DEVELOPMENT OF SOLAR A-SI PV/THERMAL(PVT) SYSTEM FOR TROPICAL REGION

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1. Introduction

The tropical countries like Singapore possess good solar energy resource that can yield more than 1460kWh m^{-2} per year. However, the PV technologies available in the current PV market can just convert less than 20% of the available solar energy to electricity due to limited band gap of PV cells, system losses and the high ambient temperature in the tropic region. The solar energy that can not be captured by PV cells is mostly changed to heat and dissipate to the air. The integration of photovoltaic (PV) modules with solar thermal panel helps to harvest more solar energy to produce electricity and hot water for tropical domestic use.

This paper presents a $93W_p$ solar photovoltaic/thermal(PVT) prototyping system developed for tropical region and its annual performance. The objective of the project is to provide us with feasibility study for design of PVT collector and PVT system. The prototyping system is a forced circulating PVT system that is mainly composed of unglazed $93W_p$ a-Si thin-film PVT collector, a 180 liter water tanker and a forced water circulating system and data acquisition system. The $93W_p$ PVT consists of thermal panel and three $31W_p$ frameless triple junction a-Si PV modules mounted on top of thermal collector. The PV modules facing the Sun convert the solar energy to electricity and convey the heat to thermal collector below for heat transfer.

The operation of PVT prototyping system was monitored by data acquisition system and a set of parameters which included solar irradiance, system voltage, current, temperatures, flow rate and pressure were sampled and stored in the datalogger for performance analyses. The analytic data presented in this paper explain the results of annual operation of the PVT prototyping system and show that the conversion efficiency of solar PVT system can reach 34% or higher which has been further proven by the second $1.536kW_p$ a-Si PVT system equipped with newly developed $256W_p$ a-Si PVT collector.

2. $93W_p$ PVT prototyping system

A photovoltaic-thermal (PVT) system is a combination of photovoltaic components/systems and solar thermal components/systems which produce both electricity and heat from one integrated component or system as described(J. Hansen and H.Sorensen. 2006). According to the applications, different PVT collectors are commercially available and can be classified as following four categories as given(H.A.Zondag. 2006):

PVT liquid collectors

PVT air collectors

PVT concentrators

Ventilated PV with heat recovery

In the equatorial area where the Sun is high, the weather is consistent hot and the annual ambient temperature varies within a small range. The PVT liquid collectors that can provide the hot water ranging from 45 °C to 50 °C are adequate for the domestic use in the region. Two types of solar PVT collector can meet the requirement of our application, ie. 1). glazed collector and 2). unglazed collector.

A glazed collector in Fig.1a is made from good heat conductor tubing on a metal plate and it has an iron tempered glass covering, which is the reason they usually are more expensive. A glazed collector operates more effectively because it can absorb more sunlight than unglazed collectors. They can be used through the whole year and in many different climates.

(a) **(b)**

Fig. 1: sectional view of (a). a glazed PVT collector and (b). an unglazed PVT collector

Unglazed collectors as shown in Fig. 1b don't have any glass covering on top of solar PV module that directly conveys the heat to the solar thermal panel below it. Due to the cheaper parts and the easy design the unglazed collectors are less expensive than glazed collectors. Although an unglazed collector has higher heat losses from its front surface than a glazed collector through convection and radiation, it is still capable of converting enough solar energy to electricity and hot water at adequate high temperature for the domestic use. A typical arrangement was the direct attachment of PV modules on to a solar thermal collector surface as indicated(H.A. Zondag et al 2004; Chow TT et al 2005).

To investigate the feasibility of unglazed PVT collector in the tropical region, a 93W_p PVT collector consisting of amorphous triple junction PV modules was developed by Grenzone Pte Ltd, Singapore and the corresponding PVT system was set up in Singapore Polytechnic for performance testing. The system started to operate in March 2010 and has been operating for more than one year. The structure and annual performance of the system are depicted in this section.

