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# Comparison study on domestic photovoltaic/thermal, photovoltaic and solar thermal systems based on validated TRNSYS model

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**Abstract**

In this investigation, a revised photovoltaic/thermal collector model based on TRNSYS TESS type 560 was developed to do the year-round performance prediction of both glazed and unglazed PV/T system. Simultaneously, a photovoltaic/thermal collector with the designed parameters was fabricated and tested to validate the model. Results showed that the simulation has a good agreement with experiment results. The mean error of both thermal and electrical efficiency is less than 15%. Furthermore, four domestic systems, including glazed and unglazed photovoltaic/thermal, photovoltaic and solar thermal systems, were built in TRNSYS. Annual performance of the four systems was obtained and analyzed. Compared with PV， glazed PV/T can supply extra 3850.4 MJ heat, but the power generation decreases by 24.1%. The glazed PV/T SDHW system shows a similar trend of SF and auxiliary heat with the flat plate SDHW system. The variation of SF is between 19.2% and 80.5% with an annual average value of 45.9%. The unglazed PV/T system can supply 339.5 kWh electricity and offer 806.3 MJ heat for preheating, which result in a low SF of 12.9%. Based on the view of comprehensive utilization of solar energy, the glazed PV/T system seems to be a more promising solution in SDHW system.

Keywords: *photovoltaic/thermal collector; TRNSYS simulation; performance comparison*

## 1. Introduction

Solar photovoltaic (PV) modules are now widely used for power generation to lead a sustainable and low-carbon economy. However, the temperature of PV modules is increased by the absorbed solar radiation that is not converted into electricity, causing a decrease in conversion efficiency. Increasing the temperature of the PV module by 1 °C will lead to a decrease of the solar electrical efficiency of crystalline and amorphous silicon cells by 0.5% and 0.25%, respectively(Skoplaki and Palyvos 2009). Thus, a variety of researches have been done to decrease the temperature of PV panels in order to increase their conversion efficiency. The very first attempt to explore the possibility of using the heat generated on PV panels as usable thermal energy was conducted in the late 70s(Kern Jr and Russell 1978), while the experimental studies utilizing proprietary devices showed up in the mid 90s(Bhargava, Garg et al. 1991, Garg, Agarwal et al. 1994, Bergene and Løvvik 1995).

Although the idea of combining the PV panel and solar thermal collector has shown a lot of advantages, the development and research on commercial PV/T system is slow. The early experimental studies involving PV/T systems were performed by modifying a commercial PV panel with a heat exchanger installed at the back of it(Huang, Lin et al. 2001). During the past few years there have been significant technological advancements concerning all types of PV/T collectors (Daghigh, Ruslan et al. 2011, Ibrahim, Othman et al. 2011, Tyagi, Kaushik et al. 2012) and some commercial products start to show up in the market. At present, four types of PV/T collectors that focus on working media: air(Joshi and Tiwari 2007, Kumar and Rosen


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2011), water(Dubey and Tiwari 2008, Chow, Pei et al. 2009), refrigerant(Chow, Pei et al. 2010) (Omojaro and Breitkopf 2013)and heat pipe(Wu, Zhang et al. 2011), are available.

With the low price of PV modules and the high government subsidies, many families in China now choose to install household photovoltaic systems. Meanwhile, most of them have already installed the solar thermal collector systems for domestic hot water (DHW) supply. As the demand for electricity and thermal energy shows up in the same time, in this way, the PV/T system seems to be the most promising renewable energy solution without extending the installation area.

In this paper, A system model is built in TRNSYS and the year-round performance comparison of PV/T (glazed and unglazed), solar thermal and PV system is conducted. The performance characteristics of the four different systems are analyzed to supply the basis for selection of different domestic solar systems.

## 2. PV/T component model and validation

### *2.1. Unglazed PV/T component*

Type 560 in TRNSYS Electrical Library (TESS) is intended to model an unglazed solar collector which has the dual purpose of creating power from embedded photovoltaic (PV) cells and providing heat to a fluid stream passing through tubes bonded to an absorber plate located beneath the PV cells. It relies on linear factors relating the efficiency of the PV cells to the cell temperature and also the incident solar radiation. The cells are assumed to be operating at their maximum power point condition. Fig.1 shows the heat transfer model of this type and the thermal model of this collector is based on algorithms presented in Chapter 6 of the classic “Solar Engineering of Thermal Processes” textbook by Duffie and Beckman(Duffie and Beckman 1980).

