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ENERGY, ECONOMIC AND ENVIRONMENTAL PERFORMANCE ANALYSIS OF A NOVEL SOLAR-POWERED ZERO-BILL RURAL HOUSE SPACE HEATING SYSTEM

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ABSTRACT

This paper presents a social, economic and environmental study on a novel solar-powered zero-bill rural house space heating system compared to the conventional coal-powered and gas-powered systems. The system can significantly reduce the fossil fuel consumption, and reach to zero-bill operation, thus decreasing the operation charge and air pollution. By using the established model, the research analyses the energy performance of the novel zero-bill solar-powered system under a typical northern China weather condition (Taiyuan city). Then, it compares the economic and environmental performances between three space heating systems. It is found that, for a 100m^2 typical rural house, the total heat demand is 8081kWh during the heating season. According to the local feed-in tariff, 0.75RMB/kWh [1], the PV model can earn 1297.2RMB per year, which is higher than the annual system electricity bill, 732.48RMB, and thus the novel system can reach to zero-bill and zero energy consumption. When it comes to economic analysis, due to the zero-bill and zero energy consumption characteristics, the system has a cost payback period of 14.8 years and a life-cycle net cost saving of 17573RMB compared with the coal-powered system. In contrast with the gas-powered system, the system has a cost payback period of around 5.9 years and a life-cycle net cost saving of 52723RMB. Furthermore, under the view of environment, one set system can annually save 1320kg standard coal or 1022.39m^3 natural gas. Besides, it also annually reduces the 897.6kg harmful dust, 3220.8kg CO_2, 99kg SO_2 and 49.5kg NO_x compared to the most environmentally contaminated coal-powered system. The widely use of the novel solar-powered system can enormously help to improve the living standard of the residents staying in a wide range of rural areas in northern China, and thus the system can harvest greater social, environmental and economic benefits subsequently.

Keywords: Zero-bill, Solar-powered, Space heating, Social, economic and environmental analysis

NONMENCLATURE

T_a	Ambient temperature(ºC);
η_{it}	solar thermal efficiency of an individual mini-channel solar thermal panel;
T_{in}	Inlet temperature of an individual solar thermal panel (ºC);
Q_{se}	Electricity generation by PV panels (kWh);
N	Number of the PV panels;
η_e	Photoelectric efficiency;
A_e	Area of a single PV panel (m^2);
τ_{wy}	Electricity generation time (h);
η_{rc}	Initial electrical efficiency at reference temperature 25ºC;
β_{PV}	Temperature coefficient;
T_c	Working temperature of the panel (ºC);
T_{rc}	Reference temperature, 25ºC;
$NOTC$	Nominal operating cell temperature;
COP	Coefficient of performance;
ΔT_{aw}	Temperature difference between T_a and T_{w2} (ºC);
T_{w2}	Temperature of heating water (ºC);
PP	Cost payback period;
CS	Life-cycle net cost saving (RMB);

1. INTRODUCTION

In the contemporary energy sector, reducing fossil fuel consumption and carbon emission has become one of the most significant global concerns. The rural area in

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northern China accounts for 27.5% of the nation's territory as well as represent 46.7% of the total building area. Northern China rural houses consume around 24.8% of the total building energy consumption [2,3].

To date, most of the rural houses are using coal and gas as the main energy source for cooking and space heating, which has caused severe fossil fuel shortage and environmental pollution that contains a high level of harmful dust, PM2.5 concentration, greenhouse gas, CO_2, and harmful airs, i.e. SO_2 and NO_x [4]. However, the development of renewable energy during recent years can bring revolutionary changes to present states.

In view of the present situation, technologies for this purpose have been developed substantially but meanwhile exhibited by some inherent problems [5]. Zhao studied the performance of a solar-based heat pump system, indicating that the average thermal COP of the system was 5.51 [6-8]. Shan et al. studied the thermal performance of a solar heating system integrated with the air-source heat pump in a rural house. The results showed that 25% of electricity consumption has been reduced by reasonably adjusting the control procedures. However, the economic cost payback period was not considered [9]. The problems of the existing solar-powered space heating systems mainly lie in high electricity consumption and sophisticated configurations.

To remove the above addressed technical barriers remaining with the existing solar-based heating systems, a novel zero-bill solar-powered rural house space heating system has been designed to supply space heating to rural houses during the heating season.

On the basis of the authors' previous research achievement on this topic [10], the social economic and environmental issues of the system under a typical northern China weather condition are studied in the paper. The research results will be able to assist in the decision making in the implementation of the proposed solar-powered space heating technology and analyse of the associated economic and environmental benefits, thus contributing to the realisation of regional and global targets on fossil-fuel energy saving and environmental sustainability.

