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Project：PV-GSHP System for Cost Effective High Energy Performance Buildings in Cold Region

PV-GSHP System for Cost Effective High Energy Performance Buildings in Cold Region

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ABSTRACT

Application of renewable energy is the most effective way of building energy efficiency. Solar PV-GHSP system is proposed in this paper. An experiment was conducted in the north of China,Harbin.The results show that the system has several advantages. First, the average ground temperature can be kept constant, because the heat from the PV panels is used to regenerate the ground. Especially in residential neighbourhoods, where many of such systems may be installed close to each other, this prevents long-term cooling of the ground.Second, the prevention of declining ground temperatures also guarantees a constant coefficient of performance (COP) of the heat pump. And finally,the electrical efficiency of the PV panels will be increased, due to the strong cooling of the PV cells in summer.The system also has good economic benefits.The system discussed in this paper is expected to be most successful in cold region.

INTRODUCTION

Energy is the material basis for the human survival and development. With the development of human and society, energy consumption is increasing, leading to serious consequences such as energy depletion and environmental degradation. At present, energy consumption of urban buildings is 30% of commercial energy in our country .In recent years, it is believed that building energy conservation is the most potential and effective way in various energy saving measures through research. And is also one of the most effective measures to relieve energy tension. The application of renewable energy in buildings is the most effective way of building energy saving. Solar PV and GSHP system are effective ways to use solar energy and geothermal..

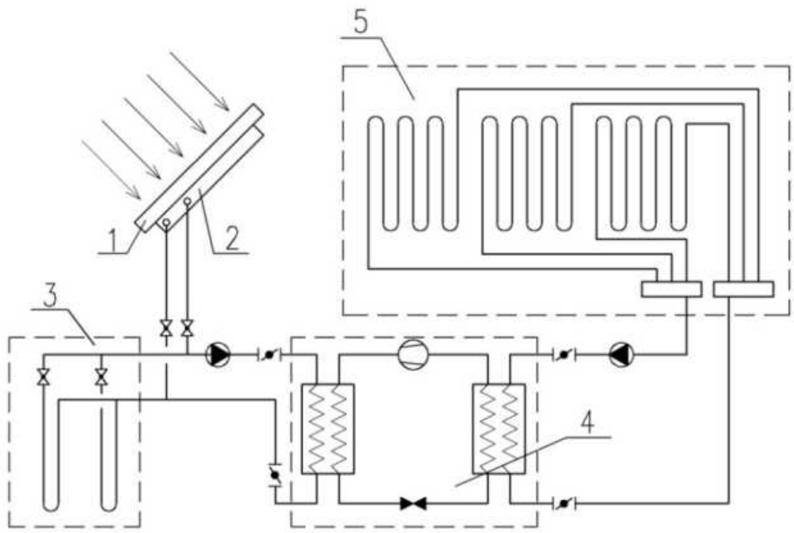
Solar PV system has become the development direction of China and the world due to its high level quality and it is clean. Low efficiency and high cost are the important factors that affect or restrict the development of the solar photovoltaic industry currently. We tend to focus on the improvement of silicon or amorphous materials to improve the efficiency of solar photovoltaic power generation. But in fact, the silicon cells’ power generation efficiency relies heavily on their temperature. Statistics show that when the battery components’ temperature reduces one degree Celsius, the power output would increase by 0.2% to 0.5%. General commercial solar battery photoelectric conversion efficiency is 6% to 15%. Some part of solar radiation is reflected but most is absorbed by the cells and translated into heat. If the heat can be immediately removed and effectively used, it will show obvious energy saving effect(Quan Z. et al. 2010).

Now more researches focus on individual PV system and Solar-GSHP system. Researches related to PV system mainly focus on improving power generating efficiency. Researches related to Solar-GSHP system mainly concentrate on increasing the solar collector collection efficiency, the soil temperature distribution and solar energy utilization coefficient and economic, etc. A system is presented in this paper which integrates PV module and GSHP. The heat exchange device is installed after the solar panels, through the buried tube heat exchanger with water as cooling medium, the heat is exchanged with the soil, so as to decrease the temperature of the solar cell components and store energy for heating in winter. Thus not only the photoelectric conversion efficiency is improved, but also the heat pump heating efficiency is increased for using this composite system. Considered the huge differences between cooling load and heat demand of buildings in cold region, this system can ease imbalance of soil temperature field to some extent by instoring the summer heat accumulated from the PV collector into soil and suppling some heat taken from soil in winter.

