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EXPERIMENT STUDY ON THE ENERGY SUPPLY SYSTEM PERFORMANCE OF SYSTEM COMBINED HEATING, POWER AND BIOGAS IN GANNAN TIBETAN AREA

Xiaoyu Yang [1,2,3,4] , Jinping Li [1,2,3,4,*], Hang Wang [1,2,3,4], Zhaofu Wang [1,2,3,4], Juanjuan Huang [1,2,3,4], Chunlong Wang [1,2,3,4]

1. Western China Energy＆Environment Research Center, Lanzhou University of Technology, Lanzhou 730050, China;

2. Key Laboratory of Complementary Energy System of Biomass and Solar Energy, Gansu Province, Lanzhou 730050, China;

3. China Northwestern Collaborative Innovation Center of Low-carbon Urbanization Technologies, Lanzhou 730050, China;

4. College of Energy and Power Engineering, Lanzhou University of Technology, Lanzhou 730050, China

ABSTRACT

Abundant solar energy resources were existed in Gannan Tibetan area where passive solar houses are widely used in this area. However, due to their functions are single and unstable , the heating load in winter is very large. In winter, Tibetan residents still need to rely on coal and dry cow dung for heating. In order to solve this problem, a thermoelectric methane supply system was established on the basis of the original passive solar house by utilizing the abundant solar energy and biomass resources in Tibet. This system can provide users with winter heating, domestic electricity, domestic hot water and gas to meet different levels of energy demand. Through the whole heating season of test of the system, the results show that the system is stable, and the system heat supply accounts for 94.4% of the total building heat demand. For most of the time, the indoor temperature is higher than 14 ℃, the cumulative output of biogas is 95 m^3, and the average daily output of biogas digester is 0.76 m^3. During the test period of PV power generation subsystem, the daily generation capacity was 3.1 kWh. The system has good economy and environmental protection. The use and promotion of this system has changed the backward energy utilization mode, improved the energy utilization efficiency, reduced the use of fossil fuels, improved the quality of life for residents, and improved the natural environment.

Keywords: Tibetan areas, energy supply systems, renewable energy

1. INTRODUCTION

At present, renewable energy represented by solar energy and biomass energy has been widely used. Biomass energy is mainly produced by anaerobic fermentation. Biogas production by anaerobic fermentation is the simplest and most direct method of using biogas organic waste as raw material in rural areas [1]. Mohammadrezaei et al. [2] determined the optimum mechanical stirring rate of biogas reactor by studying energy balance calculation and hydrodynamic simulation, in order to achieve the highest energy efficiency and net energy gain. Alkhamis et al. [3] studied the use of 1.3 m × 1 m flat plate collector to provide heat to 53 L biogas fermentation tank. It was found that the system can maintain a constant temperature and provide stable and sustained heat energy, and the collection efficiency has also been improved. Rathod et al. [4] analyzed the gas composition of the reactor at different temperatures and determined the optimum reaction temperature.The use of solar energy is more diversified.Rekstad et al. [5] compared the performance and energy consumption of solar active heating and air-water source heat pump. Ant_nio et al.[6] proposed a simple mathematical model for controlling domestic solar water heaters by switching flow. Annual cycle simulation shows that when the external insulation thickness is 20 cm, the heat loss is less than 3%. Fan et al.[7] studied the applicability of solar heating systems in different regions and under different weather conditions.The results showed that parabolic trough solar energy and heat and absorption heat pump combined system were recommended in solar energy-rich areas. Choi et al. [8] studied the influence of solar active heating system on heat collection, heat storage and heat preservation.It was found that heat preservation can reduce heat dissipation by 13.2% and increase heat release by 12%. Finally, the possibility of water tank heat storage was put forward. Furbo et al.[9] studied the annual solar collector performance of six typical places in Denmark.When the water temperature was 60 ℃, the collector performance changed between 405 kWh/m2 and 566 kWh/m2, and the annual thermal performance extreme value was about 40%. Lee et al. [10] made a comparative study of passive heating buildings with and without cellulose phase change materials. The results showed that the average daily heat flow peak reduction rate of each wall was 25.4%, and the average daily heat flow peak reduction rate of four walls was 20.1%. Perraki [11] experiments were carried out to study the influence of different materials on the performance of photovoltaic modules at 10 ℃~ 35℃ambient temperature,and the temperature coefficients of different materials were obtained. Sheppard [12] designed and tested a renewable energy storage system to improve power generation efficiency and reduce costs through metal hydride heat storage. Skoplaki et al. [13]studied the effect of temperature of silicon solar cell module on photovoltaic power generation performance. Swapnil et al.[14] studied the factors affecting the performance and output power of photovoltaic power generation system, and obtained the linear change of output power and working temperature of photovoltaic module.