2. SYSTEM INTRODUCTION

The proposed rural house solar-powered space heating system comprises a few parts: (1) two multiple-throughout-flowing mini-channel panel arrays; (2) a dedicate sized PVs array; (3) a specialist HSEU (4) an air-source heat pump that provide space heating when solar energy and stored energy cannot meet the heat demand.

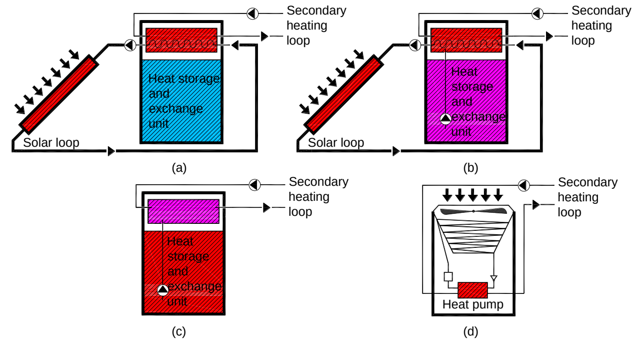

Fig 1 The control scheme of the novel HSEU operation

The system is designed to provide space heating for a 100 m^2 rural house with the peak heat load of 10 kW.

The control scheme of the proposed solar-powered space heating system is divided in four main steps as: (1) When the solar loop fluid temperature is higher than that of the heating loop fluid, the pump on the solar loop is in operation to transfer the collected heat the secondary heating loop, which is shown in Fig 1(a); (2) When the heat collected by collectors is higher than the heat demand of house, the heat storage process is in operation by employing the submerged pump, which is shown in Fig 1(b); (3) When the solar loop fluid temperature is less than that of the heating loop fluid, and the room temperature reaches the bottom limit, the heat release process takes place by employing the stored heat to provide space heating, which is shown in Fig 1(c); and (4) when the solar energy and the stored energy are not enough to provide space heating, the air source heat pump will be in operation to meet the heat demand, which is shown in Fig 1(d).

3. METHODOLOGY

The corresponding initial and boundary conditions, i.e., solar radiation, air temperature, wind speed, and water temperature, were extracted from the weather database of Energy-Plus software, which is the '537720_CSWD' for Taiyuan [11]. During the operation of the model, it was assumed that the system works 24 hours every day. The heat pump was considered to operate at 0°C/55°C. The solar photovoltaic and thermal panels installation angle was set to the same level as the local altitude in the city. The socio-economic figures, such as capital cost, renewable feed-in tariffs, system life span, and gas/coal air contaminants emission factors were also inputted into the program for calculation.

3.1 The collected solar thermal energy by solar thermal panel array

A mini-channel solar thermal panel-array was assembled by a multiple-throughout-following configuration with 8 panels. The solar thermal efficiency of the mini-channel solar thermal panel be expressed as [10]:

$$\eta_{it} = 0.87 - 3.7\frac{T_{in} - T_a}{I}$$

3.2 The electricity generation by PV panels

The electricity generated by the PV panel can be expressed as [12]:

$$Q_{se} = NA_e I \eta_e \tau_{wy}$$

In which, the photoelectric efficiency of the PV panel can be expressed as:

$$\eta_e = \eta_{rc}[1 - \beta_{PV}(T_c - T_{rc})]$$

1.1 The electricity consumption

The COP is expressed as the function of ΔT_{aw} which is expressed as a difference between the ambient temperature T_a and the temperature of heating water T_{w2}. The COP and the temperature difference have the following polynomial expression [13]:

$$COP = 0.0023 \cdot \Delta T_{aw}^2 - 0.2851 \cdot \Delta T_{aw} + 10.677$$

1.2 Economic analysis of the systems

The cost payback period (PP) for operating such a novel zero consumption solar-powered space heating system to replace conventional gas-powered and coal-powered space heating system can be expressed by [14]

$$PP_{sp} = \frac{CapitalCost - Incentives}{Annual\ (Operational\ \&\ maintenance)CostSaving}$$

The maintenance cost of three heating systems is normally estimated at 2% of the initial system cost [15]. As a solar-based heating system is usually considered to have a lifespan of 25 years [16], the life-cycle net cost saving, CS_{sp}, of this system in energy bills can be determined by

$$CS_{sp} = (Lifetime - paybacktime) \times Annual(Operational\ \&\ maintenance)CostSaving$$

2. CASE STUDY

In this section, a rural house located in Taiyuan City, Shanxi Province in northern China (37.52°N, 111.15°E) is selected as a case study. The system is in operation for 24h a day for space heating in winter and domestic hot water supply in summer. This research focuses on space heating performance during the heating season in winter. The served house has an area of 100m^2 which has a length of 14m, a width of 7m and a height of 4m. The front façade of the house faces south. The structure of the served house is shown in Fig 2, and the heat transfer coefficients of building envelopes are listed in Table 1. Thermal properties of the building components are the same as the actual parameters of the common rural houses, thus enabling a real reflection to the heat load of the rural house.