2.1 The 93W_p a-Si prototyping PVT system

The PVT prototyping system shown in Fig. 2 mainly consists of 93W_p triple junction a-Si water PVT collector, water storage tank, forced circulating system and a stand-alone PV system with grid backup. The 93W_p PVT collector developed and made in Grenzone Pte Ltd, Singapore was composed of three 31W_p a-Si frameless flexible PV modules(UniSolar PVL-31) that were directly mounted on the top of thermal panel as illustrated in Fig. 2. The parameters of PV module are listed in Table.1.

In this closed-loop fluid system, the incoming potable water is routed to the solar storage tank through a valve, a cold water in the water tank is pumped to the PVT collector and the hot water produced in the PVT collector flows back to the storage tank. In order to harness the solar energy effectively, water circulation should normally only be activated when the temperature in the PVT collector is above that of solar storage. Since these temperatures change throughout the day, a Differential Temperature Control(DTC) unit is needed to control circulation pump for sufficient thermal gain. Essentially the DTC unit compares the difference between the hot water temperature at outlet of PVT collector 'T_{out}' and the cold water temperature at inlet of the PVT collector 'T_{in}' (see Fig.3). For reliable control, the hysterisis with a 'dead-band' is necessitated and can be adjusted to avoid unnecessary short cycling or hunting of the pump. In our system, the hysterisis is 3°C . When the temperature difference reaches or exceeds 6°C, the DTC unit activates the water pump to circulate the water through the PVT collector. When the temperature difference is below 3°C, the DTC unit stops the water pump to maintain the water temperature in the tank. During night time, the water in the tank is continuously circulated through the PVT collector to simulate the use of hot water stored in the tank. As indicated in Fig. 3, the 93W_p PV modules were connected to a charge controller with MPPT to charge the 12V/100Ah battery and power the water pump, controllers, dataloggers and all other devices. To avoid the power interruption caused by poor weather condition in long period, a change-over switch was installed to allow to connect the prototyping system to main grid for backup power supply(not shown in Fig.3).

Table 1: The parameters of a-Si PV modules used for 90W_p under STC

Module model	P_{mp} (W_p)	V_{mp} (V)	I_{mp} (A)	V_{oc} Temperature coefficiency	P_{mp} Temperature coefficiency	Conversion efficiency
PVL-31(Unisolar)	31	7.5	4.13	-0.374%/C	-0.215%/C	6%

2.2 Performance of the prototyping PVT system

Many researchers used the total efficiency 'η_o' to evaluate the performance of a PVT system as demonstrated(Bergene T. and Bjerke B. 1993; Bergene T. and Lovik O. 1995; Fujisawa T. and Tani. T. Binary, 1997; Zondag. H.A. et al, 2002). The total efficiency is defined as the sum of solar electricity efficiency, 'η_e' and solar thermal efficiency, 'η_{th}' as given in Eq.1:

$$\eta_o = \eta_e + \eta_{th} \qquad \text{(eq. 1)}$$

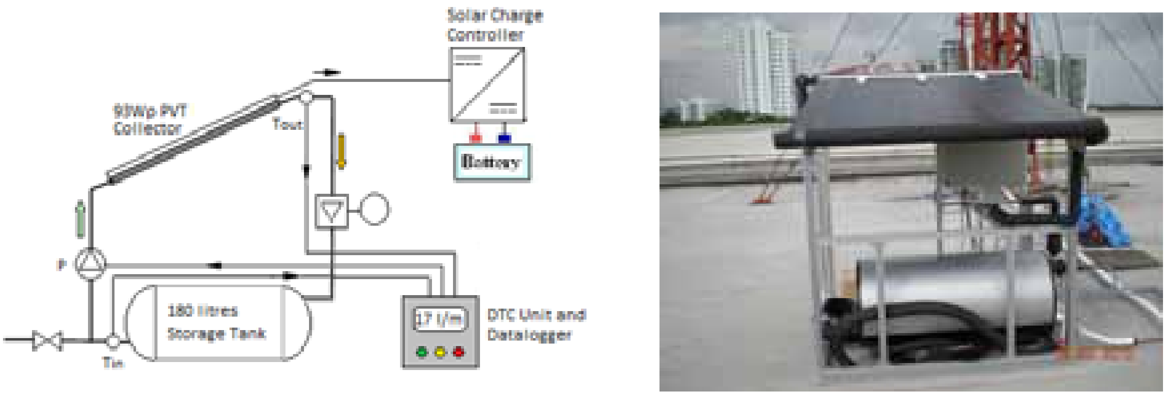


Fig. 2 Structure of 93W$_p$ forced circulating PVT prototyping system

The electrical efficiency of PVT system is mainly dependent on the incoming solar irradiation, 'G', and the PV cell temperature, 'T_{cell}'. It can be calculated in terms of

$$\eta_e = \frac{E_{PV}(G, T_{cell})}{G \times A} \qquad \text{(eq. 2)}$$

where $\boldsymbol{E_{pv}}(G, T_{cell})$ is the electrical energy yield of PV modules which is the function of solar irradiation and cell temperature and can be measured directly and '***A***' is the area of PV module.

The thermal efficiency of the PVT system is determined by the incoming solar irradiation, '*G*', the hot water temperature at outlet of PVT collector, 'T_{out}' and the cold water temperature at inlet of PVT collector, 'T_{in}'. The thermal efficiency can be worked out by use of Eq. 3:

$$\eta_{th} = \frac{\dot{m} C_p (T_{out} - T_{in})}{G \times A} \qquad \text{(eq. 3)}$$

Where $\dot{m}$ is the fluid mass flow, C_p is the fluid specific heat.

The parameters of Eqs 2 and 3 are measured and recorded using two data loggers, ie. one for electrical system and another for thermal system. The average daily irradiation, thermal and electrical energy yield in each month are depicted in Fig. 3a, while the average monthly conversion efficiencies of PVT system obtained by use of Eqs 1-3 are indicated in Fig. 3b. It can be concluded from the analytic results that the average thermal efficiency is 30.26% and the average electrical efficiency is 3.78%, resulting in 34.04% of the average system efficiency. In operation, the three temperature sensors were installed to monitor the fluid temperatures at inlet and outlet of PVT collector as well as the internal temperature of PVT collector. The variation of water temperature in PVT collector and water tank is summarized in Fig. 4. The measured data show that the average temperature of water in PVT collector was 50.08 °C and the average temperature of water in tank 46.2 °C which is suitable for domestic applications. The highest fluid temperatures in PVT collector and tank are 62 °C and 56 °C respectively as shown in Fig. 4b.

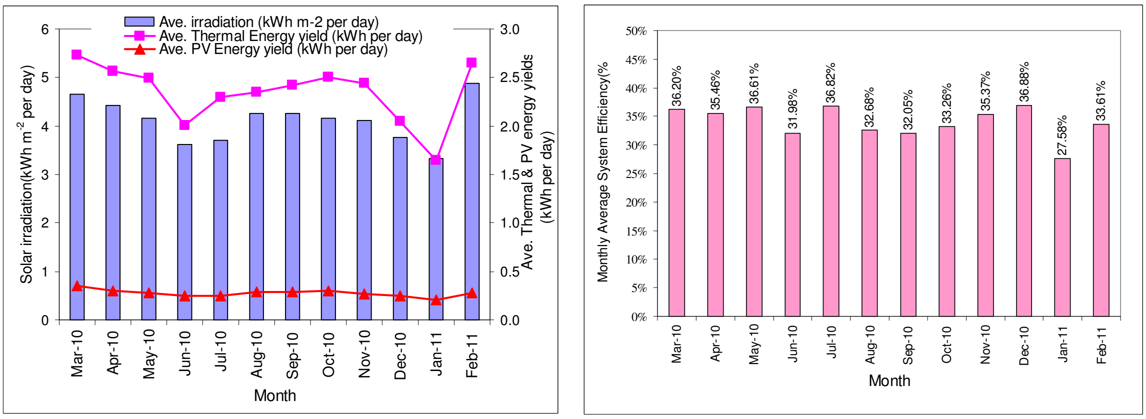


Fig. 3: (a) monthly solar irradiation & energy yields of PVT system and (b). efficiency of 93W$_p$ PVT system

