Energy performance of a Building-integrated Photovoltaic/thermal system for rural residential buildings in cold regions of China

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ABSTRACT

Building integrated photovoltaic (BIPV) technology provides an aesthetical, economic, and technical solution for electricity self-sufficiency in buildings. The incorporation of PV modules into buildings not only introduces an on-site electricity producing opportunity, but also brings about some by-produced advantages, such as better natural lighting, enhanced thermal comfort, reduced heating/cooling energy consumption, as well as aesthetical pleasing. This paper proposes a novel triple-skin BIPV/T system for rural residential buildings in north China. Firstly, the electrical performance of the proposed system was simulated using the System Advisor Model (SAM) from National Renewable Energy Laboratory (NREL). Secondly, the ANSYS Fluent software was used to simulate the heat transfer condition of the BIPV/T system in a typical winter day. The results show that the total electricity output of BIPV/T system in a typical year is 6128 kWh. In a typical winter day, the proposed system operates from 8:00 to 13:00 and outputs 9.84 kWh electricity in total. By collecting the accumulated heat from the PV module, the exposure temperature of the structural wall/roof is significantly improved. Accordingly, during the operation of the system, the total heat loss of the building envelope could be reduced by 2.85kWh and 2.75kWh by the closed mode and the ventilated mode, respectively.

1. INTRODUCTION

Building integrated photovoltaic (BIPV) technology provides an aesthetical, economic and technical solution for electricity self-sufficiency in buildings (T. Zhang, et al., 2018). In BIPV involved buildings, the incorporation of PV technologies into buildings not only introduces an on-site electricity producing opportunity, but also brings about some by-produced advantages related to architectural aesthetics and energy efficiency aspects, such as better natural lighting, enhanced thermal comfort, reduced heating/cooling energy consumption, as well as aesthetical pleasing (T. Zhang, et al., 2016).

Peng et al. (2013) examined the annual thermal property of a multi-layer PV façade. Through numerical investigation, the heat loss and heat gain of this system in winter were found to be 32% and 69% lower than conventional walls and the heat gain through this south-facing façade in summer was 51% lower than that of a conventional wall. Yang et al. (2000) examined the suitability of PV walls for different climate regions of China, mainly focusing on its thermal performance. Their simulation results showed that by substituting a conventional wall with a PV wall, the cooling load could be cut down by 33–50% in different regions. Ji et al. (2003) investigated the dynamic thermal property of a PV wall system designed for the Hong Kong climate. The results demonstrated that the proposed system was effective in reducing the total heat gain by 53–59.2% during the summer period, compared to normal external walls. Wang et al. (2006) compared the thermal performance of four rooftop PV systems. The numerical results revealed that the ventilated PV roof enjoyed a higher power efficiency and lower cooling load. Therefore, it was more appropriate for summer applications, while the non-ventilated PV roof was more suitable to be used in winter since it helped to reduce the heating load.

Although much literature concerning the space-cooling load reduction of BIPV systems has been published, there is limited research focusing on the space-heating load reduction effect of BIPV systems in cold regions. When applied in cold climate regions, ventilated BIPV configurations with reserved air layers would be a better solution, since the air-circulation can not only improve the power efficiency by removing the accumulated heat generated by the photovoltaic effect, but also reduce the respective heat gains and heat losses in summer and winter via the building envelope. Additionally, the warmed air discharged from the air layer can serve as a supplementary space heating resource in winter (T. Zhang, et al., 2019). A novel triple-skin BIPV/T design is proposed for rural residential buildings in north China in this paper. This paper aimed to investigate the electrical and thermal performances of the proposed system. Firstly, the electrical performance of the proposed system was simulated using the System Advisor Model (SAM) from National Renewable Energy Laboratory (NREL). Secondly, the ANSYS Fluent software was used to simulate the heat transfer condition of the BIPV/T system in a typical winter day. The effect of the proposed system on the heat loss reduction of the building envelopes can be calculated based on the numerical simulation results.