Table 2.1 Measuring Instruments and Parameters

Instrument	Model	Range	Accuracy
Temperature sensor	PT100	-50～100℃	±0.1℃
Solar Radiometer	TBQ-2-B	0～2000W·m-2	±2%
Turbine flowmeter	LWGY-20A	0.4～ $8m^3$·h-1	±0.5%
DC voltmeter	RH-DV71	0～220V	±0.5
DC ammeter	RH-DA71	0～10A	±0.5
Single-phase watt-hour meter	--	--	0.1kWh
Gas meter	G16	--	$0.001m^3$
Biogas analyzer	Gas600	CH4:0～100% CO2:0～100%	±3%
Data Acquisition Instrument	34980A	--	--

In summary, some achievements have been made in the research of distributed energy supply system based on renewable energy utilization, but the requirement for building environment is very high, which is not suitable for the Tibet Plateau. Therefore, it is necessary to develop renewable energy systems suitable for the region. Solar energy active and passive combined heating system, solar energy constant temperature biogas system and PV system are combined to form suitable plateau agriculture and pastoral areas. Renewable energy supply system can satisfy the energy demand of farmers continuously and steadily on the premise of satisfying their own energy consumption, and has good environmental protection and economic benefits. The popularization and application of this system can improve the living standard of farmers and herdsmen in plateau. Precision poverty alleviation is of great significance.

2. MATERIALS AND METHODS

2.1 Experimental Energy-Generation System

The system as shown in Fig.2.1,which includes solar heating subsystem, PV power generation subsystem and solar constant temperature fermentation subsystem. The client side is shown in Fig.2.2.The system uses solar energy and biomass energy as energy input to provide users with winter heating, domestic hot water, cooking gas and domestic electricity. Specific working principles are as follows: solar active and passive combined heating subsystem is composed of solar active heating system and additional sunshine room, solar collector collects heat in winter daytime, indoor heating through additional sunshine room, hot water in night collector enters indoor heating through ground heating coil driven by water pump; PV power generation subsystem converts solar energy into indoor heating. Electric energy can not only meet the power consumption of the whole system itself, but also provide users with electricity for daily use. The solar energy thermostatic biogas subsystem maintains the relative constant temperature of biogas slurry through temperature controller, and the biogas produced is stored in biogas bags for daily cooking. Each part of the system is designed as follows:

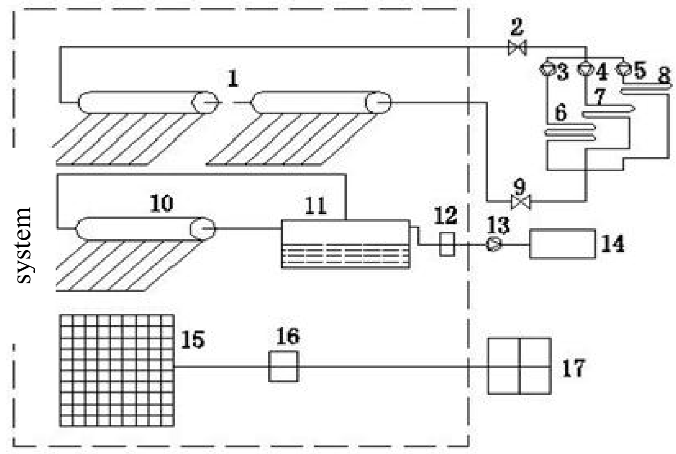

Fig.2.1 Schematic of household heat-power- biogas system 1—Solar collector for heating 2、9—Valve 3、4、5—Water pump 6、7、8—Dissipate heat 10—Solar collector for biogas digester 11—Biogas digester 12—Desulfurization purifier 13—Air pump 14—Biogas stove 15—PV array 16—Inverter Controller 17—Battery pack

