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Article

A simulation-based study on the energy efficiency of green façade retrofitting for different types of facades in rural China

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Abstract: As China's urbanisation continues, the building area is expanding, of which the occupancy of rural residential buildings is also very large. However, most rural buildings have poor thermal performance. This paper analyses the energy-saving potential of green facades for rural buildings in China by simulating typical buildings with different types of facades in rural China. The simulation results show that indirect green façades can achieve good energy savings. Buildings with four types of facades: red brick, rubble, hollow brick, and concrete achieve energy savings of 18.39%, 17.85%, 14.47%, and 11.52%, respectively, after retrofitting with green facades.

Keywords: green façade; energy efficiency; renovation; simulation; rural area

1. Introduction

China, as the world's largest developing country, is currently in a phase of rapid urbanisation. In recent decades, a large number of buildings have been constructed. By the end of 2023, the number of existing buildings in China had reached a staggering 660 million, with a total building area of over 50 billion square metres. Of these buildings, more than 90 % are located in rural areas. Rural building area accounts for more than 50 % of the total area. However, due to cost constraints, most of the rural buildings are lacking insulated structures. This leads to poor thermal performance of buildings. To maintain indoor thermal comfort, more energy has to be used, which leads to a significant amount of additional energy being used, resulting in great waste.

Vertical greenery systems are becoming more and more familiar and accepted as passive energy saving systems that have become very popular in recent years. Vertical greenery systems can provide a variety of positive effects. Firstly, vertical greenery can provide extremely effective shading to reduce the overall heat gain of a building by absorbing and reflecting a large amount of solar radiation, providing passive cooling to the building and reducing the load on the air-conditioning system (Hoelscher et al., 2016; Ip et al., 2010). Secondly, it can also increase the relative humidity around the building through transpiration, cooling the air around the building (Blanco et al., 2021). Again, it can effectively reduce the wind speed near the building facade, creating a good wind environment (Perini et al., 2011). Finally, it can also alleviate the urban heat island effect (Blanco et al., 2021; Karimi et al., 2022; Xing et al., 2019), improve air quality (Viecco et al., 2021; Weerakkody et al., 2017), reduce noise pollution (Pérez et al., 2016; Wong et al., 2010a), promote biodiversity (Chiquet et al., 2013; Madre et al., 2015), provide physiological and psychological help to the occupants (Magliocco and Perini, 2015) and enhance the aesthetic and economic value of the building (Wong et al., 2010b).

As a cost-effective type of vertical greenery system, green façade is very suitable to be used for energy-saving renovation in rural areas of China. Currently, many scholars have studied the energy-saving properties of green façade. Among them, some of the researchers have done experimental studies. For example, Perez et al. 2019 studied the energy-saving effect of indirect green façade in two cases, with and without heat load inside the room, by experiment in Spain. According to their results, the indirect green façade achieved an energy saving rate of 16.7% in the presence of a heat load and 43.4% in the absence of a heat load (Coma et al., 2020). They also conducted experiments in 2021 to address the effect of leaf area index on energy efficiency for indirect green façades. The results showed that the leaf area index was greatest in early summer, with the best energy savings of 54 %, and that 30 % energy savings could be achieved in late summer (Pérez et al., 2022). Li et al. (2019) studied the energy saving effect of vertical greenery system on public buildings in Ningbo, China. The experimental results showed that the green façade was able to reduce the cooling load of the air-conditioning system by 8.8%. Hang et al. (2020) investigated the energy efficiency of vertical greenery systems by building experimental rooms in Xiangtan, China. According to them, the vertical greenery room was able to achieve 25% energy savings in summer and 18% in winter.

In addition, some other scholars have studied the energy saving effect of green façade through energy simulation software. Ayah et al. studied the energy saving effect of vertical greenery system in Egypt through Design Builder. According to their data, the average annual electricity consumption was reduced by 75% after the application of the vertical greenery system (Ramadhan and Mahmoud, 2023). Li et al. (2019) similarly simulated the year-round energy savings of an indirect green façade in a public building in Ningbo, China, through Design Builder, and showed that the vertical greenery system was able to reduce building energy consumption by 28% over the course of the year (Li et al., 2019). Poddar et al. (2017) conducted a simulation study on energy savings in winter heating at a Korean university. According to the results of Design Builder, the vertical greenery system was able to save 60%, 7% and 3% of heating energy in the dormitory building, research building and administration building respectively (Poddar et al., 2017).

