

Performance and Economic Evaluation of a Hybrid Photovoltaic/Thermal Solar System in Northern China

E. Sok, Y. Zhuo, and S. Wang

Abstract—A hybrid Photovoltaic/Thermal (PV/T) solar system integrates photovoltaic and solar thermal technologies into one single solar energy device, with dual generation of electricity and heat energy. The aim of the present study is to evaluate the potential for introduction of the PV/T technology into Northern China. For this purpose, outdoor experiments were conducted on a prototype of a PV/T water-heating system. The annual thermal and electrical performances were investigated under the climatic conditions of Beijing. An economic analysis of the system was then carried out, followed by a sensitivity study. The analysis revealed that the hybrid system is not economically attractive with the current market and energy prices. However, considering the continuous commitment of the Chinese government towards policy development in the renewable energy sector, and technological improvements like the increasing cost-effectiveness of PV cells, PV/Thermal technology may become economically viable in the near future.

Keywords—Hybrid Photovoltaic/Thermal (PV/T); Solar energy; Economic analysis;

I. INTRODUCTION

CHINA is today one of the world's largest energy consumers and carbon dioxide emitters. With the continuous economic and demographic growth, China's energy consumption in electricity, heating and hot water especially in the residential sector are expected to grow rapidly in the near future. To response these issues, China has promoted clean energy for the last few years. With more than 2000 hours of sunlight per year, the application of solar technology is favourable.

The global solar thermal market is currently dominated by China. PV technology is currently highly promoted, however, its disadvantage lies in the low conversion efficiency and the high price of the PV cells, resulting in high payback times. To improve the performances, hybrid Photovoltaic/Thermal systems have been developed. In such technology, a coolant such as water or air is used to cool the PV module, increasing its efficiency. At the same time, the heat extracted can be used

for heating applications. The electrical and thermal output per unit area is increased. For a country like China with good penetration of solar water heaters and photovoltaic panels, and considering the recent limitation of roof space per household inherent to the urban growth, the hybrid technology seems to be an attractive option.

Since 1978, various designs of the PV/T collector have been developed and studied theoretically, numerically and experimentally around the world [1]-[13]. The research work performed to date has revealed the potential of the hybrid technology for a variety of applications. Liquid PV/T systems seem particularly suitable to domestic hot water production in warm climate locations. However, their performances in regions facing the water-freezing issue during cold winters have been seldom evaluated [14]. Besides, the economics of the PV/T systems still need to be clearer to facilitate their introduction in the market [15]. Indeed, only a few economic studies have up till now been listed. Cost payback times varying over a fairly wild range were found, depending on the location, the system design and the application [16]-[22].

Therefore, the objective of our study is to assess the technical and economic feasibility of liquid PV/T systems in low winter temperature regions. For this purpose, outdoor experiments were carried out on a prototype of a PV/T collector under the climatic conditions of Beijing. Based on the energy output results, an economic analysis was performed using the discounted-payback approach. A sensitivity analysis is also included to determine the most influential parameters on the system economics.

II. DESCRIPTION OF THE EXPERIMENTAL RIG

The tests were conducted on an experimental prototype of an unglazed sheet-and-tube PV/T collector built from 2006 to 2007. The detailed design of the PV/T system can be found in the work of J. Su [23]. The electrical system is composed of 6 PV modules in a parallel-series array, two storage batteries of 12V, 54Ah capacity, an electric load and the associated switches and wiring. The resulting output power is 126 Wp, and the operating voltage 24V. Polycrystalline silicon cells of conversion efficiency 13.35% at STC are used. The total heat-collecting area equals 1.48 m². With regard to the last 10 years Beijing's temperatures records, we chose to use a 37/63 propylene-water mixture as the heat removal fluid. It can protect the system down to -22°C. The fluid is supplied at a

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fixed volumetric flow rate of $0.46 \text{ m}^3/\text{h}$ by a circulating pump. An insulated cylindrical storage tank of 150L and the associated valves and pipes complete the water-heating system. The PV/T collector is tilted 28° to horizontal and faced south.