EXPERIMENTAL APPARATUS AND PROTOTYPE

Solar PV- GSHP system

The system mainly includes PV modules,GSHP module, heat exchange device and radiant floor heating system. Instore solar panels on the roof, the heat exchange device is installed below the solar panels which is connected with buried tube heat exchanger system. Low temperature floor radiation heating of dwelling is used.The system is more practical in cold region. The system diagram is shown in Figure 1.



1.Solar panels; 2. Solar panels heat exchange device; 3.U-tube heat exchanger system; 4.Heat pump;5. Radiant floor heating system.

Figure 1. Solar PV - GSHP system diagram

In this system, the heat produced by PV panels is primarily stored in a storage vessel via a heat exchanger. In summer, any excess heat from the PV panels is stored in the ground via a set of ground loop heat exchangers. In winter, this heat is retrieved from the ground by a heat pump via the same heat exchangers: the heat from this heat pump can be directed to the floor heating.

Experimental setup

An ordinary dwelling in Harbin is put as the design object in this paper. The house is set in three rooms and the gate faces south. It has a total length of 16 meters, a width of 5 meters and a height of 4 meters. The middle room is living room, other sides are bedrooms. The model mainly includes solar PV power generation system and GSHP system.Take a family in Harbin as an example, the daily electricity consumption is shown in Table 1.

Table 1. Household daily electricity consumption (Harbin)

	Equipment	N(W)	N.O.	Time(h)	Q (Wh)
1	Lighting	11	8	4	352
2	Desktop	300	1	4	1200
3	Laptop	80	1	5	400
4	Oven	950	1	0.5	475
5	Electric kettle	1200	1	0.5	600
6	Vacuum cleaner	750	1	0.5	375
7	Washing machine	230	1	1	230
8	31 inch TV	150	1	6	900
9	Refrigerator	80	1	24	1920
10	Range hood	140	1	1.5	210
11	Hair drier	450	1	0.5	225
12	Rice cooker	500	1	1	500
13	Audio	100	1	1	100
14	HP unit	Change	1	Change	Change
15	EPS				300
	Total				7487

The thermal load of this model is simulated by DEST software. Monthly average working hours and energy consumption of heat pump are shown in Table 2. From the table,we know that household average daily consumption is 21.1kW • h.

Table 2. Operation condition of heat pump

Month	1	2	3	4	5	9	10	11	12
Average daily heat load(kWh)	13.84	11.60	6.56	3.65	1.22	1.20	3.31	8.02	11.57
Average monthly N（kW）	2.84	2.54	1.40	0.81	0.31	0.30	0.75	1.78	2.53
Average daily working hours（h）	12.87	13.29	13.36	10.40	3.80	0.97	12.06	13.00	13.85

Taking the level of Harbin's development and the prospect of grid-connected PV into account, we designed the grid-connected PV system with energy store device. After preliminary calculations, we chose the SG-180 type monocrystalline silicon solar cell module which was made in Shanggu Solar Energy Company in Hubei. The main parameters of the cells are shown in Table3 .

Table 3. Main parameters of the cell

OCV(V)	44.2	Specification	Momo-crystalline 125×125mm (5inch)
Working voltage(V)	36.8	Column	72(6×12)
SCC(A)	5.35	Size	1580×808×35mm (62.2×31.8×1.4inch)
operating current(A)	4.9A	Weight	15.5kg(34.1lbs)
P.P. (W)	180	Specification for Glass	3.2mm(0.13inch)
Tem(℃)	-40to+85	NOCT(℃)	45±2
Peak voltage(V)	1000VDC(IEC)/600 VDC(UL)	TK Pmax(%/℃)	-0.48
Fuse Ampere rating(A)	15	TK Voc(%/℃)	-0.34
Power tolerance	±3%	TK Isc(%/℃)	0.017

When the solar radiation is not too low, the photoelectric conversion efficiency can be considered as constant.According to the photovoltaic panels' property provided by manufacturer, conversion efficiency of SG-180 is 14.1% under standard condition. With analysis of GET-DATA, the result shows that the relationship between Pmax and temperature is approximately linear and the negative temperature coefficient is -0.417%. Temperature has greater impacts on the efficiency of PV power generation,So we think that the conversion efficiency's change is all caused by temperature.Calculated values of monthly average photoelectric conversion efficiency are shown in Table4.