Although many studies nowadays have confirmed the energy saving effect of green façade. However, most of these studies have been conducted in laboratories and fewer studies have been conducted on existing buildings. Moreover, the number of studies for China is also few, and most of them are concentrated in urban areas, and there are few studies for rural areas. This is very unfavourable for guiding energy efficiency retrofit projects in rural areas of China. In this study, in order to explore the energy-saving effect of green façade in rural areas of China, the energy-saving effect of residential buildings with different types of facades after green façade retrofit is simulated by Design Builder. This will help the future energy-saving retrofit of green facades in rural areas of China.

2. Methods

The top five cities in China in terms of electricity consumption are Shanghai, Suzhou, Binzhou, Beijing and Chongqing. With the exception of Binzhou, the other four cities are mega-cities with a particularly high degree of urbanisation. However, Binzhou is only a small city with a low degree of urbanisation and many villages, yet it has such a high-power consumption that it can be seen to have a great potential for energy saving. Therefore, the typical residential building selected for this study is located in a village in Binzhou, Shandong Province.

In this study, two experimental rooms were firstly set up in an open space in Binzhou, one with bare walls and the other with indirect green façade, and the plants were selected as *Parthenocissus quinquefolia*, which were used to test the actual power consumption, as shown in **Figure 1**. The energy consumption of the experimental room is then simulated in the software and the reliability of the simulation is verified by calculating the mean bias error (MBE) and coefficient of variation of the root mean square error (CVRMSE) of the experimental and simulated results, which are given in the following Equations (1) and (2).

Figure 1. Experiment room **(a)** Reference room; **(b)** Indirect green façade room.

$$MBE = \frac{\sum_{i=1}^{n}(E_i - S_i)}{\sum_{i=1}^{n} E_i} \tag{1}$$

$$CVRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{n}(E_i - S_i)^2}{n}}}{\sum_{i=1}^{n} E_i} \tag{2}$$

The simulation software used in this study is DesignBuilder, which is easy to operate, has an intuitive and easy-to-understand interface, and also has a powerful material editing function, which allows you to create a new material and set the parameters of the corresponding green façade through the green roof module. The green façade is then equated to a layer of equivalent thermal resistance attached to the building facade to produce accurate simulation results. Climate data from around the world is built into the software, making the simulation results even more relevant. Furthermore, the reliability of DesignBuilder's energy simulations has been proven in many studies.

The authors researched the local residential buildings through field visits (**Figure 2**). Among them, only a few buildings were two-storey houses, and all the rest were single-storey houses. Moreover, all the houses were facing south. By asking the villagers, it was learnt that this was to satisfy the need for light, especially in winter, as it would raise the temperature in the room.

Figure 2. Field research.

Through field research to obtain the most representative local residential layout, various building materials and people's activities. Finally, the typical house is modelled in Design Builder. The model of a typical house is set as a single-storey house, facing south, and the green façade is not set on the south wall in order to meet the light demand. **Figure 3** shows the photographs of typical houses in northern China and the floor plan of the model. **Figure 4** shows a three-dimensional view of the model. According to the data obtained from the actual research, most of the external walls of local buildings are built using the following four materials. They are, red bricks, rubble, hollow bricks and concrete. The specific parameters of the buildings are listed in **Table 1**.