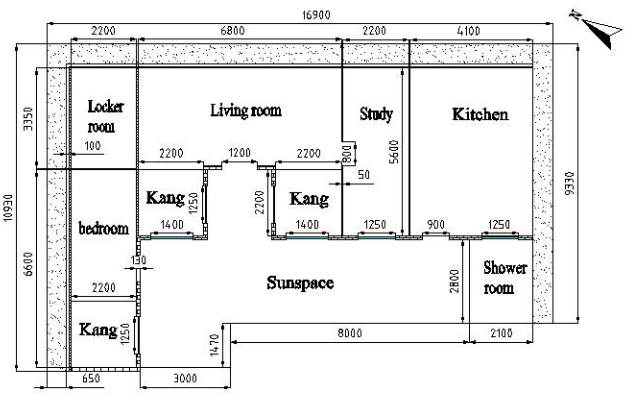

Fig. 2.2 Plan of experimental building

In order to study the performance of the test system in the plateau cold area, according to the test requirements of GB 50785-2012 "Evaluation Standard for Indoor Thermal and Humid Environment of Civil Buildings" and GB/T 50801-2013 "Evaluation Standard for Application Engineering of Renewable Energy Buildings", this paper conducts on-site test of the pre-built thermal-electric methane combined supply system from October 15th, 2018 to April 1st, 2019.

2.2 Methods

The calculation of building heating load mainly includes two items: basic heat transfer loss and cold air infiltration loss. In this paper, indoor heating temperature tn=14 ℃ is taken. Using SLR to calculate the auxiliary heat needed for additional sunspace:

$$SLR = \frac{S}{NLC \times DD_{14}} \quad (1)$$

$$Q_{\text{aux}} = (1 - SHF) \times NLC \times DD_{14} \quad (2)$$

In equation (1) and (2) *S* is the effective heat gain through glass of sunroom, *SLR* is the heat gain load ratio, *SHF* is the solar heating rate, *NLC* is the net load coefficient of solar house (kJ/℃·d), DD_{14} is the heating degree days (℃·d)。

$$Q_1 = \sum cm'(T_{in} - T_{out})t \quad (3)$$

In equation (3), *c* is specific heat capacity of water(4200 J/kg·℃), *m*′ is Heating circulating water flow (kg/s), T_{in} is Heating Intake Temperature(℃), T_{out} is Heating Backwater Temperature(℃)。

Solar photovoltaic cell power generation is calculated by the following formula:

$$E_{p} = \sum 0.8 U_{p} I_{p} t \quad (4)$$

This equation represents the PV Power Generation Subsystem which EP is generation capacity of PV (J) ,inverter efficiency is 0.8, UP is generation voltage of PV (V), IP is generation current of PV(A), t is time (s)。

3. RESULTS AND DISCUSSION

3.1 Analysis of the stability of energy supply system

3.1.1 Stability of heating system

Gannan Tibetan area has a high altitude, cold climate and frequent changes in winter, as shown in Fig.3.1, the change of the average temperature and solar radiation in the outdoor environment during the test period. It can be seen from the chart that the environmental temperature first decreases and then increases with time. The environmental temperature is the lowest in January, and the monthly average temperature is only - 8 ℃. The monthly average temperature in October and March is higher than other months. The monthly average temperature is 2.6 ℃ and 2.3 ℃. The solar radiation fluctuates greatly with the weather, but the overall change trend is the same as the environmental temperature, and the monthly average solar radiation changes. The average solar radiation was the lowest in February, 15.6 MJ/m^2, 20.4 MJ/m^2 in March, 18.2 MJ/m^2 in October, 16.3 MJ/m^2 in November, 16.5 MJ/m^2 and 16.6 MJ/m^2 in December and January respectively.