Table 4.Monthly average photoelectric conversion efficiency

Month	1	2	3	4	5	6	7	8	9	10	11	12
Value	0.167	0.165	0.158	0.152	0.147	0.144	0.142	0.143	0.147	0.152	0.159	0.165

From above,we have known the user's average daily consumption is 21.1kW • h. Considering adding 5% of the expected load, the annual power consumption is calculated by the following Eq.(1).

$$21.1 \times 1.05 \times 365 = 8087 kW \cdot h \tag{1}$$

Required Photovoltaic modules area can be calculated by Eq.(2).

$$A = \frac{P}{P_0 \alpha} \tag{2}$$

Where *Po* is annual generation capacity of monolithic solar PV panels,and its values are given in the following Table.α is modified coefficient which covers battery performance attenuation,dust,high temperature,line loss,inverter efficiency,photovoltaic phalanx install. Their values are set to be 0.9,0.82,0.95,0.9 and 0.91 respectively.

Table 5. Generating capacity per unit area

Month	1	2	3	4	5	6	7	8	9	10	11	12	Total
Value (kWh/㎡)	10.4	11.3	13.6	12.3	11.9	11.4	10.8	11.1	12.0	12.0	9.7	8.6	135.2

The photovoltaic modules' area can be calculated in following equation.

$$A = 8087 / 135.2 = 59.84\text{m}^2 \quad (3)$$

$$N = 59.84 / (1.580 \times 0.808) = 46.9 \quad (4)$$

Where *N* is the battery plate number we required.Plates often require to be installed in series or parallel and symmetrical, so the plate number N is determined as 48 after integer. The total generating capacity is 8640W. When installing PV module, it's better to face south, according to the actual situation, it can be adjusted within 20°of the south.References show that the best angle in Harbin is latitude+ 3 °,that is the angle of the ground and wall is 43 ° 45 '.

As for designing the GSHP system,based on the air conditioning load of the building simulated by Dest, a small household water source heat pump is selected as the cold and heat sources of the system, and its heating capacity is 12.8kW, the input power is 4.1kW.

Single U-pipe underground exchangers are adopted in the system, the outer diameter and inner diameter of polyethylene pipe are 32mm and 26mm respectively. Two wells are needed, depth of which is 80meters, borehole diameter is 150mm and radiant floor heating is used in the house.

RESULTS AND ANALYSIS

Technical analysis and evaluation

This paper analyses the system in the following aspects: efficiency of PV power generation and energy efficiency of GSHP. In terms of photovoltaic power generation system, energy conservation equations for lower surfaces and pipe wall of PV panels are listed as follows respectively.

Without water cooling:

$$I = I\eta + h_\infty A(T_p - T_\infty) + \varepsilon\delta A(T_p^4 - T_\infty^4) \times 2 \quad (5)$$

With water cooling:

$$I = I\eta + h_\infty A(T_p - T_\infty) + \varepsilon\delta A(T_p^4 - T_\infty^4) + (T_p - T_\infty)/R_{t,c} \tag{6}$$

$$(T_p - T_s)/R_{t,c} = h_\infty A_s(T_s - T_\infty) + (T_s - \bar{T}_m)/R_{conv} \tag{7}$$

$$\eta = 0.141 \times [1 - 0.417\% \times (T_p - 318.15)] \tag{8}$$

$$\overline{T_m} = (T_{m,i} + T_{m,o})/2 \tag{9}$$

$$\frac{T_s - T_{m,o}}{T_s - T_{m,i}} = \mathrm{esp}(-1/\dot{m}\, c_p R_{conv}) \tag{10}$$

where I is the intensity of solar radiation, η is the photoelectric conversion efficiency. $T_p, T_s, T_\infty, T_{m,i}, T_{m,o}, \overline{T_m}$ are the sheet temperature, the wall temperature, the ambient temperature, the inlet temperature of water, the outlet temperature of water and the average temperature respectively, $R_{t,c}^{'}$ is the thermal contact resistance per unit area and A_s is the contact area.