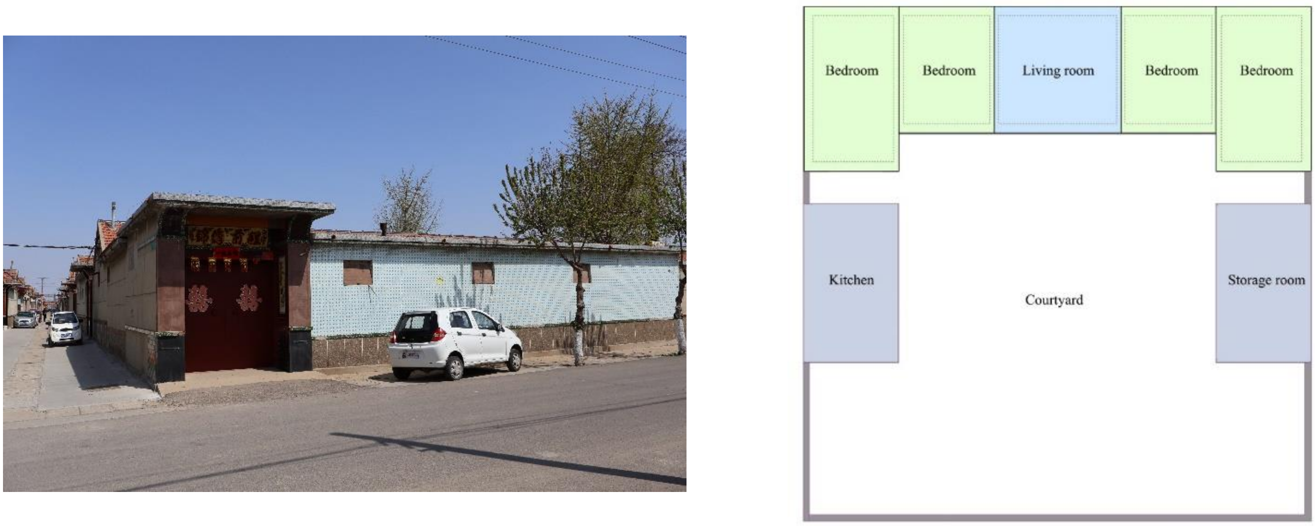

Figure 3. Typical buildings and modelled floor plans.

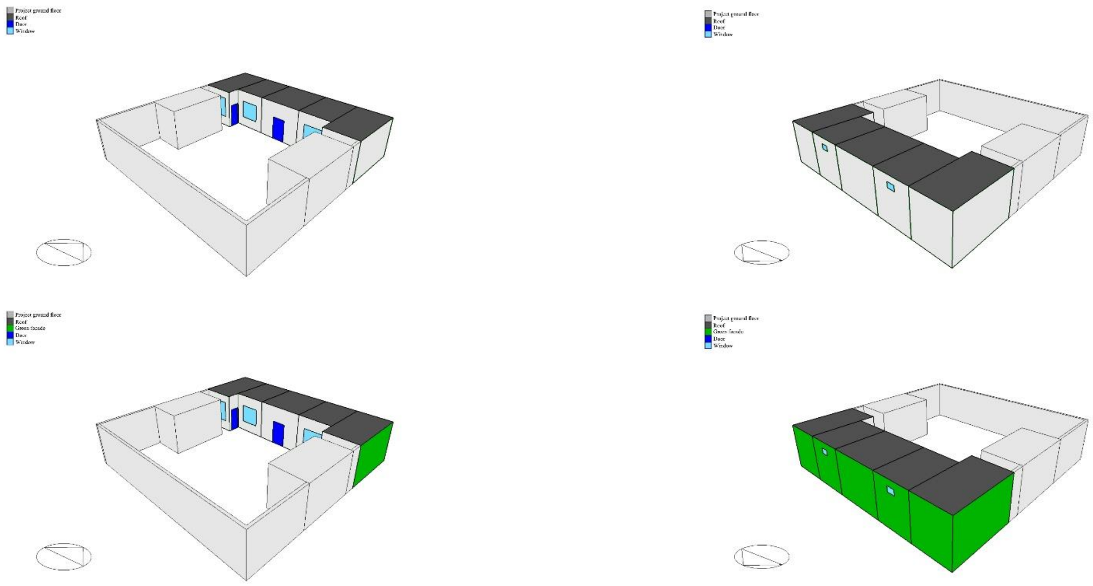

Figure 4. Typical residential model.

Table 1. Building parameters.

Project		Structure	U-Value (W/m²•K)
External wall	Red brick	Cement mortar (40 mm) + red bricks (200 mm) + cement mortar (40 mm) + gypsum veneer (10 mm)	1.898
	Rubble	Rubble (200 mm) + cement mortar (40 mm) + gypsum veneer (10 mm)	1.719
	Hollow brick	Cement mortar (40 mm) + hollow brick (200 mm) + cement mortar (40 mm) + gypsum veneer (10 mm)	1.346
	Concrete	Cement mortar (40 mm) + concrete (200 mm) + cement mortar (40 mm) + gypsum veneer (10 mm)	0.812
Internal wall		Gypsum veneer (10mm) + cement mortar (20mm) + red bricks (200mm) + cement mortar (20mm) + gypsum veneer (10mm)	1.674
Roof		Cement mortar (40mm) + reinforced concrete (200mm) + gypsum veneer (10mm)	3.108
Window		6mm single glazed and wooden window frames	5.7
Door		Wooden single-panel solid doors	3