2. METHODS

2.1 Introduction of the BIPV/T system

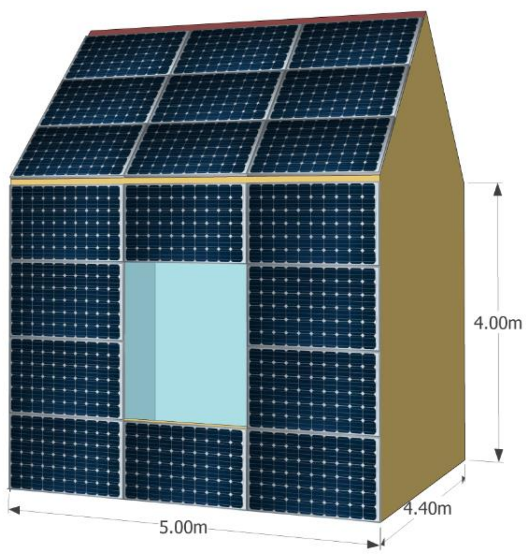


Figure 1. The proposed BIPV/T system in a typical rural house

The BIPV/T system in this paper was proposed for application in rural residential buildings in the cold climate regions of China. Fig.1 schematically illustrates the BIPV/T system applied in a typical rural house. The size of the house is 5m (width) ×4.4m (depth) ×4.0m (height), and the inclination angles of the south and north roofs are both 45°. Nineteen monocrystalline silicon (mono-c-Si) PV modules, fetched from LONGi Green Energy Technology Co. Ltd. (No. LR6-60PE-300M), are installed on the external surfaces of the house, including 10 on the south wall and 9 on the south roof. Table 1 summarizes the key electrical characteristics of the PV modules.

Table 1 Specification of the PV modules

Parameters	Value
Active area (m×m)	1.65×1.0
Maximum power at STC, P_{max} (W)	300.12
Voltage at the maximum power point, V_{mp} (V)	32.8
Current at the maximum power point, I_{mp} (A)	9.1
Open circuit voltage, V_{oc} (V)	40.1
Short circuit current, I_{sc} (A)	9.8
Module efficiency, η (%)	18.356

The BIPV/T system on the wall and the roof introduces a triple-skin design, which includes outside glazing-cover layer, a middle mono-c-Si PV module layer and a structural wall/roof layer. Fig.2 presents the cross-section diagram of the BIPV/T system on the wall. The PV module layer consists of two glass layers and a PV layer. When solar radiation arrives on the PV layer surface, the PV materials generate electricity, and simultaneously release heat. Two air layers are reserved between the three layers, in order to collect and make use of the accumulated heat from the PV module. The outer air layer is enclosed to form an insulation air layer, which helps to reduce the heat loss from the PV module. The inner air layer can work either in closed mode or in ventilated mode. In winter, when operated in the closed mode, the inner air layer also serves as an insulation layer, and the heat release from the PV layer warms up the internal air, thus, reducing the heat loss during sunny time. While in the ventilated mode, the indoor air enters the inner air layer from the bottom with the promotion of the buoyancy force; the warmed air goes back into the indoor space from the top of the layer and act as a supplementary space-heating source. The inner air layers of the wall and the roof are connected to get a lager temperature increment of the induced air. The structural wall layer consists of four material layers, including an outer decorative mortar layer, an EPS insulation layer, an aerated concrete block layer, and an inner decorative mortar layer. Table 2 summarizes the key properties of the building materials in the BIPV/T wall system. With these building materials, the heat transfer coefficient of the structural wall layer is 0.282 W/(m^2·K). The structural roof layer has a thinner aerated concrete block layer (240mm) when compared with the wall, thus has a larger heat transfer coefficient of 0.326W/(m^2·K).

Table 2 Thermal parameters of concerned building materials

Material type	Thickness (mm)	density (kg/m^3)	Specific heat (J/(kg·K))	Thermal conductivity (W/(m·K))
Air	20+100	1.18	1000	0.026
Decorative mortar	10+10	1600	1050	0.93
Glass	5+5+5	2500	850	0.95
Aerated concrete block	360	700	840	0.25
EPS	80	30	1380	0.042