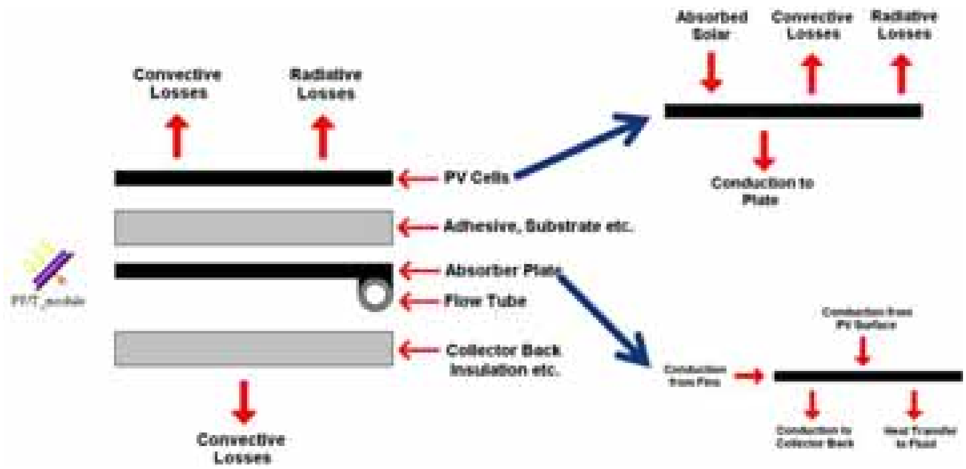


**Fig. 1: Heat transfer model of unglazed PV/T component**

### *2.2. Glazed PV/T component*

In order to model a glazed PV/T module, a single glaze cover model is appended to the existing model of type 560. The glaze cover heat transfer and solar transmission model is based on the Chapter 6 of the classic “Solar Engineering of Thermal Processes” textbook by Duffie and Beckman(Duffie and Beckman 1980). The new model is complied in Fortran and name type 560b in order to call it from TRNSYS.

### *2.3. Component validation*

In order to validate the two PV/T components in TRNSYS, two PV/T solar collectors were fabricated and tested. The main parameters of the two components are listed in Tab. 1. The experiment system schematic diagram is shown in Fig.2 and the experiment system picture is displayed in Fig.3. The temperatures of the system are measured by a group of PT1000 sensors (A class, error: 0.1 °C ). The water flow rate is measured by an integrating flow meter with an accuracy of ±5% （of reading）. The ambient condition is monitored by a micro weather station (Davis 6152c) and Kipp & Zone CM22 pyranometer , and the accuracies of the radiation and temperature are ±5%（of reading） and ±0.5 °C, respectively. The power generation of the PV module is monitored by a DC voltage and current sensor with a accuracy of ±5%（of reading）. All the data is captured and handled by a Graphtec GL800 acquision system.

**Tab. 1: Main parameters of PV/T components**

| | |
|---|---|
| Collector area ($m^2$) | 2 |
| Nominal efficiency of PV panel (%) | 15 |
| Tube spacing(m) | 0.125 |
| Tube diameter(m) | 0.01 |
| Absorber thickness | 0.0003 |
| Glass cover transmittance | 0.9 |
| Number of glass cover | 0/1 |
| Glass cover spacing (m) | 0.03 |
| Temperature coefficient of PV cell efficiency(1/°C) | -0.005 |
| Radiation coefficient of PV cell efficiency(h.$m^2$/kJ) | 0.000025 |
| Storage tank volume ($m^3$) | 0.15 |