A data acquisition system was used to record various parameters as illustrated by Fig. 1. Nine thermocouples were used to measure the PV modules temperature at nine different positions. The fluid temperature at inlet and outlet, in the storage tank, as well as the ambient temperature were measured by thermoresistances. A pyranometer was used for measuring the incident radiation on the PV cells. Multimeters were used to obtain the electrical characteristics of the PV modules (current and voltage). The water mass flow and the storage tank fluid level were also recorded by a level transmitter and a turbulent flow sensor respectively. The monitored data were recorded every minute by the data logging device. The outdoor experiments were conducted at the geographic location of Beijing ($39^\circ 54' \text{N}$, $116^\circ 23' \text{E}$) from November 2009 to August 2010. During the experiments, the generated electricity was stored in the batteries during daytime (from 7:00 to 18:00). Then those latter would discharge the electricity stored to the electric load during night time. The system is an open-loop system and does not incorporate a heat-exchanger to transmit the tank anti-freezing mixture's warm to the potable water located in a second storage tank. So enabling the fluid to circulate in the collector continuously was a convenient way for the fluid temperature to decrease at night in order to guarantee the cooling effect of the PV panels on the following day; at the same time, that made possible to simulate the average use of the hot water by a typical family. In order to enhance the decrease of fluid temperature, a heat exchanger had been installed at the outlet of the PV/T collector. Under this operating mode, the cooling fluid was supplied at a temperature ranging between -11°C and 41°C within the year. That permitted to examine the thermal and electrical performance of the system for different operating temperatures.

III. RESULTS AND DISCUSSION

A. Thermal Performances

The thermal performance of the system is assessed through its daily thermal efficiency, which is calculated by the equation

$$\eta_{th} = \frac{m \cdot C_p \cdot (T_f - T_i)}{A_c \cdot G} \quad (1)$$

where m , C_p , T_f , T_i , A_c , G are the fluid total mass, heat capacity, final and initial temperatures, the collecting area, and the daily total incoming solar radiation respectively. Concerning the effects of the climatic conditions, in winter the low amounts of incident solar radiation limited the temperature reached by the PV modules. On particularly sunny but very cold and windy days, the convective heat losses from the modules surface to the exterior could also play

an important role in reducing the thermal efficiency. On average, the panels' temperature did not exceed 15°C from December to February for any fluid supply temperature. Though, we observed that the thermal efficiency could be enhanced with lower supply temperatures of the cooling fluid. However, the range of application of the thermal energy generated was on the other hand limited by the lower final fluid temperatures reached at the end of the day. From April onwards, the fluid generally started to be heated from 10°C , and the daily thermal efficiency was 38% on average.