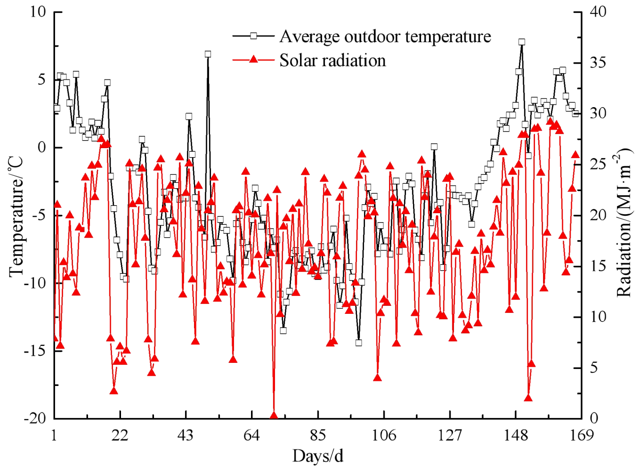

Fig.3.1 Outdoor temperature and solar radiation

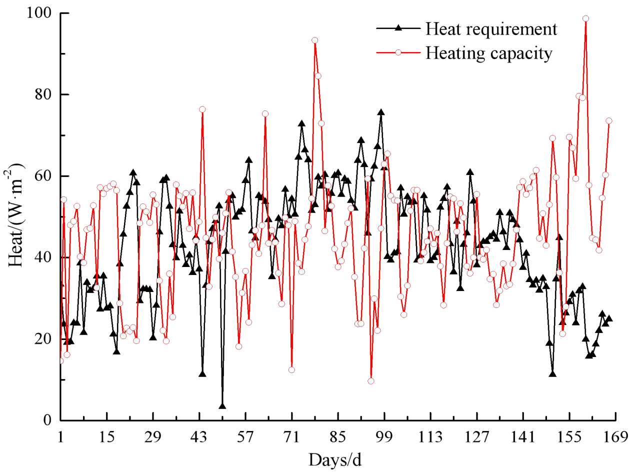

Fig.3.2 System Heat Supply and Building Heat Demand

In order to analyze the stability and reliability of the heating system, the heat demand of the system and the building during the test period is calculated by formula (1) and formula (2). As shown in Fig. 3.2, it can be seen that the heat demand of the system can be met in October, November and March except for some extreme weather, but in the coldest months, December, January and February. In January, the heat demand of the building can not be met by the heating system for most of the time. This is due to the fact that the change trend of the building heat demand is opposite to that of the outdoor environment temperature. The change trend of the heating quantity is the same as that of the solar radiation. In the coldest month, the building heat demand is the most, but the heating quantity of the system is usually the least, which results in the disparity between the heating quantity and the heat demand match.

3.1.2 Power generation stability of PV system

Because of the frequent climate change in Tibet area. Whether the PV power generation subsystem can continuously and steadily provide power for users is the key to measure its performance. The variation of power generation and consumption for 10 days from December 4th, 2018 to December 13rd, 2018 is shown in Fig. 3.3. From the figure, it can be seen that from December 4th to December 6th are sunny, December 7th to December 12th are continuous snow days and December 13th are sunny days. The power generation were 3.7 kWh, 3.9 kWh, 4.6 kWh, respectively which in the first three days. The power generation from December 7th to December 12th was 1.9 kWh, 2.4 kWh, 2.3 kWh, 2.4 kWh, 2.4 kWh, 1.1 kWh and the power generation in December 13th was 3.7 kWh. The power generation of the system was in turn 2.2 kWh、 2.1 kWh、 2.2 kWh、 2.3 kWh、 2.4 kWh、 2.4 kWh、 2.5 kWh、 2.6 kWh、 2.7 kWh、 2.5 kWh. The system generates is 28.4 kWh in 10 days, of which 24.7 kWh and 21.4 kWh are generated in the first nine days. In addition, users mainly use two 15 W energy-saving lamps for daily use, which consume 0.18 kWh in the light of 6 hours per day. Although the power consumption of the system is higher than that of the power generation in continuous cloudy and snowy days, the surplus power consumption can still meet the demand of power consumption and the remaining power consumption will be 2.2 kWh depending on the previous sunny days. This shows that the PV power generation system can also provide users with domestic electricity on the premise of meeting the system's power consumption. It has less power consumption in cloudy days, but it will not stop generating electricity. When the power consumption is higher than the power generation, it can rely on the energy stored in the battery to supplement the system's power demand and ensure the normal operation of the system.

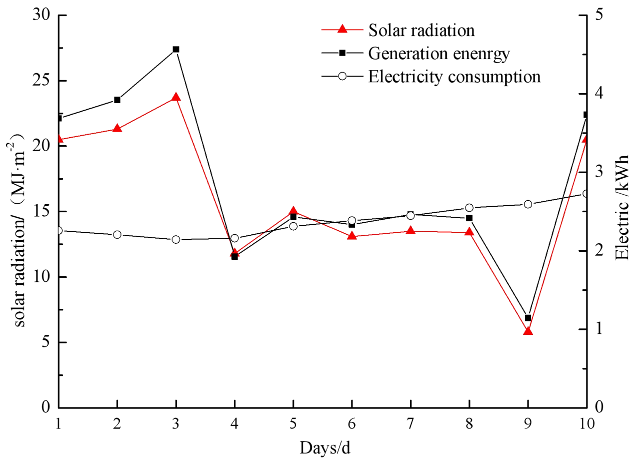

Fig.3.3 Power Generation and Power Consumption of PV from Dec, 4th, 2018 to Dec, 13th, 2018

3.1.3 Stability of biogas system

In order to research the anti-interference ability and the stability of solar energy thermostat fermentation system in extreme rain and snow weather, the change of solar hot water temperature and biogas temperature was analyzed one day after three successive days of snow (November 17th, 2018).