According to the data from the field study, the floor area of a typical residential house is about 100 m^2, of which only the bedroom and the living room, which will use air-conditioning, are about 70 m^2. On average, there are about 3 people per household who are at home all year round, so the room's occupant density is set at 0.043 people/m^2. According to the ASHRAE standard, it is recommended to keep the indoor temperature between 22 ℃ and 26 ℃ in summer. Therefore, in this study, the air conditioning set temperature was taken as an average value and set at 24 ℃. According to the national standard GBT17758-2010 for unitary air conditioners in China, the cooling period in Binzhou is from 13 April to 11 October. In this study, the split air-conditioning unit is used to cool the building in summer, and then the building energy consumption is quantified in terms of electrical energy consumption, and the specific parameters are shown in **Table 2**.

Table 2. Parameter settings for air-conditioning systems.

Projects	Parameter settings
Refrigeration setting temperature	24 ℃
Cooling period	13 April to 13 October
Personnel density	0.043 people/m^2
Room Illumination	150lux
Equipment heat gain	12W/m^2

Since there are no studies related to the biological characteristics of the *Parthenocissus quinquefolia* in the Binzhou area. Therefore, this study was set according to the typical values specified in the document ‘The Encyclopedic Reference to EnergyPlus Input and Output’. The physiological characteristics associated with the plants used in vertical greenery and the parameters that have an impact on the thermal performance are shown in **Table 3**. In this study, it is assumed that the data of the plants remain constant and are not affected by external influences.

Table 3. Green façade parameter settings.

Projects	Parameter settings
Height of plants(m)	0.2
Cavity thickness(m)	0.2
Leaf area index	1.94
Leaf reflectivity	0.4
Leaf emissivity	0.8
Minimum stomatal resistance(s/m)	120
Max volumetric moisture content at saturation	0.5
Min residual volumetric moisture content	0.01
Initial volumetric moisture content	0.15

Finally, the energy consumption of typical residential buildings with different types of facades is simulated for the bare wall case and the green façade case, respectively, to analyse the energy savings provided by the green façade.

3. Results and discussion

The experiment was conducted with 15 July 2024 to 19 July. According to ASHRAE standards, it is recommended to keep the indoor temperature between 22 ℃ and 26 ℃ in summer. Therefore, in this experiment, the air conditioning set temperature was taken as an average value and set to 24 ℃, and the air speed was set to automatic. The experimental and simulation results are shown in **Table 4** and the related international standards are shown in **Table 5**.

Table 4. The results of experiment and simulation.

Room	Experimental energy consumption	Simulated energy consumption	MBE	CVRMSE
Bare wall	39.373KWh	39.56 KWh	-0.48%	6.87%
Green facade	21.358 KWh	21.7 KWh	1.57%	7.03%

Table 5. Range of acceptable error indicators for calibration of energy consumption simulation models.

Standard	Monthly (%)		Hourly (%)	
	MBE	CVRMSE	MBE	CVRMSE
ASHRAE Guideine-14	±5	15	±10	30
IPMVP-2002	±20	5	±5	20
FEMP	±5	15	±10	30

As can be seen from **Tables 4** and **5**, the indirect green façade achieves good energy savings and the results of the modelling are within the relevant international standards for reliability.

The annual cooling period in Binzhou is from 13 April to 11 October. **Figure 5** shows the outdoor air temperature and solar radiation intensity during the simulation period. From the figure, it can be seen that the hottest months of the whole cooling period are June, July and August, and the dry-bulb temperature of the outdoor air in these three months is above 25 ℃, and the intensity of the solar radiation is around 80,000Wh/m^2, both of which are at a high level. The temperatures in April and October, on the other hand, are significantly lower than the other months.