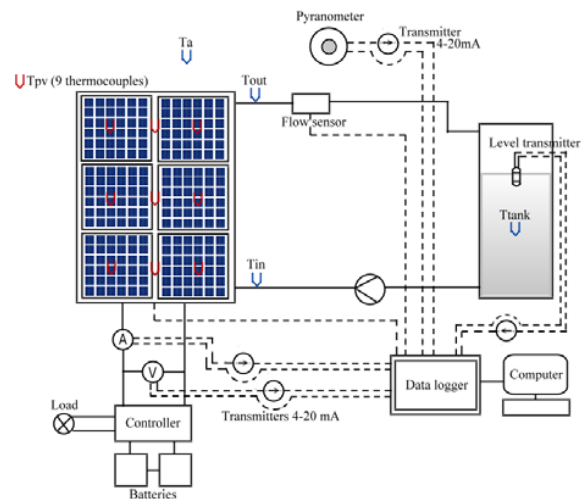


Fig. 1 Schematic diagram of the data acquisition system

B. Electrical Performances

The system daily electrical efficiency η_{elec} is calculated by the equation

$$\eta_{elec} = \frac{\int_{day} I \cdot U}{A_{PV} \cdot G} \quad (2)$$

where I , U , A_{PV} are the current, voltage and surface area of the PV modules. During the coldest months for which the PV modules daily mean temperature was generally under 15°C , various values of efficiency ranging from 6% to 11% were obtained for a same PV cells temperature. Further investigations will be needed to assess more accurately the complex electrical behavior of the system under low temperatures. Apart from those conditions, the efficiency smoothly varied between 5-8%. Maximum efficiency was reached for PV modules temperatures around 28°C . It has been noticed that the system electrical performances are lower than the 2007's ones measured by J. Su at the same period of the year. On average, the system was 9-11% electrically efficient. Since the experimental system has remained outside and exposed to multiple external climatic conditions during 2 years without thorough maintenance, there are chances the PV modules may have suffered from degradations, e.g. top surface soiling and optical degradation. The system electrical energy outputs may thus be underestimated. Though, this will not significantly affect the system economic viability as it will

be shown in the next section, while giving a good idea of the minimum possible electrical energy production.

C. Energy Production for Domestic Hot Water Applications

We will here discuss the potential of the system to produce energy for domestic hot water. In such applications, the fluid initial temperature is actually the temperature of the cold tap water, which fluctuates within the year from 4°C on cold winter days to 25°C on hot summer days. The system monthly energy outputs from November to May were directly averaged from the test results. However, during the hottest months, i.e. June to August, the fluid temperature did not fall below 28°C as the nighttime ambient temperatures remained quite high. The system energy production for starting temperatures between 20-25°C was thus estimated based on approximation models. Those were obtained by performing several multiple regression analysis on the available experiment data. For September and October, we assumed the system would produce the same amount of energy as in May and April respectively, since Beijing's mid-season climatic conditions are very similar. The estimated monthly thermal and electrical energy output of the system are presented in Fig. 2. Winter lasted from November to March, with December, January and February being the coldest months. Several heavy snowfalls hit the city during this season, increasing the days with no energy production. We also observed that no thermal energy could be produced even on partially cloudy days when the mean ambient temperature was negative, since the PV module temperature did not exceed 5°C. Apart from those conditions, the system could produce thermal energy that would serve to pre-heat water. Rise in temperatures of 7.7°C on average could be achieved. During other seasons, the system monthly thermal energy output is twice to three times higher, with a maximum in May. Indeed, rainstorms and overcast days were quite frequent in July and August, so that the system received on average the maximum amount of solar radiation during the mid-seasons. Rise in temperatures of 32°C could be obtained on the sunniest days; the fluid could be heated up to 54°C. The low monthly electricity outputs are the result of the low electrical conversion efficiency of the PV cells. The cooling fluid contributed well towards keeping low the PV modules temperature during the sunniest and hottest days, as only a slight decrease in their efficiency was observed.

IV. ECONOMIC ANALYSIS

The present experimental PV/T system will serve as the reference case of the economic analysis, and the discounted payback method will be used. In this technique, the concept of time value of money is taken into account, and the cost payback time of the system is defined as the time required for the accumulated savings to equal the present cost of the system.

A. Reference Case Assumptions

The system is assumed to have no decline in performance

over its lifetime and no salvage value. No fund is borrowed to pay for the equipment, meaning the discount rate equals the interest rate for saving accounts. The system energy outputs will be calculated under the climatic conditions of Beijing for domestic hot water applications. In that case, we assume that the thermal energy output replaces equivalent amounts of energy consumed by a 85%-efficient gas water heater, which is the most common type of water heater used in China. Finally, the cost payback time will be first calculated without considering any tax deduction or subsidy. Table I lists the values of different parameters used for the reference case.