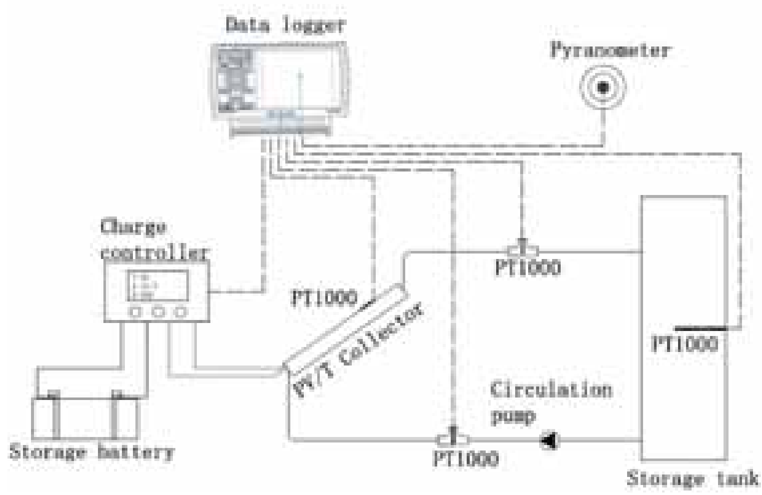


**Fig. 2: Schematic diagram of experiment system**

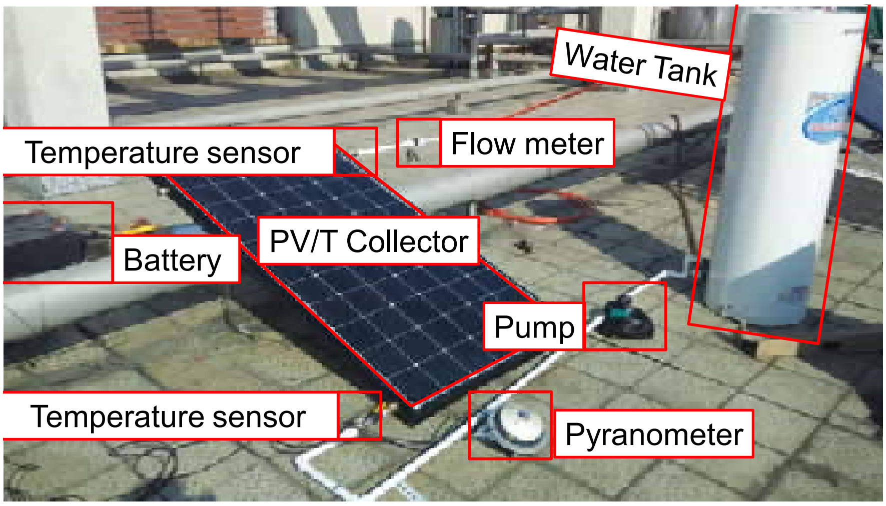


**Fig. 3: Picture of experiment system**

The experiment was done on June 13th and the ambient conditions including solar radiation intensity and ambient temperature are shown in Fig. 4. The average solar radiation intensity on the titled surface and ambient temperature during the test are 767 W/m$^2$ and 22.1 $^o$C, respectively. The initial water temperature in the tank is 20 $^o$C.

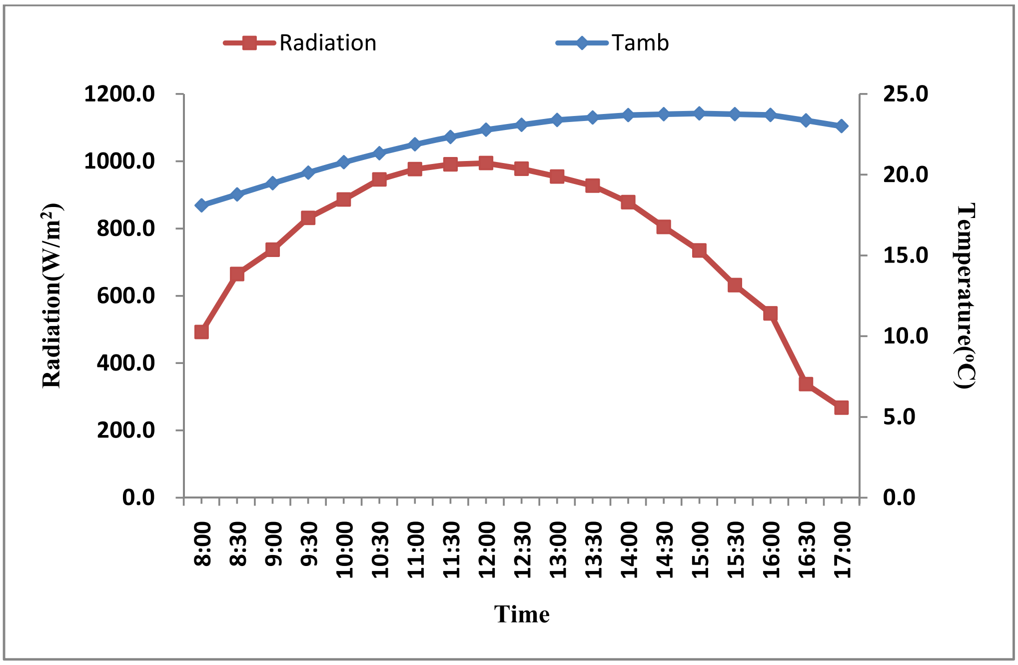


**Fig. 4: Ambient condition of experiment**

The comparison of electrical efficiency of both systems is shown in Fig. 5. The simulated result shows nearly the same trend with the experiment value. The maximum relative error (RE) of the electrical efficiency is about 8.5% due to the loss of efficiency in MPPT controller.