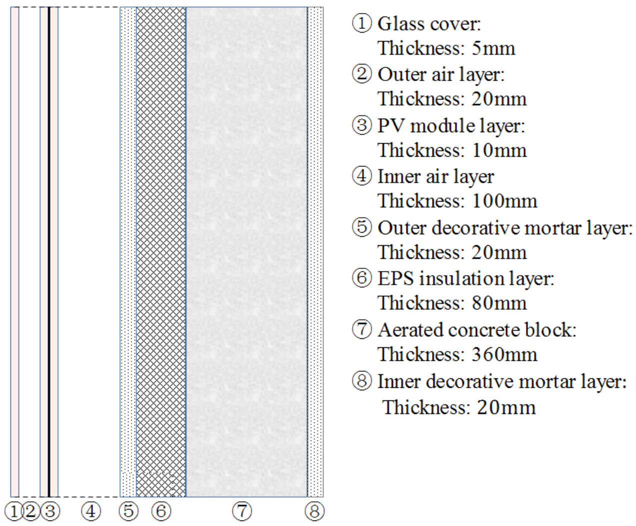


Figure 2. Cross-section diagram of the BIPV/T system on the wall

2.2 System performance investigation of the BIPV/T system

This study focus on the electrical and thermal performance of the proposed system in typical winter climate conditions of northeast China. Therefore, the electricity generation capacity and the heat transfer condition of the system need to be investigated. Two types of professional software were used in combination to investigate the power generation and thermal performance of the system. The System Advisor Model (SAM) from National Renewable Energy Laboratory (NREL) was employed to simulate the electricity generation capacity of the proposed BIPV/T system. In this study, the SAM CEC one-diode model was adopted due to its versatility and accuracy for various types of solar cells. During the simulation, the weather data file of Harbin was imported into the program and the PV module parameter in Table 1 were treated as the computation basis of the electricity generation.

The ANSYS Fluent software was used to simulate the heat transfer condition of the BIPV/T system in a typical winter day. Firstly, a simplified two-dimensional physical model was established according to the actual size and material of the proposed system. Secondly, a numerical model is established based on the conservation equations of mass, momentum and energy, as well as the standard k-ε turbulent model. The governing equation discretization and solution are performed in the ANSYS Fluent 12.0 software after a grid independence test. In the simulation, the outdoor temperature in a typical winter day was set as the outer surface boundary condition; the indoor air temperature was kept 18℃ according to the design temperature of space heating. The thickness of the PV layer is ignored, and this layer was set at 50℃ as a constant temperature boundary condition during the sunny hours. Based on the numerical simulation results, the temperature profiles of the system and the heat flux distribution can be obtained. The effect of the proposed system on the heat loss reduction of the building envelopes can be calculated based on the heat flux variations.

3. RESULTS AND DISCUSSIONS

3.1 Electrical performance of the BIPV/T system

Fig.3 and Fig.4 illustrate the annual solar radiation variation and the corresponding monthly electricity generation, respectively. The variations tendency of the monthly electricity generation agrees perfectly with that of the solar radiation. The total electricity output of

BIPV/T system in a typical year is 6128 kWh. The peak value occurs in March to be 704 kWh, while the lowest value occurs in December to be 419 kWh.