B. Estimation of the Present Costs of the System

The present cost of the system includes the initial

TABLE I
MAIN PARAMETERS FOR THE REFERENCE CASE

Parameter	Description	Value
Expected useful life	PV/T System	30 years
	Pump, antifreezing solution and batteries	5 years ^a
General inflation rate ^b (j)		2.8%
Interest rate (i)		2.25%
Energy prices ^c (residential sector)	Electricity	0.48 RMB/kWh ^d
	Natural gas	0.193 RMB/kWh

^aA common value is taken for purpose of simplification. The lifespan of the pump and the batteries usually varies between 20000-30000 hours and 4-8 years respectively. The propylene glycol has to be changed every 3-5 years.

^bThe prices of the pump, the propylene glycol and the batteries are assumed to keep up with the general inflation rate.

^cNo energy price escalation is considered for the reference case's calculations.

^d1 RMB is equivalent to 0.148 USD

investment costs, i.e. the capital and installation costs of the PV/T system (P_c and P_{inst} respectively), plus the future replacement costs (R_p , R_a and R_b for the pump, antifreezing solution and batteries respectively). The PV/T system capital costs will be based on the prototype batch production costs with Chinese market prices considered. They are presented in Table II. The installation costs were estimated to 140 RMB.

TABLE II
CAPITAL COSTS OF THE SYSTEM

Components	Price (RMB)
PV modules (Pc-Si cells)	1764 (14 RMB/Wp)
Solar charge controller	120
Storage batteries (Deep cycle)	800
Wiring and other accessories	300
Flat plate collector	1015 (685 RMB/m ²)
Water tank	900
Pump (6W)	200
Propylene-glycol	538
Pipes, valves and other plumbing parts	200
Collector frame	65
Support structure	280
Assembling costs	200

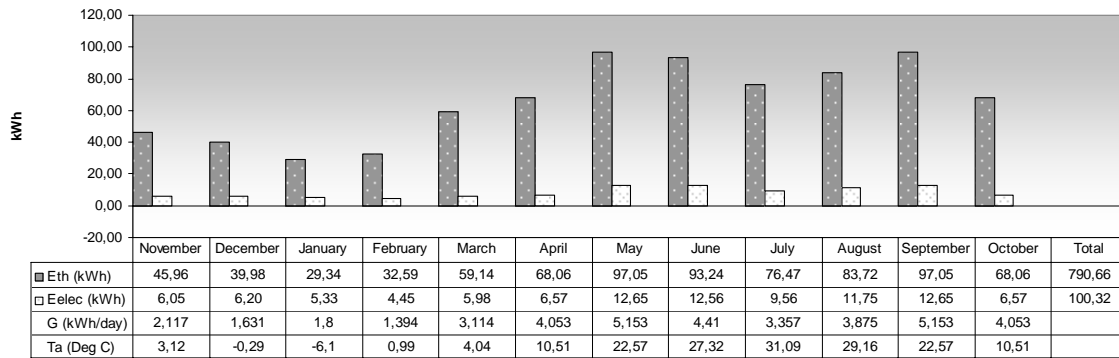


Fig. 2 Monthly thermal and electrical energy outputs

Finally, the cost P of the PV/T system in terms of present value can be expressed as

$$P = P_c + P_{inst} + \frac{(R_p + R_a + R_b) \left[1 - \left(\frac{1+j}{1+i} \right)^{25} \right]}{\left[1 - \left(\frac{1+j}{1+i} \right)^5 \right]} \quad (3)$$

C. Estimation of the Annual Savings

The annual savings are defined as the annual costs of energy saved less the annual operation and maintenance costs.

1. Thermal and Electrical Energy Saved

The energy outputs of the system for domestic water heating applications were already presented in section 3

2. Energy Losses

The thermal losses through the pipes, storage tank and heat exchanger will be taken 20%, as suggested in [21]. As for the electricity output, we assume that 10% of the electricity generated by the PV panels is lost in the batteries and 2% in the wiring [24].

3. Operation Costs

The tax and insurance costs are neglected in our study. The only operation costs result from the electrical consumption of the circulator pump. The total daily energy needed was estimated to 53 Wh.

4. Maintenance and Repair Costs

These costs can be considered very low. We will assume they represent annually 2% of the capital costs of the system and that they remain constant over the years. Table III summarizes the different costs and savings of the system.