On the other hand, in terms of GSHP system, Classical cylindrical source theory assumes that the heat transfer between the pipe wall and the soil are under the constant heat flux boundary condition and parameters of rock-soil thermal properties are isotropic. Far boundary undisturbed soil's initial temperature is *Tg*. The main objective of the classical theory of cylindrical source analysis is to determine the temperature difference ΔTg between the soil and the pipe wall. Under above conditions, based on the work of Carslaw and Jaeger, Ingersoll has derived the embed unstable cylinder heat transfer temperature difference expression within an infinite isotropic medium:

$$T_w - T_g = \Delta T_g = \frac{q}{L}\frac{G(Fo, p)}{k} \tag{11}$$

where q is the heat transfer, When the fluid absorbs heat, it is positive. When the fluid releases heat, it is negative. L is the depth of the tube well, $G\ (Fo, p)$ is a function of the theoretical solution G,k is thermal conduct ivity of soil, p is the ratio of the distance between calculated point and the tube well center to the radius of the tube well, R is Fourier number, defined as:

$$Fo = 4\alpha t / d^2 \tag{12}$$

where α is soil thermal diffusivity; t is time; d is the diameter of tube wells.Theoretical solution of G function is quite complex, when applying G function in calculation of heat transfer of cylinder embedded in an infinite medium, Ingersoll gives G fitting formula under a typical radius ratio:

$$p = 1\ G = 10^n$$
$$(n = -0.89129 + 0.36081 \times \lg(Fo) - 0.05508 \times \lg^2(Fo) + 3.5961 \times 10^2 \times \lg^3(Fo)) \tag{13}$$

From the perspective of simulation research on the operating performance of GSHP and annual energy consumption analysis, average temperature of the circulating fluid of buried tube heat exchanger is the main parameter to be determined. Because the heat capacity of the buried tube and backfill material is small compared with surrounding soil, the heat transfer model of this area can be treated as steady-state, which has been used in many of the previous models. The thermal resistance between fluid and the wall of the well are composed of thermal resistances of the inner tube flow, tube wall and backfill material.

$$R_b = R_{convection} + R_{pipe,conduction} + R_{backfill} \tag{14}$$

Based on the thermal resistance calculations described above, the average temperature of the fluid can be calculated as below.

$$\Delta T_f = T_w - T_f = \frac{qR_b}{L} \tag{15}$$

On the basis of calculated average temperature of the fluid and flow of the fluid, the inlet and outlet water temperature of the buried tube heat exchanger can be calculated .

$$\begin{aligned} T_{out,ground} &= T_f + \frac{q}{2\dot{m}c_p} \\ T_{in,ground} &= T_f + \frac{q}{2\dot{m}c_p} \end{aligned} \tag{16}$$

The heat absorption of GSHP evaporator equals to heat transfer between the medium in buried tube and the soil in winter. In other words, the operating performance of the heat pump and heat transfer performance of the buried tubes are coupled to each other. The performance of the heat pump is determined by the condensing pressure and the evaporating pressure, and the evaporation pressure and the condensation pressure are affected by many factors such as circulating water flow, inlet and outlet water temperature, many of which are interrelated. In the simulation of GSHP operating performance, in winter the corresponding condensing temperature is set according to the air conditioning system, the evaporating temperature changes with flow and temperature of the circulating fluid.

Application potential estimation

The potential and value of the system are evaluated from performance, efficiency and economic characters.

Aluminum tube heat exchange is closely installed on the back of the photovoltaic panels, water circulates in the serpentine aluminum tube. The total length of the tube is 300 meters and the diameter is 25mm.The inlet water temperature of aluminum tube heat exchange is equal to the outlet water temperature of buried pipe. The solar cells are thin, heat capacity of which is ignored. Physical parameters referred in the experiment are considered as constants for simplified calculation.Convective heat-transfer coefficient of water is suggested to be 300w/（m^2·K）,that of air is to be 16w/（m^2·K）,photovoltaic panels emissivity ε is to be 0.82, specific heat of water is to be 4187J / (kg • K). The before and after power generation efficiency are compared with system without cooling pipe.The results are presented in Figure2.