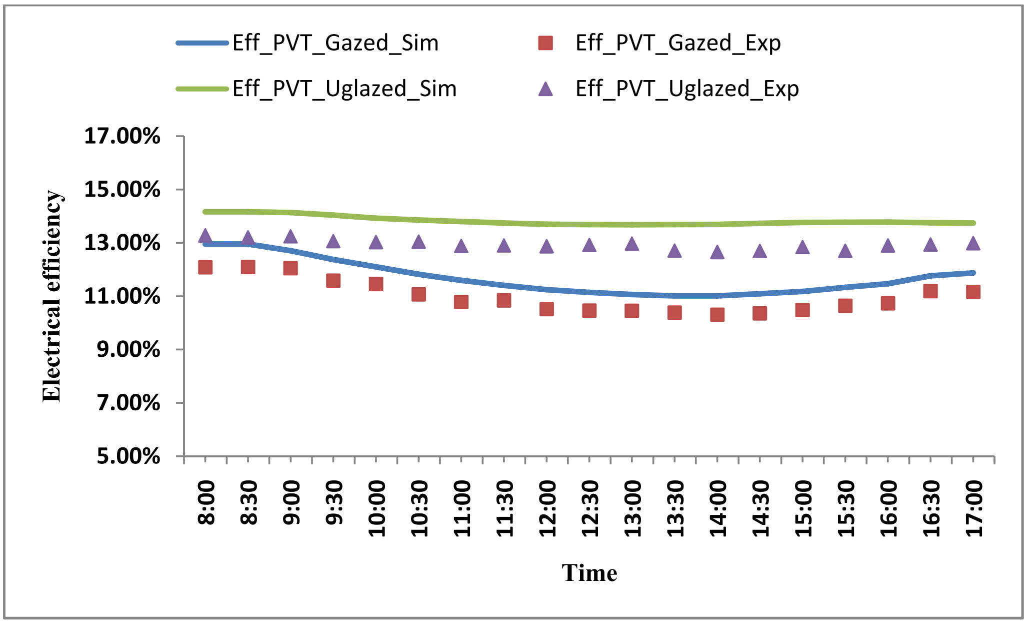


**Fig. 5: Comparison of Electrical efficiency between experiment and simulation**

Fig. 6 shows the tank temperature between experiment and simulation. The tank temperature started at 20 °C and rised to 50.1 °C and 30.3 °C for the glazed PV/T and unglazed PV/T system respectively. The simulated tank temperature is nearly consistent with the experimental value with a maximum RE of about 12.9 %. The tank loss coefficient is set as a constant in the simulation model but in the experiment, it is influenced by the ambient conditions, such as the wind speed. Furthermore, the loss of pipes and pump is neglected in the simulation model.