As shown as Fig 3.4, it can be seen that after three consecutive snowy days, the temperature of hot water in solar collector drops to 29.9 ℃ at about 10 o'clock, and then the temperature of hot water gradually rises to 41 ℃ with the increase of solar radiation intensity. Although the temperature of outdoor environment is low, the temperature of biogas slurry in biogas digester can still be maintained at about 27 ℃, the maximum temperature difference is only 1.2 ℃, and gas production on that day. With the amount of 0.82 m^3, the solar energy constant temperature biogas system can still operate normally in continuous rain and snow weather, which indicates that the system has better weather resistance and can produce gas steadily and continuously under the condition of low temperature in winter.

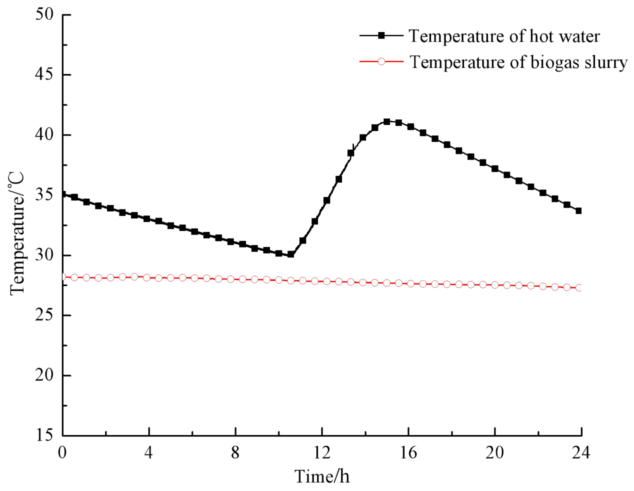

Fig.3.4 Temperature of solar hot water and biogas liquor

3.2 Performance Analysis of Heating System

In order to more clearly see the relationship between supply and demand heat in different months, according to the calculation results. As Fig. 3.3 shows the comparison between system heat supply and building heat demand in different months. The proportion of heating requirements met by the system in different months during the test period is 157.9 %, 105.5 %, 82.3 %, 84.3 %, 94.1 % and 180.1 %, respectively. It can be seen that October , November , January and March, when only solar heating system is used, it can continuously and steadily supply energy to buildings, fully satisfying the indoor heating demand. Although the system heat supply can not meet the heat demand in the coldest month, but similar, need to be a certain amount of heat supplement to meet the indoor heating requirements. Therefore, it can be considered that the system can continuously and steadily supply energy to the building throughout the heating season, and can meet the indoor heating demand very well in most of the time, which shows that the stability and reliability of active solar heating system is better.