Table 1 The heat transfer coefficients of the building envelope

Part	Structure	K[W/(m^2·°C)]
Wall	370mm brick wall Plastering + 50mm extruded polystyrene board	0.47
External doors	Pinewood door	2.9
Window	3mm common glass aluminum alloy window frame (two layers)	1.54
Roof	Cement mortar +Insulation layer + Waterproof layer + Tile.	0.37

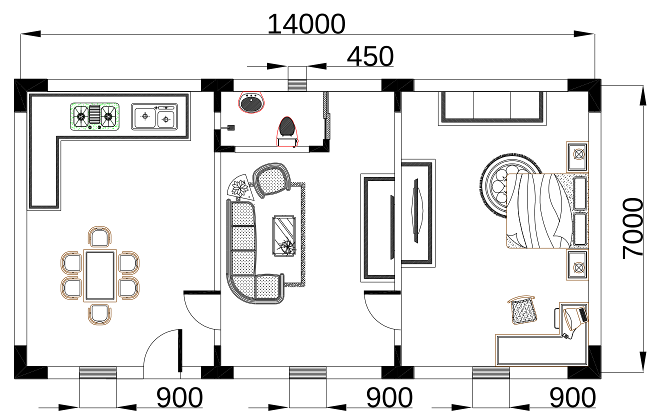

Fig 2 The structure of the served house

Table 2 The heat load and demand of the building in winter

Month	11	12	1	2	3
Set temperature (°C)	16				
Average ambient Temperature(°C)	5.86	-0.01	-2.3	1.96	7.93
Heat load (kW)	2.74	4.32	4.94	3.79	2.18
Heat demand monthly (kWh)	1232	1946	2298	1592	1013

3. RESULTS

3.1 The energy analysis

The monthly average ambient temperature and the heat demand of the served house during the heating season are shown in Table 2. Overall, the total heat demand of the service room during the heating season is 8081kWh.

Furthermore, the monthly heat demand of the served house and the collected heat by solar-powered system are shown in Fig 3.

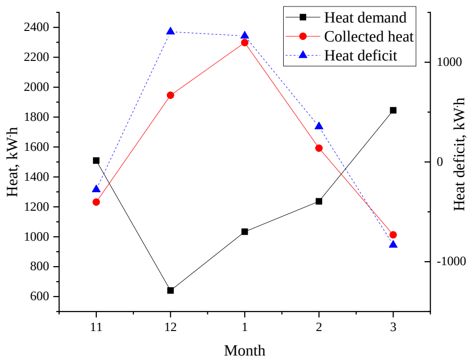

Fig 3 The variations of the head demand, heat deficit and collected heat by the solar thermal panel array

The collected heat in November and March is higher than the heat demand, and thus the served house doesn't need any other heat supply. However, from December to February, the total heat deficit is 2925.27kWh, and the heat deficit reaches the top in December, 1305.9kWh. To cover the heat deficit, the air-source heat pump is employed to supply heat to the served house. The monthly average ambient temperature and COP of the heat pump are shown in Fig 4.

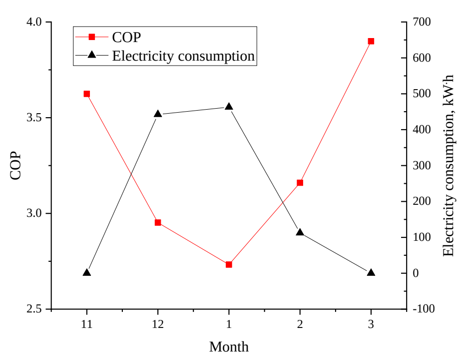

Fig 4The variations of the COP and electricity consumption of the air-source heat pump

The air-source heat pump COP decreases from November, and bottoms at 2.73 in January. Then, the COP of the heat pump increases to 3.9 in March. The COP variation directly influences on the electricity consumption of it. Due to the enough collected solar thermal energy in November and March, there is no electricity consumption. On the other hand, from December to February, according to the heat deficit and COP, the electricity consumptions of these three months are 442.3kWh, 462.7kWh and 112.3kWh respectively, which means the heat pump consumes 1017.4kWh electricity during the heating season. Furthermore, the electricity consumed by water pumps of the system is 204.3kW.h. Hence, the electricity consumption of the solar-powered system is 1221.7kWh during the heating season.

As a result, in accordance with the monthly solar thermal energy output and the monthly electrical consumption of the system, the energy breakdowns of the system in terms of the solar source, and electricity can be calculated, and the results are shown in Table 3. It is seen that to support the space heating of the testing house, the energy volumes provided by solar thermal and electrical energy produced by PV panels were 83.7% and 16.3% respectively.