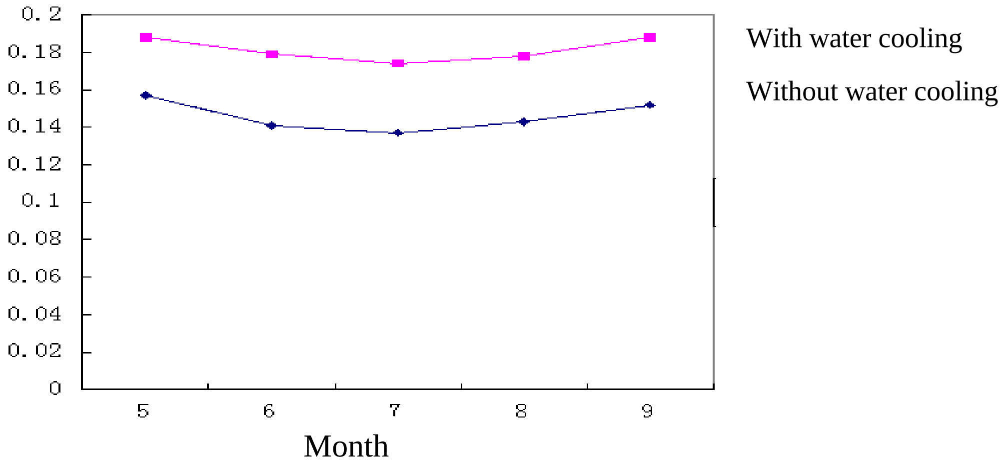


Figure 2. Power generation efficiency of PV panels

From the Figure, after using circulating water to cool the solar panels in summer, the PV power generation efficiency is improved. After the improvement, the PV system will increase power output by 110.84 kWh throughout the year.

In the combined operating mode of heat pump with PV system, the heat exchange device using water as cooling medium is installed below the solar panels. The heat is exchanged with the soil through buried tube and stored for use in winter, the temperature of soil is increased, so the heat pump can get more heat compared to the independent GSHP. The actual input power of heat pump has also increased. Considering the same amount of heat load, The heating performance of the system can be improved by testing on the combined optimized design. The coefficients of heating performance of heat pump running independently and jointly are shown in Figure 3.

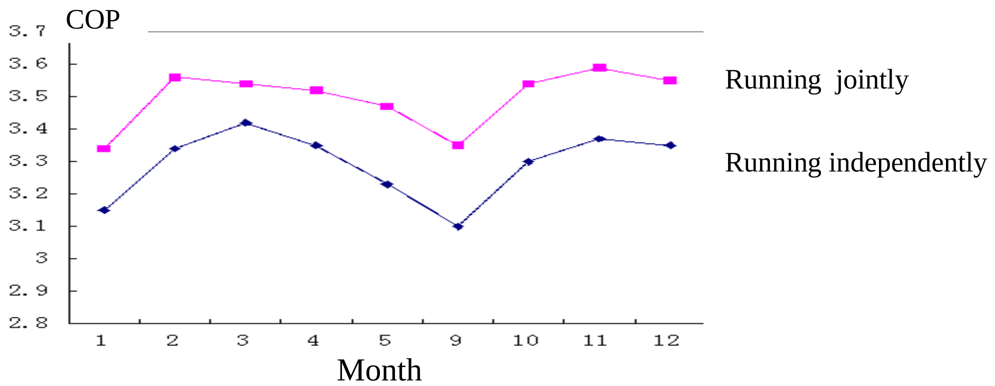


Figure 3. Coefficients of heating performance of heat pump

Huge differences between cooling load and heat demand cause gross imbalances of soil temperature field in cold region when GSHP is applied, this system instores the summer heat accumulated from the PV collector into soil and suppling some heat taken from soil in winter. This is improved to be an effective way to ease imbalance of soil temperature field to some extent .