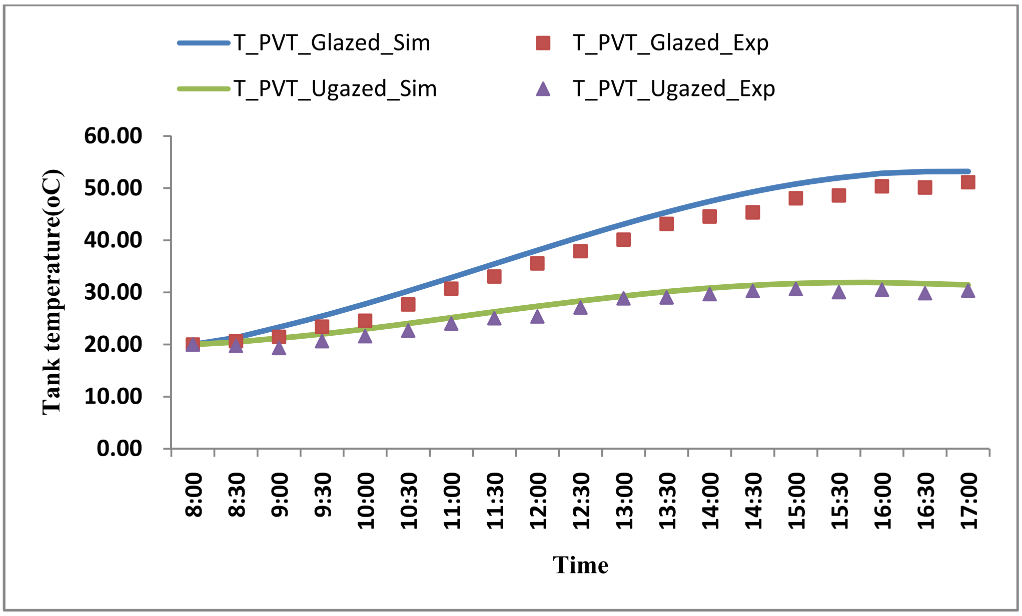


**Fig. 6: Comparison of tank temperature between experiment and simulation**

## 3. TRNSYS model description

### *3.1. System description*

In order to make a comparison of the PV/T system performance with the traditional flat plate solar collector on solar domestic hot water (SDHW) system, three system models with different solar collectors are built in TRNSYS. The schematic diagram of SDHW system is shown in Fig. 7. A diverter and a mixer is set to maintain the hot water supply temperature as 45 °C. An auxiliary heater is applied to provide auxiliary heat when the outlet temperature is lower than 45 °C . The DHW demand displayed in Fig. 8 is a real test schedule of a Shanghai family of 3 people. The peak of DHW load appears in the morning, noon and evening. Furthermore, a traditional PV panel is studied to analyze the difference of electrical performance between PV/T and PV. The main type numbers and parameters of the components in the model are listed in Tab. 2.