Table 3 The heat transfer coefficients of the building envelope

Energy breakdown	Value (kWh)	Radio (%)
Solar thermal energy	6265.1	83.7
Solar electrical energy	1221.7	16.3

3.2 The economic analysis

The total earning by financial support for such a solar-powered system in Shanxi during the life span of the system is 32430RMB. The annual maintenance cost of a solar heating system is normally estimated at 2% of the initial system cost [14]. Compared with the coal-powered system, this system has a cost payback period of around 14.8 years and the life-cycle net cost saving of nearly 17573RMB in Shanxi. Furthermore, in comparison with the gas-powered system, this system has a cost payback period of around 5.9 years and the life-cycle net cost saving of nearly 52723RMB. Furthermore, the initial capital cost and the operational cost of the gas-powered system are 9100RMB and 860RMB less than the coal-powered system. In conclusion, from an economic perspective, the coal-powered system is better than the gas-powered system which has less initial capital cost and operational cost. However, the solar-powered system has the best economic performance which has 175.73RMB/m^2/yr and 527.23RMB/m^2/yr life-cycle cost saving compared with the coal-powered system and the gas-powered system.

3.3 The environmental analysis

Among all kinds of fossil fuels, coal and natural gas are always used as energy sources for the conventional heating system. The efficiency of a domestic coal-powered heating system is about 75%, and the efficiency of a domestic gas-powered heating system is about 80%. The heat generated by burning 1t standard coal and 1m^3 natural gas are 8141kWh and 9.88kWh respectively, which means the winter heating for a standard Chinese northern rural house will cost 1320kg standard coal or 1022.39m^3 natural gas. Owing to the zero-consumption characteristic of the brand-new solar-powered heating system, it implies one set of the system can annually save 1320kg standard coal or 1022.39m^3 natural gas.

It is noticed that the contaminants mass generated by the coal-powered system is much higher than the gas-powered system. Accordingly, the gas-powered system is more environmental-friendly. However, these two systems are both environmentally harmful when compared with the zero-bill solar-powered system. Because of the zero-bill characteristic, the novel solar-powered system saved contaminants compared with other two conventional space heating systems are showed in Table 4, which is a breakthrough advantage for the solar-powered space heating system.

Table 4 The annual contaminants generated by coal-powered and gas-powered systems

Contaminants	Coal-powered (kg)	Gas-powered (kg)
Harmful dust	897.6	0.026
CO_2	3220.8	2003.9
SO_2	99	0.015
NO_x	49.5	0.061

4. CONCLUSION

This paper proposed a dedicated socio-economic and environmental performance study of a novel zero-bill solar-powered space heating system for application in a cold area, Taiyuan, Shanxi, China, where the city mainly uses coal and natural gas as the main energy sources to supply space heating, suffers from severe air pollution and desperately needs to use renewable energy to improve the life quality of local residents and environment. The study involved the prediction of the fossil fuel energy saving, cost payback period on investment and life cycle carbon emission reduction of the new system, relative to the conventional gas-powered and coal-powered heating system.

The energy performance of the proposed solar-powered system and the served house was simulated by using the established model that presents the monthly collected heat and heat demand over a typical heating season and generated electricity over a typical year.

The summary of the heat demand of the served house during the heating season is 8081kWh. And the heat generated by the solar thermal panel array is 6265.12kWh. From December to February, the heat deficit of the system can reach to 2925.27kWh. The heat deficit needs to drive the air-source heat pump as an auxiliary heating device during the heating season, during which the average COP of the heat pump reaches to 3.27, and needs to consume 1017.4kWh electricity. Furthermore, the electricity consumed by water pumps of the system is 204.3kW.h. Hence, the electricity consumption is 1221.7kWh during the heating season.

In this case study, the PV model can annually produce 216.2kWh/m^2. Hence, with 4 pieces 2m^2 photovoltaic panels, the novel solar-powered system can produce 1729.6kWh. According to the feed-in tariff in Shanxi, 0.75RMB/kWh, the served house can earn totally 1297.2RMB per year by transferring the generated electricity to the power grid. The total electric charge of the solar-powered system is 732.48RMB which is lower than the photovoltaic electricity sold price, and thus the novel system can reach to zero energy consumption, which is a great advantage of the novel system.

When it comes to the economic and environmental performance, for the 100m^2 served the house, the coal-powered annually generates 897.5kg harmful dust, 1216.9kg CO_2, 99kg SO_2 and 49.4kg NO_x higher than the gas-powered system. Compared with the coal-powered system, the system has a cost payback period of around 14.8 years and the life-cycle net cost saving of nearly 17573RMB in Shanxi. Furthermore, in comparison with the gas-powered system, the system has a cost payback period of around 5.9 years and the life-cycle net cost saving of nearly 52723RMB.

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