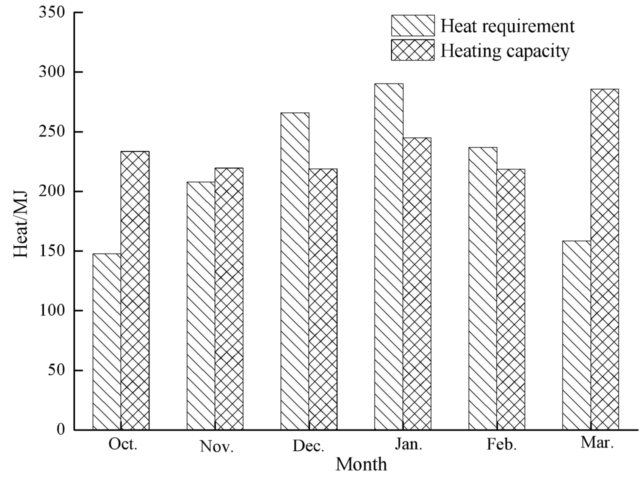

Fig.3.5 Comparison of average heat supply and heat demand in different months

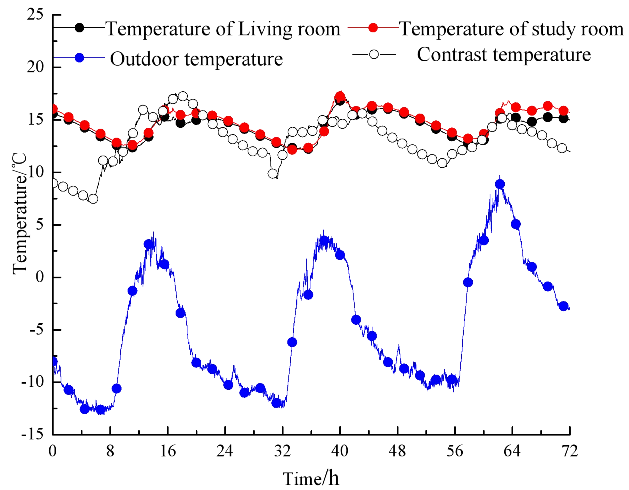

Fig.3.6 Indoor and outdoor temperature（2018-11-21～23）

Figure 3.6 shows the curves of indoor temperature, building temperature and outdoor ambient temperature of the living room and study in three consecutive sunny days on November 21, 22 and 23, 2018. Through the analysis of the curves in Figure 4.4, it is found that there are two peaks in the temperature of the test group every day. The first peak occurs at noon every day. Because of the gradual increase of daylight intensity, additional sunshine time occurs. The temperature of the indoor air is also rising, reaching the highest at noon and then gradually decreasing with the weakening of solar radiation. When the indoor heating begins at 18 o'clock, the temperature rises. From the graph, it can be seen that the lowest outdoor temperature is - 13.1 ℃, the average temperature is - 4.7 ℃, the average living room temperature of the test group is 14.4 ℃, the highest temperature is 17.1 ℃, the wave amplitude is 4.9 ℃, the highest temperature of the study of the test group is 17.8 ℃, and the average temperature is 14.7 ℃. It can also be found that the average temperature of the study is slightly higher than the average temperature of the living room through the curve in the figure. On the one hand, the contact area between the study and the outside world is smaller and the loss of heat dissipation is less. On the other hand, the heating coil enters the building first through the study and then into the living room, resulting in a slightly higher heat supply to the study than to the living room, which makes the temperature of the study slightly higher than that of the living room. The contrast group was heated by traditional coal stove, and the indoor temperature fluctuated in the range of 5.7-13.9 ℃. The average indoor temperature was 8.2 ℃ and the amplitude was 10.4 ℃. Through comparison, it was found that the indoor temperature of the experimental group with solar active-passive combined heating met the requirements of GBT50824-2013 "Standard for Energy Conservation Design of Rural Residential Buildings" not less than 14 ℃, and the indoor temperature changed less. The degree is also more stable, which greatly improves the indoor thermal environment of local residents and improves indoor comfort.

3.3 Analysis of power generation and power consumption in PV system

Fig.3.7 shows the variation of daily power generation and system power consumption of photovoltaic power generation system during the 101-day test period from November 20, 2018 to February 28, 2019. The power consumption of the system mainly includes two aspects: heating circulating pump and biogas heating circulating pump. The heating circulating pump works the same time every day with constant power consumption. The power consumption of biogas heating circulating pump ferments with biogas digester. Temperature changes. When the outdoor solar radiation intensity is weak and the ambient temperature is low, the working time of the circulating pump is longer and the power consumption is more.

From the figure, we can see that the PV power generation system generates more electricity than electricity in most of the time. In the continuous rain and snow weather, the system can meet its own electricity demand through power generation and storage devices. In the figure, the power consumption increases with time, and the power generation decreases because the outdoor temperature decreases with time, the heat dissipation of the biogas digester increases, the working time of the biogas heating circulating pump increases, and the power consumption of the system increases. In addition, because the temperature of the biogas digester decreases after feeding, the power consumption of the system increases, while the solar radiation increases. Compared with other months, the intensity of photovoltaic power generation in December and January has decreased slightly, which means that the power generation of photovoltaic power generation system in December and January should be the lowest in the whole year, and the power consumption of the system should be the highest in the whole year. During the 101-day test period, the total solar radiation absorbed by the PV system was 14397.4 MJ, equivalent to 3999.3 kWh. The cumulative power generated by the system was 307.2 kWh. The heating cycle pump consumed 199.1 kWh, the biogas heating cycle pump consumed 67.2 kWh, and 40.9 kWh was also provided for users. The actual photoelectric conversion efficiency of the photovoltaic power generation system was 7.6% from the whole test period. In the meantime, the photovoltaic power generation system can not only meet the system's own power consumption, but also provide users with domestic electricity. The PV power generation system has good power supply performance.