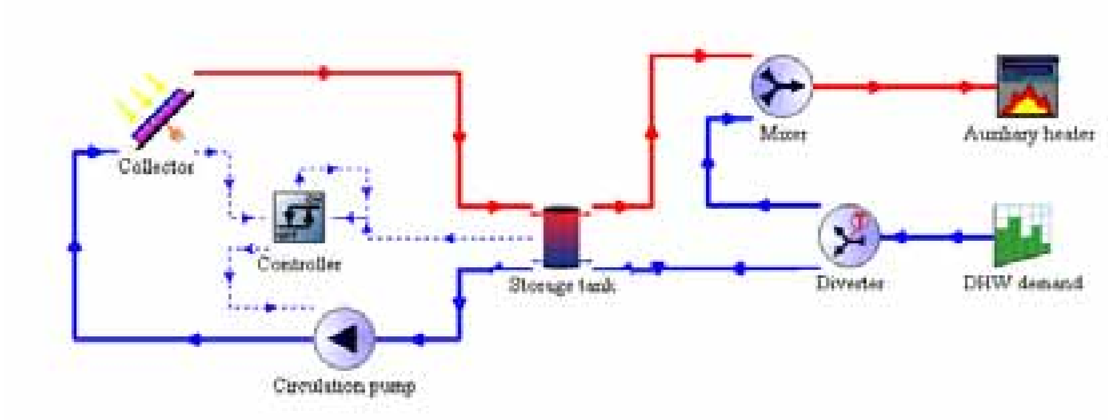


**Fig. 7: Schematic diagram of SDHW system**

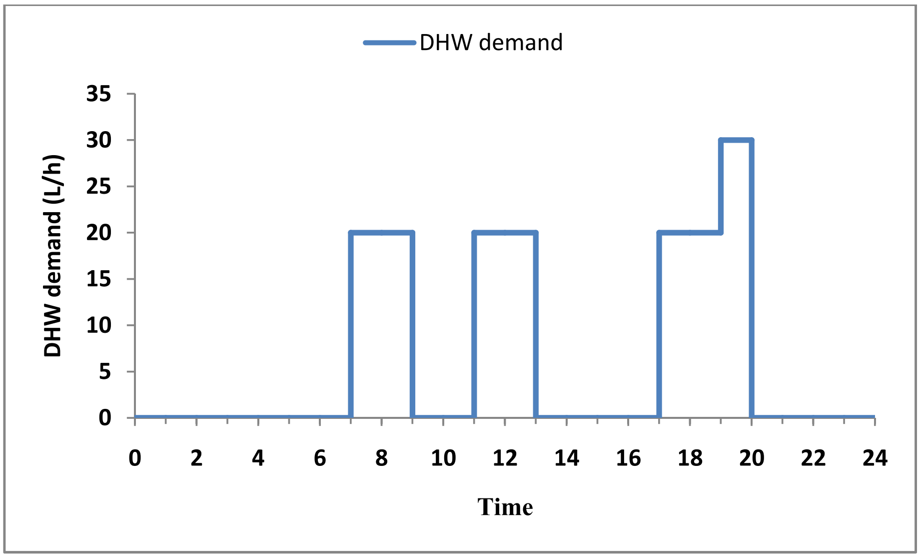


**Fig. 8: Schedule of DHW demand**

**Tab. 2: Main type numbers and parameters of the components**

| Component name | TRNSYS type number | Main parameters |
|---|---|---|
| PV/T (glazed/unglazed) | Type 560b/560 | area: $2m^2$<br>rated electrical power: 300W<br>inclination angle: $30^o$ |
| Flat plate solar collector | Type 1 | area: $2m^2$<br>efficiency curve:<br>$\eta = 0.749 - 5.6 * (T_{in} - T_{amb})/G$<br>inclination angle: $30^o$ |
| PV panel | Type 562 | rated electrical power: 300W<br>inclination angle: $30^o$ |
| Tank | Type 4e | volume: 150L |
| Circulation pump | Type 3d | rated power: 45 W<br>rated flow rate: 140kg/h |
| Controller | Type 2b | temperature difference: 8(on)/4(off) |
| DHW demand | Type 14h | shown in Fig.8 |
| Diverter | Type 11b | |
| Mixer | Type 11d | |
| Auxiliary heater | Type 700 | |

A CN-Shanghai-583670. tm2 (Typical Meteorological Year Version 2) format weather data file is read as the boundary conditions of the simulation model. The replenishment water temperature of the storage tank is set as the mains water temperature, which changes with the ambient conditions seasonally.

### *3.2 Performance index*

For purpose of evaluating the performance of the four different systems, the following performance index is calculated based on the simulated results:

(1) Average thermal efficiency

$$\eta_{th} = \frac{Q_{tank}}{\int A*G_{solar}} \quad \text{(eq. 1)}$$

(2) Average electrical efficiency

$$\eta_{ele} = \frac{E_{PV}}{\int A*G_{solar}} \quad \text{(eq. 2)}$$

(3)Solar fraction

$$SF = \frac{Q_{total}-Q_{aux}}{Q_{total}} \quad \text{(eq. 3)}$$

## 4. Results and discussion

### *4.1 Electrical performance*

The annual electrical performance of PV/T and PV system is displayed in Fig. 9. Compared with pure PV system, the unglazed PV/T system shows a slight enhancement on the electricity generation and electrical efficiency. The annual electricity output of the unglazed PV/T and PV system are 339.5 kWh and 335.2 kWh, respectively. However, the glazed PV/T system shows a significant decrease in electricity generation due to the high temperature of the PV panel. The annual electricity output of the glazed PV/T is 254.6 kWh, which is 80.6 kWh lower than the PV system. The average electrical efficiency of unglazed PV/T, glazed PV/T and PV system are 12.5%, 9.4% and 12.3%.