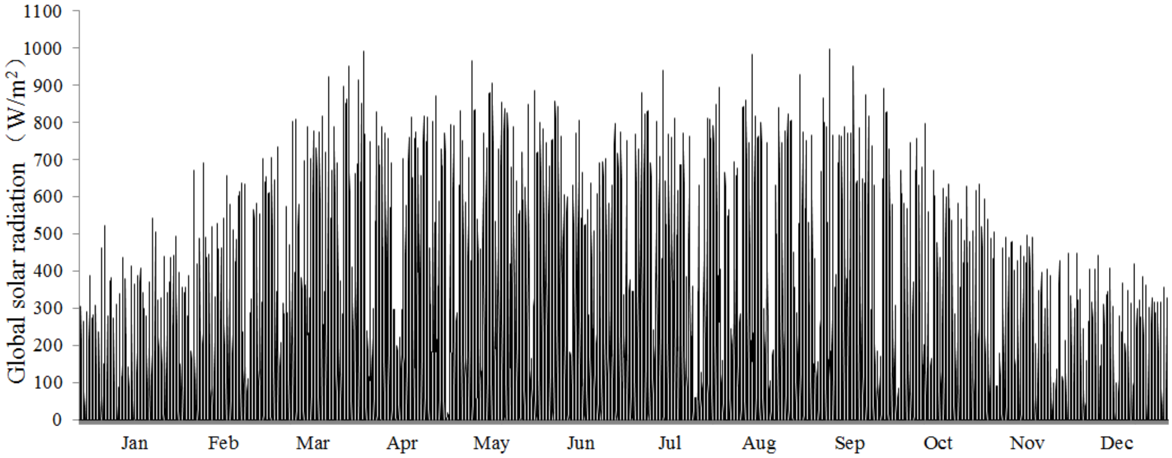


Figure 3. Annual solar radiation variations of Harbin city

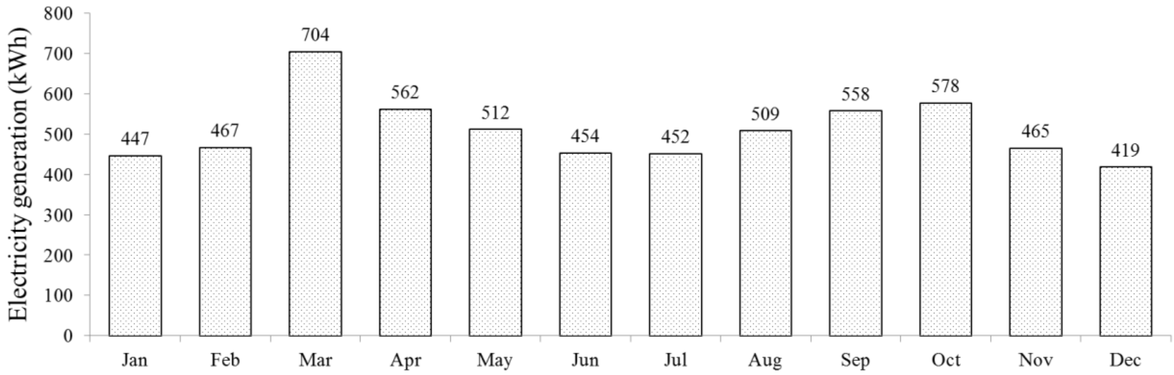


Figure 4. Monthly electricity generation capacity of the system

Fig.5 presents the hourly solar radiation variation and the corresponding electricity generation capacity in a typical winter day. Again, the variations tendencies of the solar radiation and electricity generation agree well with each other. The peak values occur at 12:00 as 265 W/m^2 and 2.94 kW, respectively. The BIPV/T system operates from 8:00 to 13:00 and outputs 9.84 kWh electricity in total in this typical day.

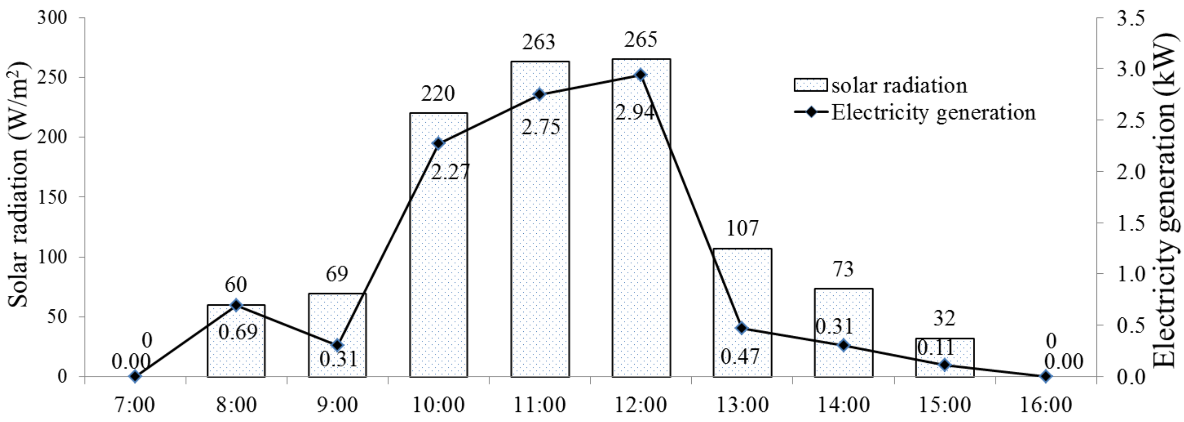
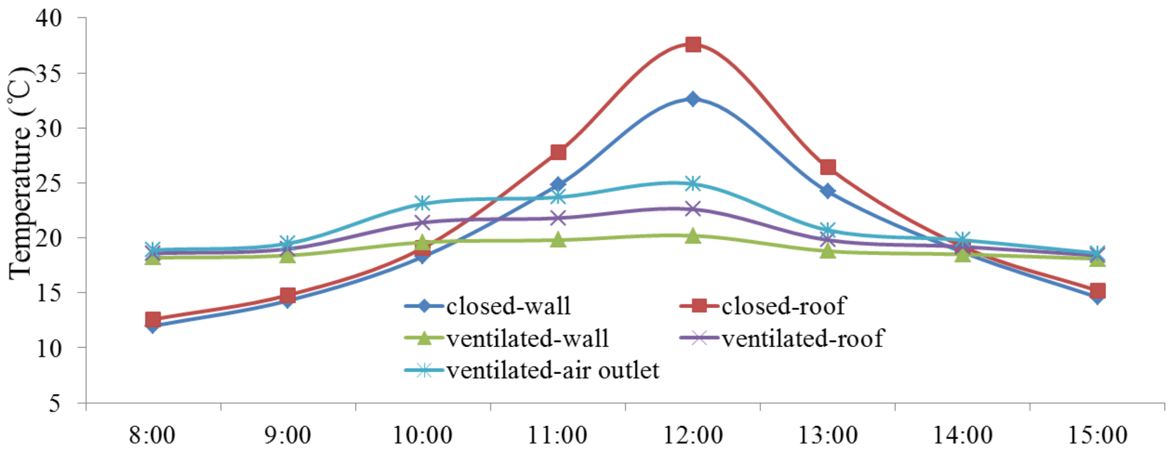


