and ventilation.

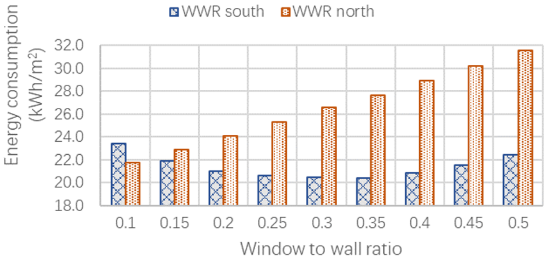

Fig. 6. The diagram of ECPUBA with WWR of both the south and north window.

3.1.3 South window aspect ratio and windowsill height

It was found that the windowsill height and window aspect ratio of the south window had an impact on annual ECPUBA when the area of the window remained the same in the simulation (Figure 7). The window aspect ratio was the width of the window divided by height. It was speculated that when the indoor heat loss was fixed, the change of shape and position of the south window affected the efficiency of solar heat gain. The simulation results indicated that elevating the windowsill height and reducing the window aspect ratio was beneficial to energy saving. Both these 2 changes elevated the height of the upper edge of the south window, which helped to extend the depth of direct sunlight entering the room.

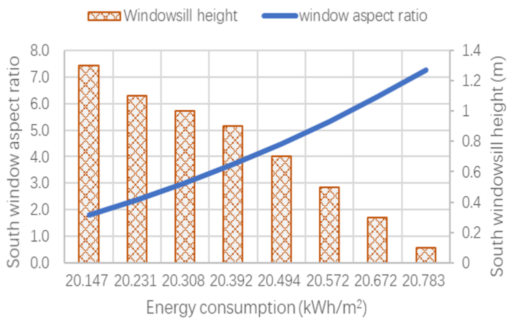

Fig. 7. The diagram of ECPUBA with windowsill height and window aspect ratio.

3.1.4 Orientation and floor height

The solar radiation transmission and the solar heat gain depended heavily on the orientation and the form of the rural house. The azimuth of the rural house archetype in this simulation was from 120° to 240° (180° was south) for 9 levels. The results showed that annual ECPUBA was the lowest when the azimuth angle was about 180° (Figure 8). And the same azimuth angle change towards the West increased energy consumption than that of change towards the East. The greater the azimuth angle was deflected away from the south, the larger the energy consumption could be. A low building energy consumption could be achieved when the house azimuth angle was within both 15° south by east and south by west.

There was a positive correlation between the floor height and energy consumption, which was because a higher floor height increased the heating load.

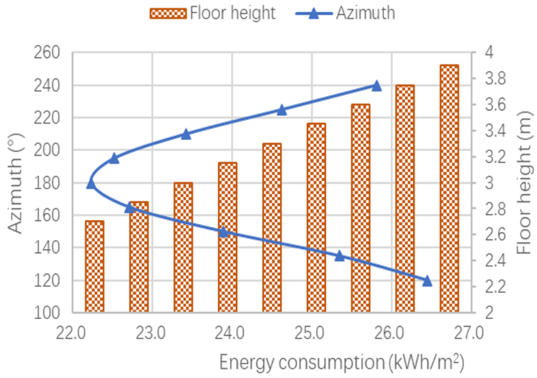

Fig. 8. The diagram of ECPUBA with house azimuth and floor height.

3.2. Effect of BIPV roof tilt angle and azimuth angle on PV power generation

Based on the methodology described before, the tilt and azimuth angle for all levels were simulated. The results showed that each angle had a different PV energy yield. To compare the difference between each simulation, a reference value was defined as the PV generation yield value in tilt angle 0°. Because power generation capacity remained a fixed value in this tilt angle. The growth rate of other PV generation yields relative to the reference value was calculated, and the results were illustrated in Figure 9. The red area had higher PV energy generation than the reference value, and a brighter colour presented a higher yield. Otherwise, the blue area had lower PV energy generation than the reference value, and a darker colour presented a lower yield.

According to Figure 9, there were 4 change regularities of the energy yield of BIPV systems in the rural house archetype in the Xining region. 1) PV energy generation when PV modules in the horizontal direction (tilt angle was 0°) was significantly larger than that in the vertical direction (tilt angle was 90°). 2) The azimuth angle of PV modules was closer to 180°, the greater PV energy generation. 3) The tilt angle of PV modules was closer to 30°, the greater PV energy generation. 4) There was a higher PV energy generation when the azimuth angle changed between 150° and 195°, and the tilt angle changed between 20° and 40°. The optimum tilt and azimuth angle after further simulation for PV installation in Xining was 180° and 33° respectively with an annual energy generation of 7866 kWh.