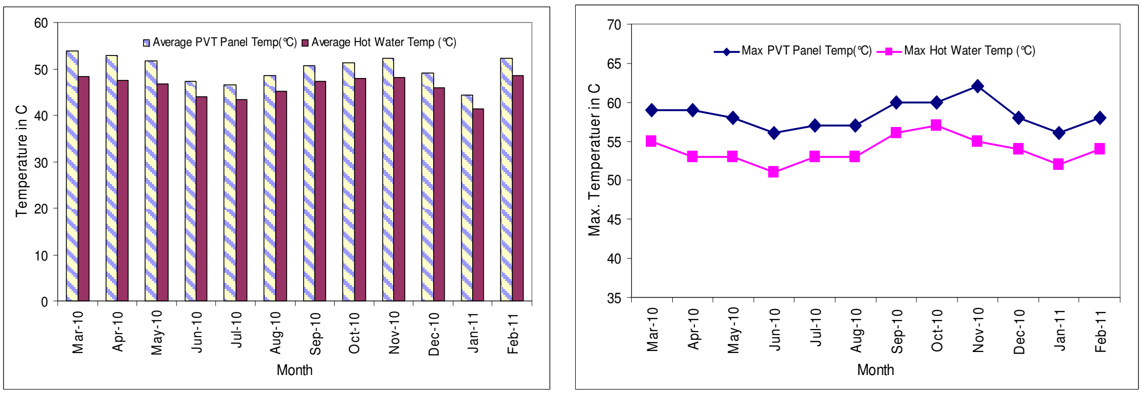


Fig. 4: (a). Monthly average PVT Panel temperature and tank hot water temperature
(b). Monthly maximum average PVT Panel temperature and tank hot water temperature

3. Development of 1.532kW$_p$ a-Si PVT System Based on the Prototyping PVT System

The experiments on 93W$_p$ prototyping PVT system proved the feasibility of unglazed a-Si PVT system for the domestic use in the tropical area. To further improve the system efficiency, we developed a bigger capacity of a-Si PVT collector and design a larger PVT system to undertake more comprehensive test.

3.1The 1.532kW$_p$ a-Si forced circulating PVT system

Based on the experimental results of 10 months operation of the 93W$_p$ PVT system in Singapore Polytechnic, a new 256W$_p$ a-Si PVT collector was developed and tested in Grenzone Pte Ltd. Each 256W$_p$ PVT collector was composed of two 128W$_p$ a-Si thin-film PV modules(Unisolar PVL-128) that were stacked on top of thermal panel. The technical specifications of Unisolar PVL-128 are given in Table 2.

A 1.536kW$_p$ PVT system consisting of six new PVT collectors and nine 400 liters water tanks was designed and set up in Singapore Polytechnic for system performance study. The system was divided into three subsystems, each having two 256W$_p$ PVT modules connected to three water tanks connected in series. Six PVT collectors that were tilted at 10° facing the South were connected in such a way that three subsystems had the common cold water input but three separate hot water outputs to their water tanks. The area of 1.536kW$_p$ PVT system is 27.55m^2. The schematic shown in Fig.5 illustrates the configuration of PVT system. The operation of PVT system was monitored by a datalogger and the operating data of electrical system and thermal system were collected every one minute for analyses on system performance.