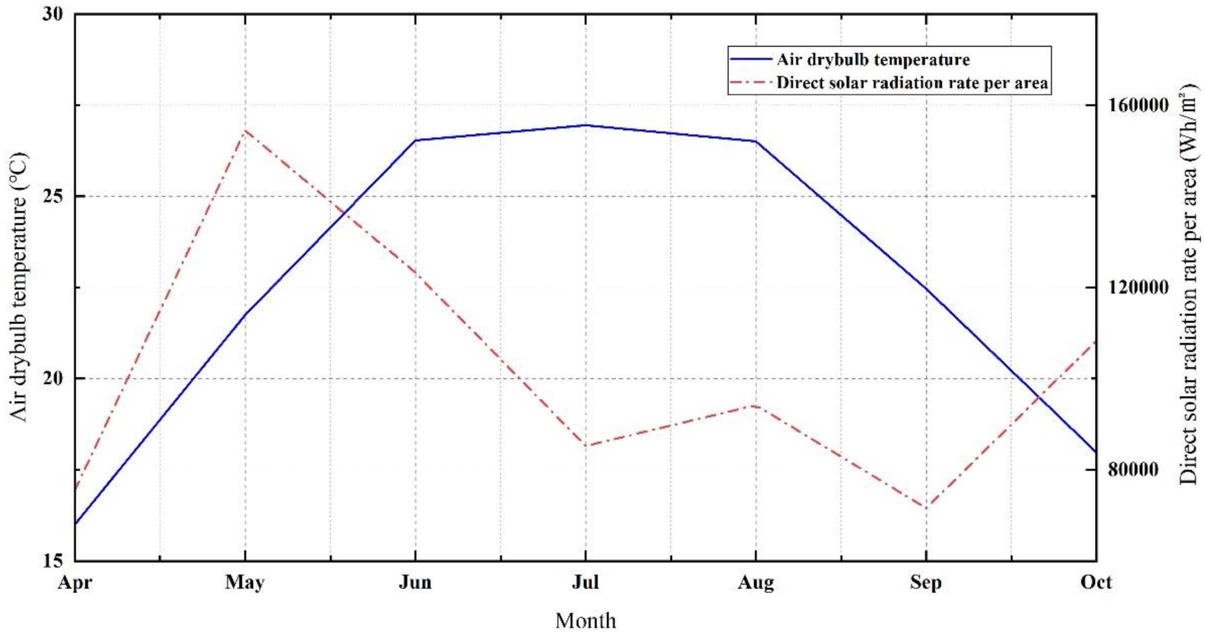

Figure 5. Outdoor air temperature and solar radiation intensity.

Figure 6 shows the monthly energy consumption of different types of facades in both bare wall and indirect green façade cases. **Figure 7** shows the cumulative building energy consumption. The energy consumption of each facade and the energy saving rate for the whole cooling period are summarised in **Table 6**. It can be clearly seen that the energy consumption of either type of façade is significantly reduced after the green façade retrofit.

In the case of bare walls, the red brick facade, which has the worst thermal performance, consumes the most energy, amounting to 5750.06 KWh. After the green façade retrofit, it only consumes 4693.27 KWh of energy during the whole cooling period, with an energy saving rate of 18.39 %. And the concrete facade with the best thermal performance consumed the least amount of energy, only 5286.3 KWh. after retrofitting with green facade, it consumed only 4677.42 KWh of energy for the whole cooling period, with an energy saving rate of 11.52%. Then, the energy saving rate of the rubble façade is 17.85 %, and the energy saving rate of the hollow brick façade is 14.47 %. The thermal performance of all types of façades was well improved after the green façade retrofit. The simulation results under green façade conditions show that the energy consumption of all types of façades is basically the same, this situation is because after the green façade retrofit, the difference in the U-value of each type of façade is no longer as huge as before, and the thermal insulation performance is very similar, so that very approximate results are obtained.