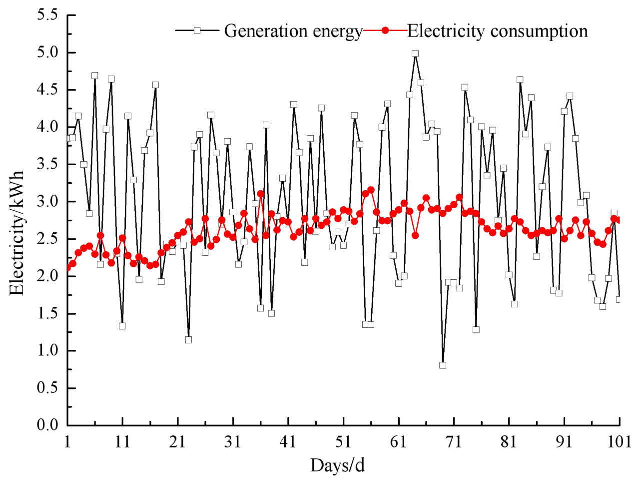

Fig.3.7 Generation and consumption of PV system

3.4 Analysis of solar energy constant temperature fermentation system

The weather conditions during the test period are shown in Table 3.1. In the 126 days test time, there are 62 sunny days, accounting for 49% of the total time, and 28% cloudy and snowy days, of which the longest continuous cloudy and snowy days are 5 days.

Table 3.1 Weather conditions during the test period

Weather	Sunny	Cloudy	Overcast	Snowy
Days	62	29	11	24
Ratio	49 %	23 %	9 %	19 %

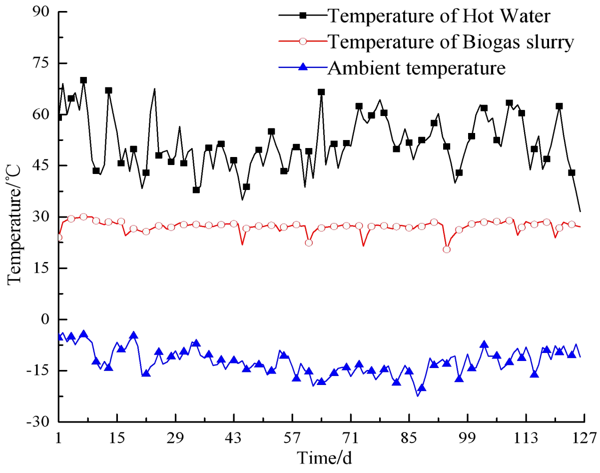

Fig.3.8 Environmental temperature, fermentation temperature and solar hot water temperature

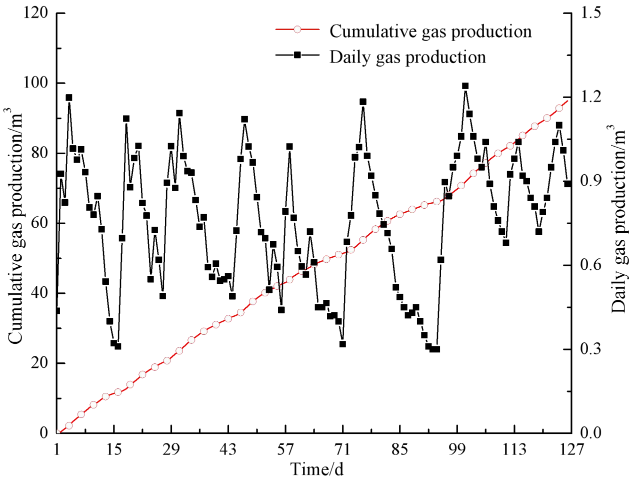

Fig.3.9 Daily and cumulative gas production

Fig.3.8 shows the variation curves of solar hot water temperature, biogas liquid temperature and ambient temperature. It can be found that the average ambient temperature during the test period is - 12.3 ℃, and the minimum ambient temperature is - 22.5 ℃. The temperature of biogas slurry in the biogas digester is stable at about 28 ℃. The temperature of biogas slurry decreases due to mixing sheep manure with warm water at each feeding stage, but the temperature of biogas slurry increases gradually to a constant level after setting temperature through the solar heating system. The temperature of biogas slurry can be maintained due to four consecutive snowy days after the second feeding, but the temperature of biogas digester external thermal insulation layer is thicker. The temperature of hot water in solar collector is slightly lower than that of biogas slurry due to the decrease of outdoor environment temperature, which can ensure that the solar heating system can provide heat for biogas digester to maintain the stable fermentation temperature of biogas digester.

Fig.3.9 shows the daily and cumulative gas production of biogas during the test period. The raw material for biogas digester fermentation is local sheep manure, and the feeding mode is semi-continuous feeding. During the whole test period, sheep manure is treated with 2.7 m^3, Communist methane 95 m^3, and the average daily gas production of biogas digester is 0.76m^3, which can meet the gas demand of three households cooking.