Azimuth (°) \ Inclination (°)	0	10	20	30	40	50	60	70	80	90
90 / E	0.00	0.00	-0.02	-0.05	-0.08	-0.13	-0.18	-0.25	-0.32	-0.39
105	0.00	0.02	0.02	0.01	-0.01	-0.05	-0.07	-0.17	-0.25	-0.33
120	0.00	0.04	0.06	0.06	0.04	0.01	-0.05	-0.11	-0.20	-0.29
135	0.00	0.06	0.09	0.10	0.09	0.06	0.00	-0.07	-0.16	-0.26
150	0.00	0.07	0.11	0.13	0.13	0.09	0.04	-0.04	-0.14	-0.25
165	0.00	0.08	0.13	0.15	0.14	0.11	0.05	-0.03	-0.13	-0.26
180 / S	0.00	0.08	0.13	**0.15**	0.15	0.11	0.05	-0.03	-0.14	-0.26
195	0.00	0.07	0.12	0.14	0.13	0.10	0.04	-0.04	-0.15	-0.27
210	0.00	0.06	0.10	0.11	0.10	0.07	0.01	-0.07	-0.17	-0.28
225	0.00	0.05	0.08	0.08	0.06	0.02	-0.03	-0.11	-0.19	-0.29
240	0.00	0.03	0.04	0.03	0.01	-0.03	-0.09	-0.16	-0.24	-0.32
255	0.00	0.01	0.00	-0.02	-0.05	-0.10	-0.15	-0.22	-0.29	-0.37
270 / W	0.00	-0.02	-0.04	-0.08	-0.12	-0.17	-0.23	-0.29	-0.35	-0.43

Fig. 9. Relative PV energy generation with different tilt and azimuth angle

Simulation results showed that there was a good output energy yield of the BIPV system every month, but a better performance of power generation efficiency from March to May. It also showed that most energy yield could be fed into the grid from March to November, which could increase electricity sales revenue for households. Some electricity needed to be purchased from the grid to meet the heating load and other electrical equipment's energy demand in winter. Continuous snowfall and low solar direct radiation also lead to the decline of the energy yield of the BIPV system. In the early-stage design, the tilt angle of BIPV panels should not be too small to better remove the snow on its surface. Although solar radiation was more abundant in summer, energy generation in this season was not the highest, because the high temperature in summer led to low-performance efficiency of the BIPV system. So, it is necessary to strengthen the natural ventilation of the courtyard to reduce the temperature of BIPV modules.

4 Discussion and Conclusions

The low-energy solar rural house design was a complex process. A reasonable consideration of BIPV at the early design stage along with passive design techniques could effectively reduce building energy consumption and improve PV power generation yield. However, the building systems integration and the intersection of the correlation disciplines make it more complex in low-energy solar rural house design in the QTP. The impact pattern of one or several design parameters on energy consumption, could not give a comprehensive guide for the early-stage design process. New technologies pose designers and architects new tasks and challenges, as well as opportunities for creating new, to create low-energy and sustainable environments and buildings.

Local architectural practices could be learned and utilized in the design and analysis of low-energy buildings in a region. Rural houses with AFGS structure were found in the field investigation and used to design a rural house archetype, which made the research for early-stage design parameters of this paper more conform to the local actual situation. The discovery and utilization of local building wisdom had meant for low-energy solar rural house design.

The early-stage design parameters for low-energy solar rural houses in the QTP were analyzed and collated in this paper, which enriched and improved the study on the design of low-energy buildings in the plateau area. Part of these parameters were simulated and analyzed by various simulation software. The influence characteristics of these parameters on building energy consumption were presented. For example, for low-energy solar rural houses, the shape coefficient was not necessarily lower, but rather there was an optimal value that could achieve the lowest energy consumption. Although a smaller shape coefficient could reduce energy consumption, it also reduced the acquisition of solar radiation. Therefore, the relationship between shape coefficient and energy consumption should be considered during design.

The climate in the QTP was cold. The north-facing window received less solar radiation, when meeting lighting needs, the smaller the north window, the better. The south window can receive heat from solar radiation and is also a heat loss component. Therefore, the window-to-wall ratio of the south window has an optimal value. For the south window, elevating the windowsill height and reducing the window aspect ratio was beneficial to energy saving.

A low building energy consumption could be achieved when the house azimuth angle was within both 15° south by east and south by west. The energy consumption of rural houses facing south was the lowest. An increase in building floor height will increase building energy consumption, so a lower floor height should be selected within a reasonable range.

Using BIPV was necessary for the development of low-energy solar rural houses in the QTP. The building should provide a reasonable platform for carrying the BIPV module. The highest photovoltaic production was achieved at an azimuth angle of 180° and a tilt angle of 33° in the Xining region. A better performance of power generation efficiency was from March to May. It is important to reduce the temperature of BIPV modules to improve PV electric production in summer. The QTP was rich in solar energy resources, and researching PV production played a significant role in developing low-energy solar rural houses.

Although the material of envelopes had a great impact on building energy efficiency, this paper mainly discussed the parameters in the early stage of design. Further research could be conducted on the patterns of energy consumption changes under the comprehensive influence of morphology and structure.

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