D. Calculation of the Cost Payback Time

The cost payback time is the number of years required for the accumulated savings to equal the system's present cost. Without the effect of inflation in energy and maintenance prices, the annual savings are constant over the system lifetime, and the payback time N_{PB} can be determined by solving the following equation:

$$P = A \frac{(1+i)^{N_{PB}} - 1}{i(1+i)^{N_{PB}}} \quad (4)$$

We consider that the system starts to be attractive for a cost payback time lower than its lifetime, i.e. 30 years. The calculations give a payback time in the hundreds of years, which shows that under the conditions considered, our system is not economically viable. Such a result contrasts with those found in the literature. The next section will discuss the parameters that may contribute the most towards making the hybrid system economically attractive.

TABLE III
PRESENT COSTS AND ANNUAL SAVINGS OF THE SYSTEM

	Symbol	Value (RMB)
Capital costs	P_c	6382
Installation costs	P_{inst}	140
Replacement costs	R	7920
Total present costs	P	14442
Annual thermal energy savings	E_{th}	143.4
Annual electrical energy savings	E_{elec}	33.1
Annual maintenance costs	M	127.6
Total annual savings	A	48.9

V. DISCUSSION AND SENSITIVITY STUDY

A. Influence of the System Present Costs

The present PV/T system incorporates an antifreezing solution and two batteries, which is not the case of the similar hybrid systems studied in the literature. This might result in additional initial costs. Still, compared to them, the initial costs of our hybrid collector are quite of the same order, if not inferior. However, the future replacements costs are seldom considered in the previous economic studies. One can see that those account for half of the total present cost of our system. But even if they were not considered in the present study, the system would still be non viable. Several parameters can play a role in reducing the costs of the system: government initial subsidies, lower PV modules costs, and lower frequency of components replacement. Though, we found that neither of those would permit to significantly improve the economics of the system under the current energy prices. Finally, it can be concluded that the system present costs have a small impact

on the system's economic viability.

B. Influence of the Annual Savings

The annual savings depend mainly on the amount of energy production and the conventional fuel prices. From Table III, one can see that very low savings are generated by the present system. Indeed, the climatic conditions of Beijing are first not as favourable as in low latitudes regions, so that lower energy outputs are obtained. Secondly, the electricity and gas prices are much cheaper in Mainland China compared to other countries'. The variations of the system cost payback time in function of increasing energy prices are presented in Fig. 3. Under the current electricity rate of 0.48 RMB/kWh, the investment starts to be economically attractive from a gas price of 1.05 RMB/kWh. Under the current gas tariff, the critical electricity rate is as high as 7.74 RMB/kWh. Hence, the gas price has a great impact on the system's economic viability. The PV modules conversion efficiency also plays a role, though less notable. Fig. 4 shows the variations of the payback time in function of energy prices, assuming the PV modules were 20%-efficient over the whole year. One can see that under the current energy pricing regime, the system would still be unviable. That reveals the negligible influence of the drop in electrical performance of our system on its economic viability. On the other hand, the impact of the electricity price is enhanced, since the critical electricity rate under the current gas price drops to 2.20 RMB/kWh.