3.5 Economic and environmental benefits

The whole thermal and electrical cogeneration system includes three subsystems: solar heating subsystem, photovoltaic power generation subsystem and solar constant temperature fermentation subsystem. The solar heating subsystem adds 7 sets of solar collectors to form active and passive heating on the basis of the original passive solar house. The system has a floor heating coil placed on the floor and under the roof. The cost includes 7 sets of solar vacuum tube collectors for 13650 CNY, floor heating coils for 50 CNY/m^2, plus valves and pipes and other related accessories, the total cost of the entire solar heating subsystem is 17,875 CNY; The cost of photovoltaic power generation subsystem includes photovoltaic panels and inverter control boxes. The battery pack and related accessories total 20,000 CNY; the cost of the solar constant temperature fermentation subsystem includes 1,500 CNY for the biogas tank, 500 CNY for the thermal insulation coil and the external insulation material for the biogas tank, plus the accessories such as valves and connecting pipes, the whole solar constant temperature The total investment cost of the fermentation subsystem is 3,080 CNY, ignoring the labor cost, so the initial investment cost of the entire thermal and electrical joint supply system is 40,955 CNY. The system equipment cost and cost calculation results are shown in Table 3.2.

Table 3.2 System installation fee schedule

System unit cost			Raw material cost	Maintenance costs	Total
Solar heating subsystem	PV subsystem	Thermostatic fermentation subsystem			
￥17875	￥20000	￥3080	￥0	￥100	￥41055

Assuming the lifetime of system is 15a and the benchmark discount rate is 5.5%, the dynamic investment payback period of the system is 7.5a calculated by economic formula. The system is economically feasible and the benefits are considerable.

For the building using the thermoelectric biogas co-supply system, the local abundant solar energy and biomass energy resources are fully utilized to provide users with continuous and stable supply of domestic electricity, cooking gas and winter heating, the system is convenient to use, clean and pollution-free, and reduce carbon dioxide. The discharge of pollutants enhances the quality of life of the users. According to the calculation results above, assuming that the coal stove has a combustion efficiency of 32%, the power standard coal conversion coefficient is 0.404, and the biogas stove has a combustion efficiency of 75%, the system can save annually. The standard coal situation is shown in Table 3.3.

Table 3.3 Quantity of saving standard coal

Type	Heating	Electricity	Gas and hot water	Total
Weight/kg	5120	457	890	6467

According to the data, the complete combustion of 1 kg of standard coal produced 2.49 kg of CO_2, 0.68 kg of dust, 0.075 kg of SO_2, and 0.0375 kg of NO_x [22]. The system can reduce CO_2, dust, SO_2 and NO_x emissions by 16.1 t, 4.4 t, 0.49 t and 0.24 t, respectively, indicating that the energy saving and emission reduction benefits of the system are significant.

4. CONCLUSIONS

The energy supply performance of the system was studied through experiments. The energy analysis of the system was carried out and the system optimization scheme was proposed. The economic, environmental and social benefits of the system were evaluated. The results showed that the system was stable in energy supply and good in performance, and the following conclusions were drawn:

The system has good running stability and continuity. For the solar energy active and passive combined heating subsystem, the building heat demand can be fully met in most of the test time. In the coldest month, the system heat supply is slightly lower than the building heat demand. In the whole heating season, the heat supply of the system accounts for 94.4% of the total heat demand of the building. During most of the time, the indoor temperature is higher than 14 °C. The PV power generation subsystem generates 3.1 kWh everyday during the test. The actual photoelectric conversion efficiency is 7.6%, the power generation is higher than the electricity consumption for most of the test. The temperature of the biogas in the biogas tank is stable at around 28 °C. After three days of snow, the temperature of the biogas in the biogas tank can still be maintained at around 27 °C. Due to less environmental impact, the gas production is relatively stable. During the test period of the fermentation system, a total of 2.7 m^3 of sheep manure was treated, and the cumulative production of biogas was 95 m^3, and the average gas production per day of the biogas tank was 0.76 m^3.

The initial investment of the system is 41055 CNY, and the dynamic investment payback period is 7.5 years. Compared with the traditional energy consumption mode, the combined heat and power biogas supply system can save 6908 CNY per year, which is equivalent to reducing the burning standard coal by about 6.5 t, which can reduce CO_2 and dust , SO_2, NO_x are 16.1 t, 4.4 t, 0.49 t, 0.24 t, respectively.

The use and promotion of the system has changed the local backward energy use mode, improved energy utilization efficiency, reduced the use of fossil fuels, improved the quality of life of residents and improved the natural environment. Therefore, the economic benefits and environmental and social benefits of the system are significant.

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