The effect of government subsidies and electric power price on the economics (payback period) of the combined PV-GSHP system is analyzed in this paper. Assume that the users adopt "one household one meter". According to the “price exoteric [2012] No. 8” documents, for urban and rural residents who adopt "one household one meter" in Helongjiang Province, if monthly electricity consumption is lower than 170 kWh (including), the sales price is 0.51 Yuan/kWh. If it is between 171 kWh and 260 kWh (including), the sales price is 0.56 Yuan/kWh. If it is higher than 260 kWh, the sales price is 0.81 Yuan / kWh. The feed-in tariff can be calculated as 1.0 Yuan/kWh. Table 6 shows the users’ electricity fee.

Table 6. Harbin residential electricity fee

Month	Average daily power consumption (Wh)	Day	Monthly power consumption (kWh)	Monthly power production (kWh)	Electricity fee without PV (Yuan)	Electricity fee with PV (Yuan)
1	44037	31	1365.1	634.7	1032.3	518.2
2	41243	28	1154.8	693.8	861.9	300.0
3	26191	31	811.9	832.6	584.2	-20.7
4	15911	30	477.3	756.8	313.1	-279.5
5	8665	31	268.6	729.0	144.1	-460.4
6	7487	30	224.6	701.1	117.3	-476.4
7	7487	31	232.1	663.7	121.5	-431.6
8	7487	31	232.1	682.1	121.5	-450.0
9	7778	30	233.3	732.9	122.2	-499.6
10	15032	31	466.0	736.7	304.0	-270.7
11	30627	30	918.8	592.9	670.7	190.5
12	42527	31	1318.3	526.0	994.4	568.3
Annual electricity fee (Yuan)					5387	-1312

From the Table, if maintaining the same heat load and power consumption under the same environmental condition, the user can save 6699 Yuan each year. The cost to build a solar PV system is calculated as follows. At present, grid construction and maintenance costs about 12 Yuan / W, the power of this system is 8640W, so the system costs about 103680 Yuan, thus needing 15.5 years to recover costs. If all the investment cannot receive government subsidies, the system is not suitable for construction in the economic aspect. With more and more national photovoltaic(PV) engineering starting,and the PV industriesaredeveloping rapidly, the government is giving grant to the photovoltaic industry. PV industry will enjoy a substantial subsidy in recent years. If the government bears 50% of construction costs, it will pay back in 7.7 years. And the working life of grid-connection PV power system is 25 years.

As for heat pump, compared with the independent ground source heat pump system, the added parts of the combined system is just the heat exchanger below the PV panel. The diameter of the tube is 25mm and total length is 300 meters. The price of 25mm aluminum tube is about 10 Yuan / m in the market currently, so the system needs 3000 Yuan additionally. The combined system can save electricity by 567.30kWh each year, with electricity price is 0.8 Yuan / kWh, we will need 6.6 years to recover the added cost. The energy-saving effect of combined PV-GSHP system is shown in Table7 and the payback period of the system is shown in Table 8.

Table 7. Energy-saving effect of combined PV-GSHP system

Month	1	2	3	4	5	9	10	11	12
E_Q (PV-GSHP) (kWh)	30.26	29.52	16.85	6.32	0.98	0.11	6.71	17.29	28.54
E_Q (Independent GSHP) (kWh)	33.29	33.00	18.70	8.37	1.17	0.28	8.51	20.35	31.82

Table 8. Comparisons of performance and economics

	Monthly power generation growth rate	Annual power generation growth rate (kWh)	payback period (Year)
PV cells	3.8%	110．84	7.7
	COP growth rate	Annual energy-saving（kWh）	payback period
GSHP	7.5%	567.3	6.6

CONCLUSION

When the combined PV-GSHP system operates in summer, with circulating water in buried pipes cooling PV panels, the solar cell conversion efficiency is improved. And the heat from the PV panels is used to regenerate the ground in summer,the prevention of declining ground temperatures not only alleviates the imbalance of soil temperature field in cold region,but also guarantees a constant coefficient of performance (COP) of the heat pump.From the economic perspective, the investment recovery period of the system can reach the desired effect with government subsidies. Last but not least, imbalance of soil temperature field can be alleviated to some extent by instoring the heat accumulated from PV in summer. Of course, the system also needs further optimization and improvement.

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