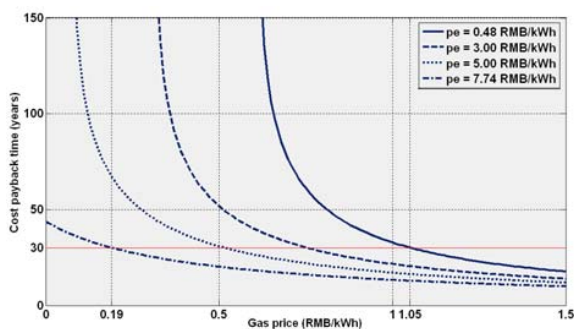


Fig.3 System cost payback time in function of energy prices

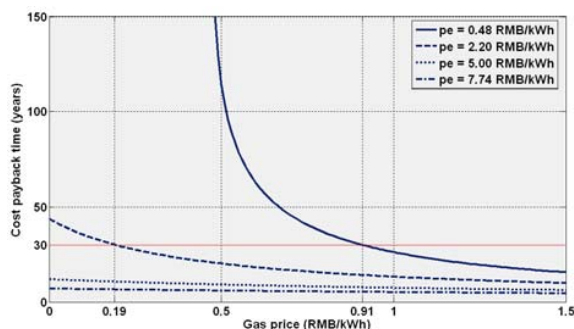


Fig. 4 System cost payback time in function of energy prices, with 20%-efficient PV modules

C. Combination of Different Parameters

To reveal the effect of both reduced system costs and increased annual savings, the variation of the cost payback time in function energy prices and subsidies have been studied, as shown in Fig. 5. One can see that under higher gas prices, providing an initial subsidy becomes beneficial. For instance, for a gas price of 0.63 RMB/kWh an initial subsidy of 30% of the system capital costs already cuts the original payback time by half. In the same way, other combinations of different parameters could be made towards making the system attractive. The determination of the optimal combination is left for a future work.

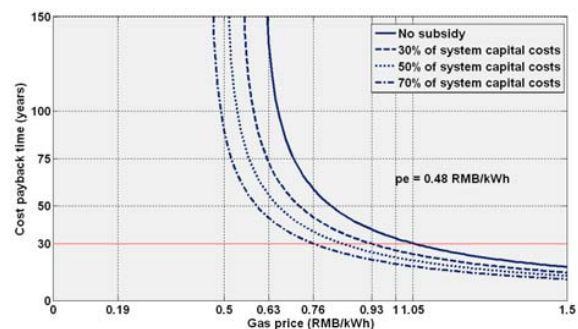


Fig. 5 Cost payback time in function of gas price and subsidy

D. Suggestions

According to the previous results, the PV/T system economics are highly sensitive to the conventional fuel prices. Future adjustments of the gas price are foreseen as China is starting to face serious natural gas supply shortages while the demand continues to rise. Residential electricity rate hike may also be expected in a way to balance the rising coal prices. Though, the shift will be gradual, so that other policy options will have to be explored. Financial incentives can be one of them. Since 1949, several national subsidies programs have been launched in China, while some local governments have also established their own provincial-level incentives [25]. The major forms of financial incentives in existence today that may be applied to PV/Thermal systems include direct financial subsidies, tax credits, low-interest loans, and preferential feed-in-tariffs for grid-connected systems. In the mean time, the intensive R&D work currently conducted over the world on the improvement of the PV cells cost-effectiveness and performances should improve the economics of the PV/T systems. Other ways to reduce the system present costs may besides be considered: natural circulation operation mode, direct consumption of the electricity without storage etc. Otherwise, applications requiring lower water starting temperatures the whole year may permit to take more advantage of the potential of the liquid PV/T technology, though they might be rare. The investigation of those possible solutions is left for a future work.

VI. CONCLUSION

Outdoor experiments were conducted on a prototype of a liquid PV/T collector. Daily thermal and electrical efficiencies were found in the range of 27-75% and 5-11% respectively. The system technical performances were strongly related to the supply temperature of the cooling fluid, especially under cold ambient temperatures. Our hybrid system was found to be not that suitable to domestic hot water production in mid-latitudes regions like Beijing. An annual production of 790.66 kWh thermal energy and 100.32 kWh electricity has been estimated. Considering the current low energy prices, those energy amounts do not generate enough annual savings to make the system economically viable. Our sensitivity analysis revealed that no individual parameter could contribute towards making the hybrid system economically viable on its own, although the gas price appeared to be the most influential. However, through an optimal combination of reduced capital and replacement costs, higher PV cells conversion efficiencies, coupled with rising conventional fuel prices and financial support, the PV/T systems are expected to turn into an attractive investment in northern China.

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