Table 2. The parameters of a-Si PV modules used for 128W$_p$ under STC

Module model	P_{mp} (W_p)	V_{mp} (V)	I_{mp} (A)	V_{oc} Temperature coefficiency	P_{mp} Temperature coefficiency	Conversion efficiency
PVL-128(Unisolar)	128	33.0	3.88	-0.374% °C^{-1}	-0.215% °C^{-1}	6%

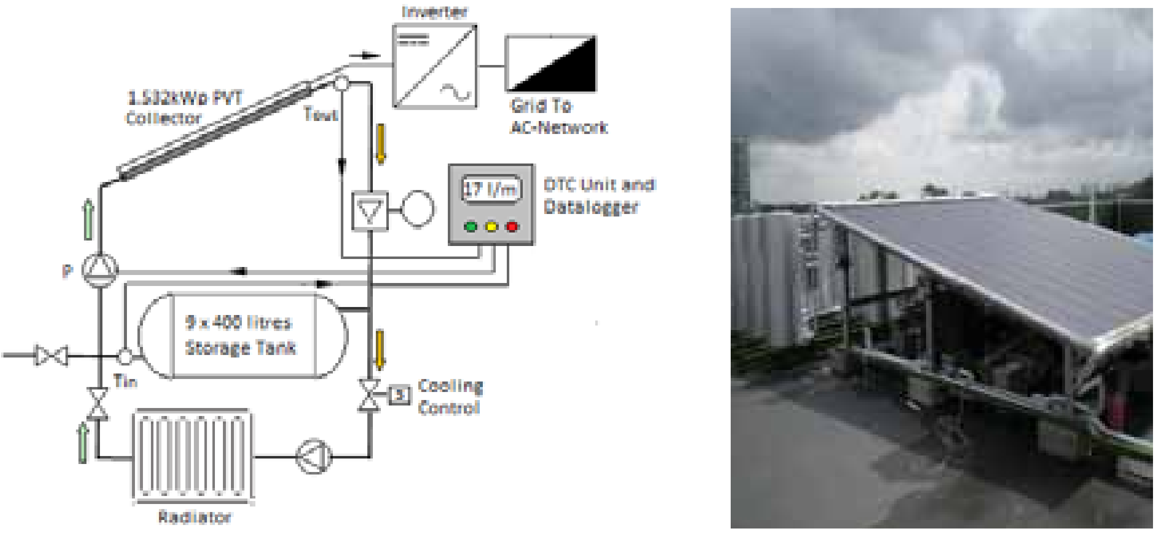
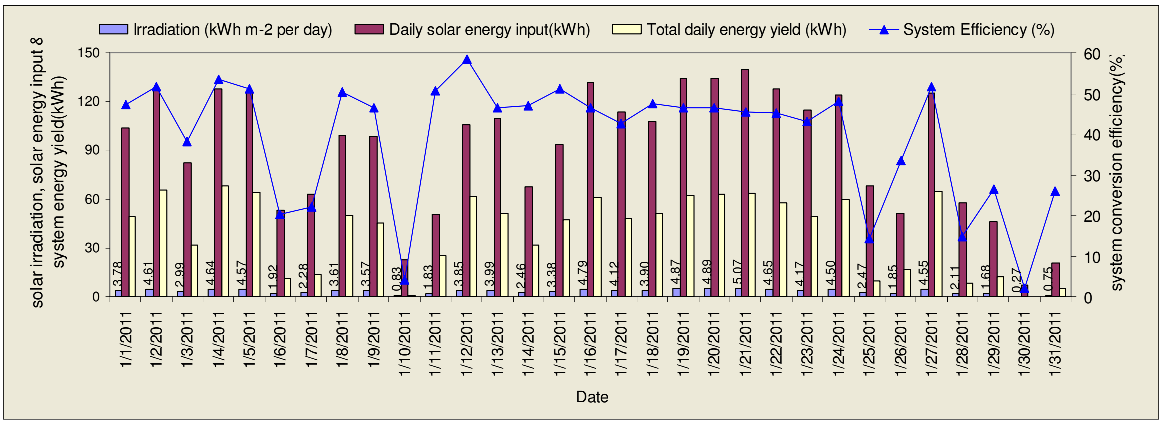