Figure 5. Variations of the solar radiation and electricity output in a typical winter day

3.2 Thermal performance of the BIPV/T system

Besides the electricity generation, the proposed BIPV/T system also benefits from reducing the heat loss at the wall and roof area, since the accumulated heat is collected to warm up the air outside the structural wall/roof layer. Fig.6 demonstrates the average temperature variations of inner air layer under different operation modes, and the outdoor air temperature T_0 is also attached below the figure. In both of the closed and ventilated mode, the average inner air temperature at the roof area is generally higher than that at the all area, since the warmed air moves upward due to the buoyance force. In the closed mode, the biggest air temperature difference between the roof area and the wall area occurs at 12:00 to be 5℃, and from an overall point of view, the roof air temperature is 1.65℃ higher that the wall air temperature. In the ventilated mode, the roof air temperature is 1.15℃ higher that the wall air temperature. At 11:30-14:00, the inner air temperature of the closed mode is higher than the ventilated mode; while at the rest time of the day, the ventilated mode produces a higher inner air temperature. As before 11:30 and after 14:00, the solar radiation is lower, the heating effect of the PV module on the inner air is weak; and in the ventilated mode, the air layer is connected to the indoor space, thus this mode produces a higher air temperature in the inner air layer. From 11:30 to 14:00, the heat accumulation in the air layer is stronger in the closed mode, thus, this mode has a higher inner air temperature.



T_o	-23.8	-21.6	-19.1	-16.7	-14.5	-12.7	-11.5	-11.0

Figure 6. Temperature variations of inner air layer under different operation modes

Compared with the outdoor air temperature, it is clearly that inner air layer temperature is greatly improved by the collected heat from the PV module, namely, the exposure temperature of the structural wall/roof layer is significantly improved by the BIPV/T system. Accordingly, the heat transfer condition through the structural wall/roof layer is also changed. Table 3 illustrates the heat flux variations at the inner surface of the wall/roof under different operation modes. Through the comparison between the heat-transfer rates of the normal wall/roof and different modes of the BIPV/T wall/roof, the heat losses through these two areas are considerably reduced. For the normal wall and roof, the average heat losses during 8:00-15:00 are 161.44W and 168.03W, respectively. In the closed mode, before 10:00 and after 14:00, the heat losses are dramatically reduced; moreover, during 10:00-14:00, due to the warmed air outside the structural layer, heat gains occur in both the wall area and roof area, which means that the indoor space absorbs heat from the wall/roof. In the ventilated mode, during 8:00-15:00, there is no heat loss in the wall/roof area, since the indoor air at 18℃ is induced into the inner air layer and gets heated. The average heat gains during 8:00-13:00

in this mode are 4.46W and 10.27W, respectively. For both of the operation modes of the BIPV/T system, the peak heat gain occurs at 12:00 in accordance with the inner air temperature variations, and both the two modes achieve a net heat gain during sunny hours at 8:00-15:00, thus enjoying a significant potential in reducing the indoor space-heating load.