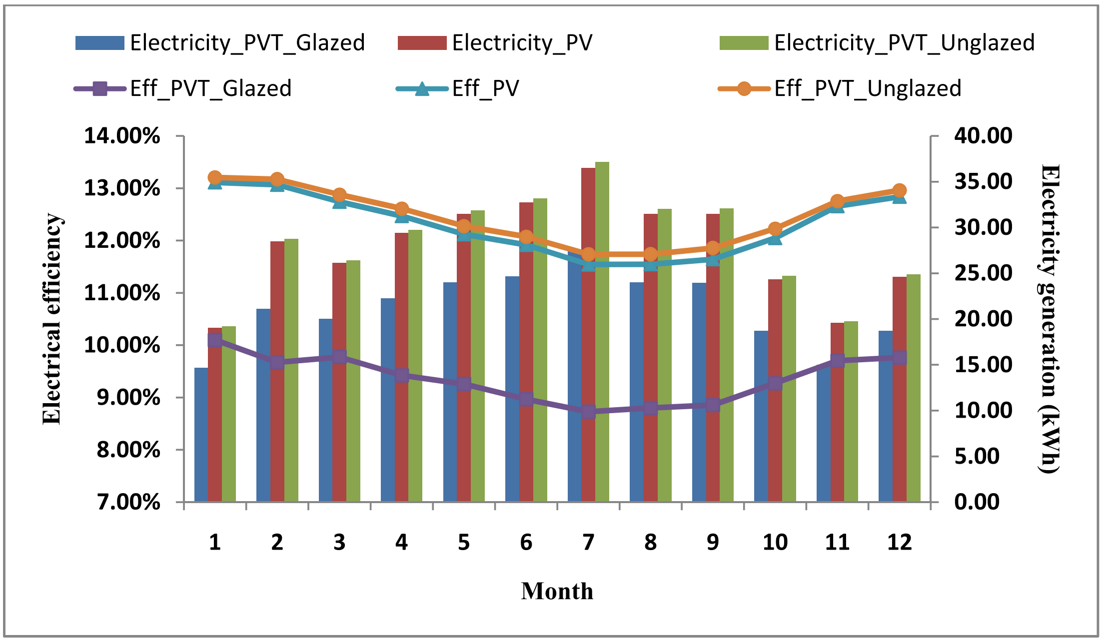


**Fig. 9: Annual electrical performance of PV/T and PV system**

### *4.2 Thermal performance*

The annual thermal performance of PV/T and flat plate solar collector system is shown in Fig. 10. Because the emissivity of PV surface in the glazed PV/T is much higher than the absorber in flat plate solar collector, the heat collected by glazed PV/T system is 24.2% lower than the flat plate solar collector. The average thermal efficiency of glazed PV/T and flat plate solar collector are 29.3% and 40.0%, respectively. Nevertheless, the heat loss coefficient of unglazed PV/T system is dramatically higher than glazed PV/T system due to lack of glass cover. The PV panel in unglazed PV/T system is exposed to the ambient, so both convection and radiation heat transfer coefficient is significantly higher than the glazed system. As a consequence, the unglazed PV/T system can only supply 806.3 MJ heat for preheating of the SDHW system.

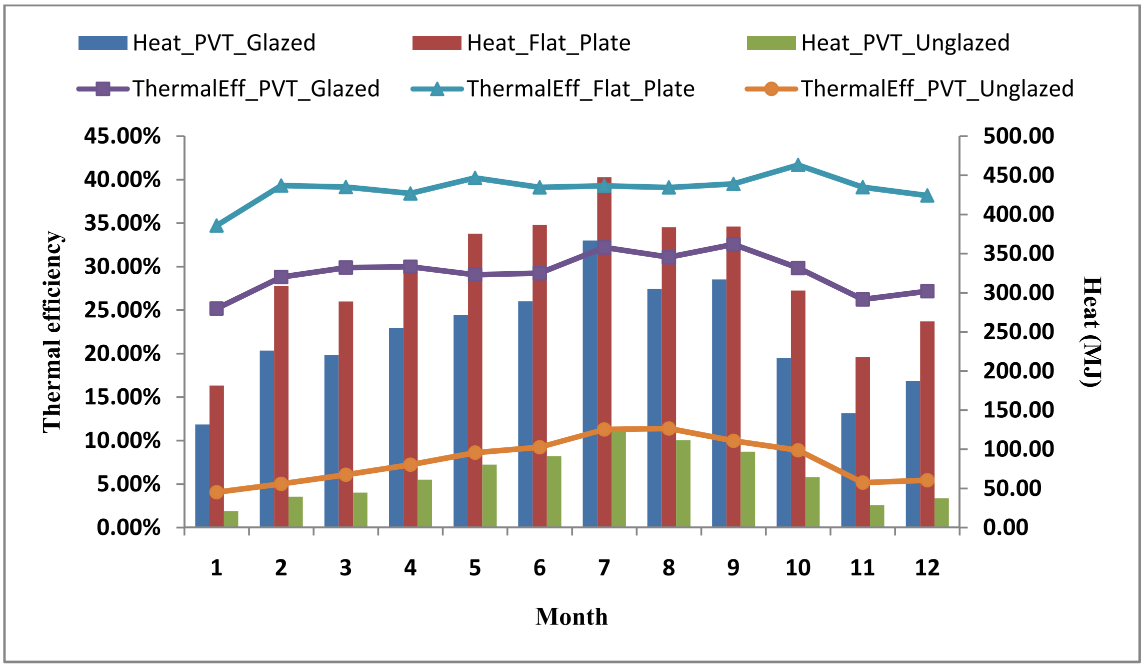


**Fig. 10: Annual Thermal performance of PV/T and flat plate solar collector system**

### *4.3 Solar fraction and auxiliary heat*

Fig.11 shows the solar fraction as well as the auxiliary heat of PV/T and flat plate SDHW system. For the flat plate SDHW system, the solar fraction (SF) ranges from 26.4% to 95.9% and the annual average solar fraction reaches 60.1%. The required auxiliary heat is about 2907.5 MJ. The glazed PV/T SDHW system shows a similar trend of SF and auxiliary heat with the flat plate SDHW system. The variation of SF is between 19.2% and 80.5% with an annual average value of 45.9%. According to the analysis above, the heat collected in the unglazed PV/T SDHW system can only serve as a preheating, which result in a low average SF of 12.9%.