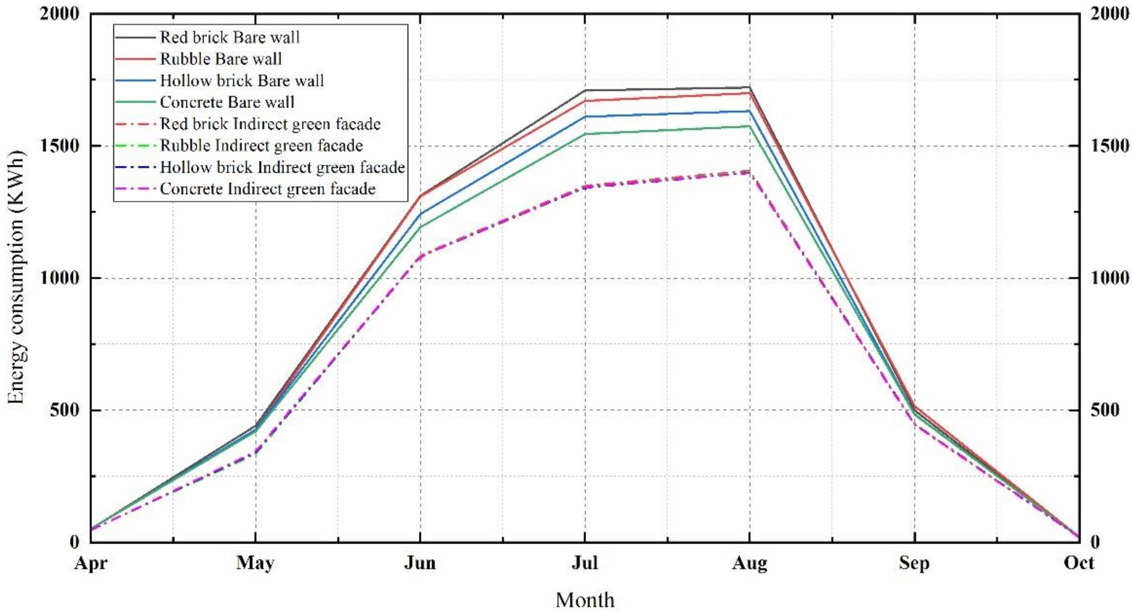

Figure 6. Monthly building energy consumption for each type of façade.

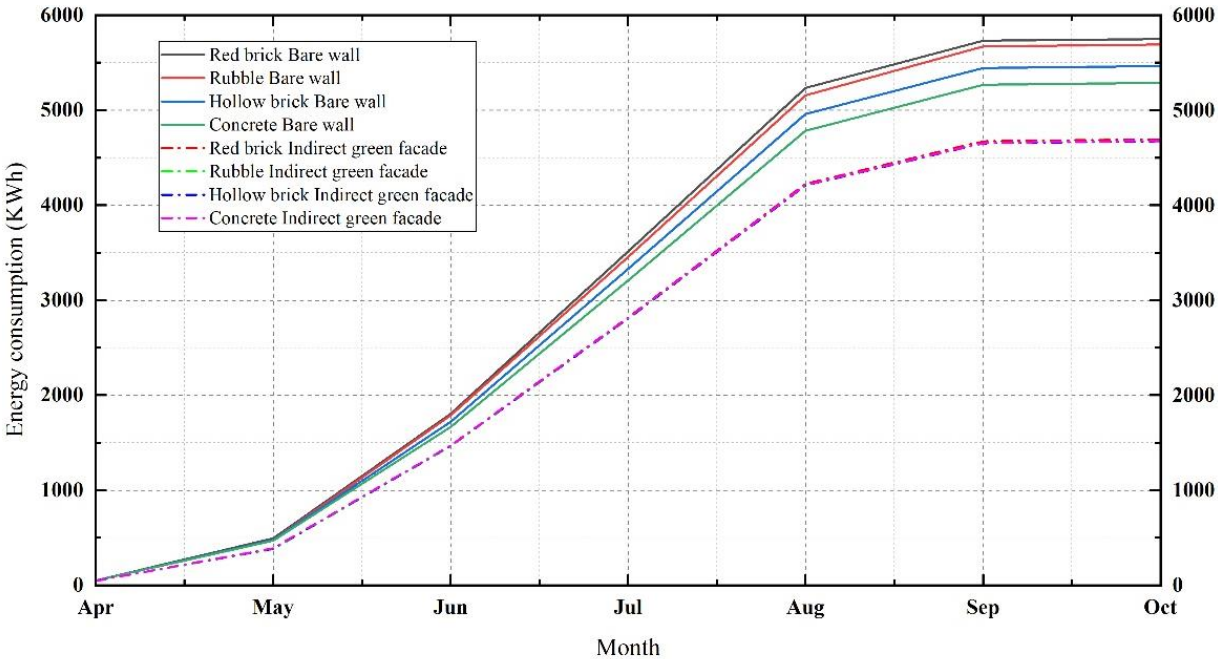

Figure 7. Total building energy consumption for each type of façade.

Table 6. Energy consumption of each type of facade.