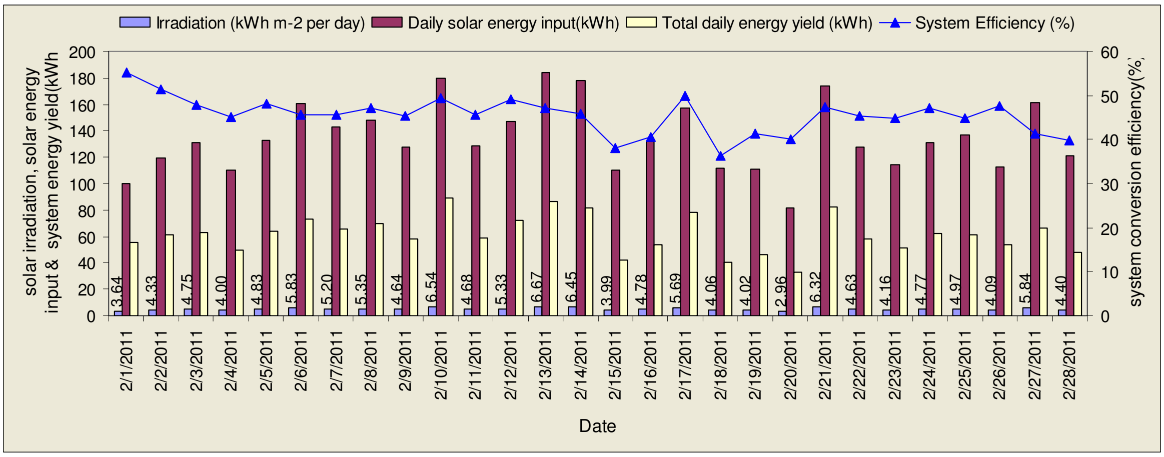
Fig. 5: Structure and photo of 1.532kW$_p$ a-Si forced circulating PVT system

3.2 The monthly performance of 1.532kW$_p$ PVT system

The new PVT system was completed and started its operation for site test from Jan. 2011. Fig. 6 presents the irradiation, the daily solar energy input, system energy yield and system conversion efficiency in Jan and Feb 2011 respectively. The study on the results revealed that the monthly conversion efficiency of the system was 39.35% in Jan and 45.50% in Feb. Compared to the results of 93W$_p$ prototyping system in the same period, the new system showed improved performance and its conversion efficiency was increased by 11.77% in Jan and 12.12% in Feb. The highest daily system efficiency recorded in two months operation was 58.45% on 12 Jan. The ratio of daily thermal energy yield to daily electrical energy yield was also ananlyzed. The average monthly ratio of thermal energy to electrical energy was 7.94 in Jan and 9.61 in Feb. respectively. The performance ratio(PR) of PV system was 79.4% in Jan and 77.15% in Feb.



(a). Daily system performance in Jan. 2011



(b). Daily system performance in Feb. 2011

Fig. 6: The performance of 1.532kW$_p$ a-Si forced circulating PVT system

4. Conclusions

This paper presents the development of a-Si unglazed liquid PVT collectors for tropical domestic use and testing results of a-Si PVT systems under the equatorial weather conditions to prove the feasibility of developed PVT collectors. It is shown from yearly site operation that our first 93W$_p$ prototyping PVT system has achieved 34% of system conversion efficiency. Based on the experimental results of our 93W$_p$ PVT system, a new 256W$_p$ a-Si PVT collector was designed and used to set up 1.536kW$_p$ PVT system to undergo the study on its performance. The results of new system in the first two months operation proved the improvement of new 256W$_p$ a-Si PVT system performance. Based on two months site experiments, the 1.536kW$_p$ a-Si PVT system equipped with 256W$_p$ PVT collectors has improved its conversion efficiency to 41% which is 11% higher than the first 93W$_p$ PVT prototyping system. The further study will be undertaken to investigate the system performance in long run and explore different control schemes for better system performance.

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