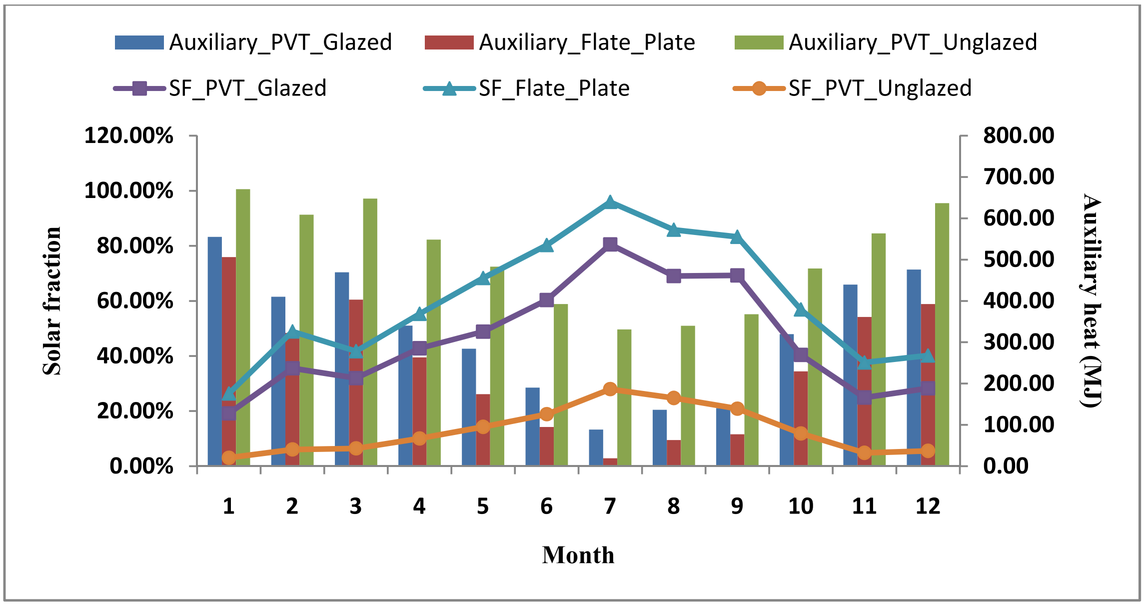


**Fig. 11: Solar fraction and auxiliary heat of PV/T and flat plate solar collector system**

## 5. Conclusion

In this investigation, a revised photovoltaic/thermal collector model based on TRNSYS TESS type 560 was developed and validated to do the year-round performance prediction. Three SDHW system as well as a PV models are built in TRNSYS to analyze the electrical and thermal performance of PV/T components applied in SDHW system. The following conclusion can be drawn from the investigation:

(1) According to the validation, the revised model based on TRNSYS TESS type 560 is accurate enough to do the performance prediction of PV/T SDHW system.

(2) Compared with pure PV system, the unglazed PV/T system shows a slight enhancement on the electricity generation and electrical efficiency. The glazed PV/T system shows a significant decrease in electricity generation due to the high temperature of the PV panel. The average electrical efficiency of unglazed PV/T, glazed PV/T and PV system are 12.5%, 9.4% and 12.3%.

(3) The heat collected by glazed PV/T system is 24.2% lower than the flat plate solar collector because of the high emissivity. The average thermal efficiency of glazed PV/T and flat plate solar collector are 29.3% and 40.0%, respectively. As a consequence of high heat loss coefficient, the unglazed PV/T system can only supply 806.3 MJ heat for preheating of the SDHW system.

(4) For the flat plate SDHW system, the annual average solar fraction reaches 60.1%, resulting in an auxiliary heat of 2907.5 MJ. The glazed PV/T SDHW system shows a similar trend of SF and auxiliary heat with the flat plate SDHW system. The variation of SF is between 19.2% and 80.5% with an annual average value of 45.9%. The SF of unglazed PV/T SDHW system is 12.9%.

(5) Based on the view of comprehensive utilization of solar energy, the glazed PV/T system seems to be a more promising solution in SDHW system.

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