Type of wall	Bare wall (KWh)	Indirect green façade (KWh)	All the energy saved (KWh)	Energy saving rate (%)
Red brick	5750.06	4693.27	1056.79	18.39
Rubble	5689.58	4674.03	1015.55	17.85
Hollow brick	5463.78	4673.21	790.54	14.47
Concrete	5286.3	4677.42	608.88	11.52

From the same point of view, the energy consumption in the cooling period of the building is reduced to different degrees after the addition of the indirect green façade. The indirect green façade is covered on top of the building, which is equivalent to adding a layer of thermal insulation material to the building facade, increasing the thermal resistance of the building facade and improving the overall thermal insulation performance of the building.

From different points of view, the energy efficiency benefits from green façade retrofitting vary for different types of façades. The better the thermal performance and the lower the U-value of the façade before retrofitting, the smaller the energy-saving benefits from implementing green façade retrofitting. The worse the thermal performance of the façade, the greater the energy saving benefit after green façade retrofit.

At the same time, this study conducted another simulation of a typical residential house with a red brick façade, which is the best in terms of energy efficiency. The green façade of the south wall was added to this simulation. The simulation results show that a total of 4545.42 KWh of energy was consumed during the cooling period with an energy saving rate of 20.95%. This is only a 2.56% improvement compared to the previous simulation. Therefore, not retrofitting the south wall with a green façade in order to satisfy the need for daylighting in Binzhou does not have much impact on the energy savings and is acceptable.

4. Discussion

In this study, the energy efficiency of buildings with different types of facades retrofitted with green facades in rural China was evaluated through software simulation. After the green façade retrofit, the building energy consumption in the cooling period was significantly reduced for all types of façades.

In the hot summer, the green façade provides additional shade for the building, increases the overall thermal resistance of the building, absorbs and reflects a large amount of solar radiation, reduces the heat gain of the building, and reduces the cooling load of the air-conditioning system, thus achieving good energy saving. Through simulation, it was found that the red brick facade, which had the worst thermal performance before the retrofit, achieved the best energy saving effect after the green façade retrofit, with the energy saving rate reaching 18.39%, and a total of 1056.79 KWh of energy was saved in the whole cooling period. On the other hand, the concrete facade, which had the best thermal performance before the retrofit, achieved the worst energy saving effect after the green façade retrofit, which was only 11.52%, with a total energy saving of 608.88 KWh. Therefore, indirect green façade is more suitable for retrofitting building facades with poor thermal performance, which can achieve better energy saving effect.

The energy saving effect of indirect green façade in a typical residential building is significantly lower than that in the experimental room, which may be caused by the fact that the ratio of the area of green façade and building façade in the experimental room is much larger than that of the typical residential building, or it may be caused by the fact that the building layout of the typical residential building is more complicated than that of the experimental room. This point deserves to be studied in depth in the future.

This study verifies the reliability of the Design Builder simulation, which is also beneficial for research in other parts of the world. In other regions of the world with similar climatic or economic conditions, the methods in this paper can be used to carry out local studies and set up local climatic conditions for simulation in Design Builder to draw appropriate conclusions.

The costs and benefits of green façade retrofitting are important factors influencing the development of green façades. From a life cycle perspective, costs mainly include initial investment costs (plant, material, and installation costs), mid-term maintenance costs, and end-term demolition costs. Benefits mainly include energy saving benefits, economic benefits and environmental benefits. Reducing costs and increasing economic benefits as much as possible in the retrofitting process can increase the attractiveness of green façade retrofitting and promote the better development of green façade.

At the same time, this study still has some shortcomings. For example, this study was conducted only for the climate of Binzhou and did not analyse the energy savings in other climate zones in China. Different climates can have a significant impact on the energy efficiency of green façades, and in the future, in-depth studies should be conducted for other climates as well. The effects of neighbouring buildings and wind were not taken into account in this study, which may have a significant impact on the simulation results, and corresponding simulations should be added in future studies to make the results more accurate. In the future, field experiments should also be conducted on typical residential buildings to produce the most realistic data, thus increasing the reliability of the simulation results. Experimentation and simulation of different types of vertical greenery systems, and comparison of the energy saving results between them, so as to come up with the vertical greenery system with the best energy saving effect. Conduct a detailed study on the costs and benefits of vertical greenery system retrofitting to explore the practical feasibility of vertical greenery system retrofitting.

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