Table 3 Heat flux at the inner surface of the wall/roof under different operation modes

Time	Heat transfer rate (W)					
	Normal wall	Normal roof	Closed wall	Closed roof	Ventilated wall	Ventilated roof
8:00	-196.38	-204.40	-28.19	-26.41	0.94	2.93
9:00	-186.05	-193.64	-17.38	-15.65	1.88	4.89
10:00	-174.30	-181.42	1.41	5.38	7.52	16.63
11:00	-163.02	-169.68	31.95	47.92	8.46	18.58
12:00	-152.69	-158.93	68.59	95.84	10.34	22.49
13:00	-144.23	-150.12	29.13	41.08	3.76	8.80
14:00	-138.59	-144.26	3.29	5.87	2.35	5.87
15:00	-136.25	-141.81	-15.97	-13.69	0.47	1.96

3.3 Effect on the heat loss reduction through the building envelopes

During the operation hours of the BIPV/T system, the heat losses through the wall and roof areas can be greatly reduced, or even can be reversed to net heat gains. Therefore, the space-heating load caused by the heat loss through building envelopes can be reduced. Fig. 7 shows the effect of BIPV/T system on the heat loss of the envelopes of the concerned building.

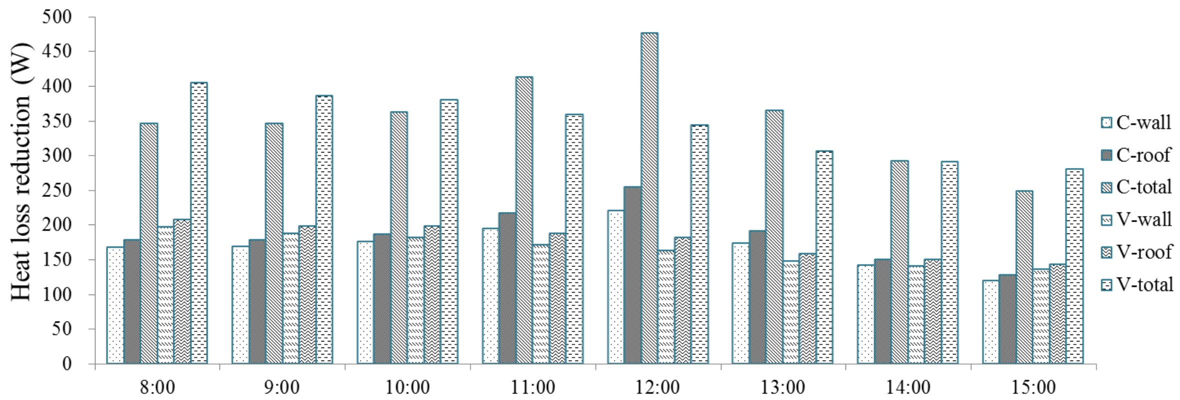


Figure 7. Heating load reduction effect of the BIPV/T system

Seen from the bar chart, when compared with a normal wall/roof room, the integration of the PV/T system on the south wall and south roof contributes a lot in reducing the envelope heat loss. For the closed mode of the system, the total reduction during 8:00-15:00 is 2.85kWh, including 1.36kWh by the south wall and 1.49kWh by the south roof. In the ventilated mode, the total reduction is 2.75kWh, including 1.33kWh by the south wall and 1.42kWh by the south roof. Therefore, the closed mode has a greater potential in reducing the heat loss through the south envelopes. However, for the ventilated mode, the circulated air can be treated as a supplementary source for space heating; therefore, the heating load reduction effect of the ventilated mode would be stronger when the air heating effect is taken into account.

4. CONCLUSIONS

This paper proposes a novel triple-skin BIPV/T system for rural residential buildings in north China. This paper focuses on the electrical and thermal performance of this system. Numerical simulation using the System Advisor Model (SAM) from National Renewable Energy Laboratory (NREL) shows that the total electricity output of BIPV/T system in a typical year is 6128 kWh, and total electricity output in a typical winter day is 9.84 kWh. Simulations from ANSYS Fluent show that, by collecting the accumulated heat from the PV module, the exposure temperature of the structural wall/roof is significantly improved. Therefore, the total heat loss of the building envelope could be reduced by 2.85kWh and 2.75kWh by the closed mode and the ventilated mode, respectively. The proposed system would benefit a lot for building energy saving in rural buildings of north China, from both electricity generation and heat loss reduction through building envelopes.

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