A HYBRID PHOTOVOLTAIC-THERMAL SOLAR COLLECTOR INSTALLATION: EXPERIENCES GAINED AND THE LESSONS LEARNT

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ABSTRACT
Hybrid photovoltaic-thermal (PVT) collectors combine the production of solar electricity and heat in a single device and thus achieve higher overall efficiency and better harvesting of solar energy than conventional photovoltaic (PV) modules. The electrical efficiency of PV cells typically ranges from 15% to 20% while the greatest amount of the solar spectrum (65%−70%) is converted into heat which increases the temperature of PV modules, in turn, lowers the electrical efficiency. These collectors are generally installed stationary and their overall efficiency depends on various factors such as technical specifications of the cell technology, surface azimuth angle, tilt angle, weather conditions, working fluid thermophysical and flow properties, electric load management. This paper presents a practical guide for their installation and efficiency management. A hybrid PVT module with 60 mc-Si cells was installed in Adana, Turkey and various design considerations were considered during installations. Based on the technical specifications of the PVT and the typical meteorological year data of the location, transient simulations were parametrically carried out using System Advisor Model software for the determination of optimum orientation by maximizing the annual electricity production. It was presented how to orient the PVT for the field installation. To benefit from the solar heat, thermal energy storage tanks were installed to use in domestic applications. Several measurement devices and their data acquisition were considered to rate the performance. The experiences gained and lessons learnt would provide a useful guide to PVT installers particularly for domestic installations.

Keywords: photovoltaic-thermal, experiences gained, lessons learnt, proper installation.

1. INTRODUCTION
Solar energy can be directly converted into electricity via the photovoltaic (PV) effect but its converting efficiency is a big concern for the technology. There is a radiative efficiency limit i.e., ~30% at band gap of 1.1 eV for a conventional solar cell using a p-n junction [1]. Most commercial solar cells have lower efficiencies under real test conditions, this means that a considerable amount of absorbed radiation is converted into heat. PV-thermal (PVT) hybrid collectors take the advantage of producing both electricity and heat simultaneously. The heat removed from the PV panel is used to warm up the fluid which cools the cells and makes them operate efficiently.

The PVT module has various applications in the domestic and industrial fields such as preheating air or water. It can be integrated into building façades and roofs for the applications like air ventilation, space or water heating [2].

This paper presents a practical guide for the installation and efficiency management of liquid-based PVTs. A test setup has been installed and the experiences gained and the lessons learnt have been suggested. Before installation, mentioned design considerations for the system components need to have cared and the manufacturing and mounting stages should be handled carefully.

2. PVT INSTALLATION

2.1. Orientation of the PVT

A collector facing south in the northern hemisphere harvests much energy throughout the year however the surface azimuth angle is to be with zero due south [3]. To determine the due south direction, the local time for solar noon is to be calculated. Solar time does not coincide with local clock time thus which needs to be converted to solar time. The local standard time (LST) is reckoned from the standard longitude (SL) i.e., Greenwich and the local longitude (LL). 1° of longitude takes 4 minutes thus longitude correction is either added or subtracted to the clock time of the local. If the location is east of Greenwich, the correction is added to the clock time and subtracted if the location is west. The equation of time (ET) takes into account the perturbations in the earth’s rate of rotation. The daylight saving time (DST) is applicable even if it is considered in the location interested. The equation for calculating the apparent solar time (AST) is [3]

$$\mathrm{AST} = \mathrm{LST} \pm 4\left(\mathrm{SL} - \mathrm{LL}\right) + \mathrm{ET} - \mathrm{DST} \tag{1}$$

The parameter ET (in minutes) can be calculated by

$$\mathrm{ET} = 229.2\left(0.000075 + 0.001868\cos B - 0.032077\sin B - 0.014615\cos 2B - 0.04089\sin B\right) \tag{2}$$

where $B = \left(n-1\right)\frac{360}{365}$, n is the day of the year.

On the other hand, plotting the shadow of the Sun on the flat ground over the course of a day using a shadow stick is another way of determining the direction of due south as shown in Fig. 1. The AST calculated by Eq. (1) can be double-checked by placing marks for each 5-minute to find the shortest shadow or the point where the sun crosses an imaginary arc – when the sun is highest for that day. For the 16th of September, 2021, the time correction for the local time was calculated on that day using Eq. (1) for Adana and obtained to be 43 minutes. This means that at 12:43 local time corresponds to solar noon on that day. The correction time fitted well with the shadow stick test.

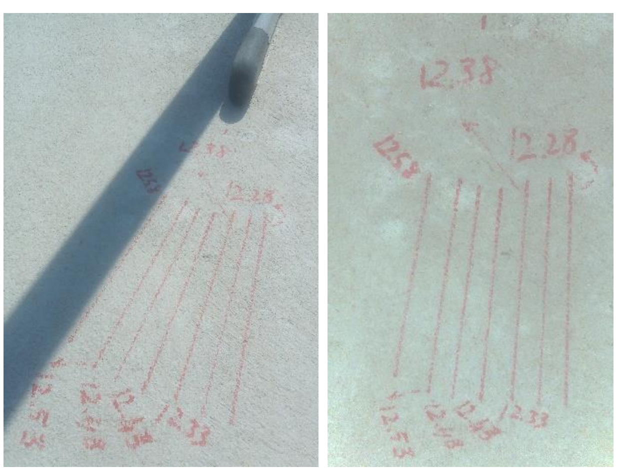

Fig. 1. Straight rod shadow and the marks lined for 5-minute intervals

The tilt angle of the PVT is significant to produce electricity at the maximum rate. To determine the optimum tilt angle, System Advisor Model (SAM) developed by the NREL [4] can be used to simulate the transient behavior of PV systems. For the long-term simulation, the typical meteorological year (TMY) data shown in Fig. 2 for the selected location (Adana, Turkey) will be useful since it may not involve unusual sequences or extremes of weather. Weather software like Meteonorm or EnergyPlus can supply this data then is added to the solar resource library of SAM in the TMY2 weather file format.

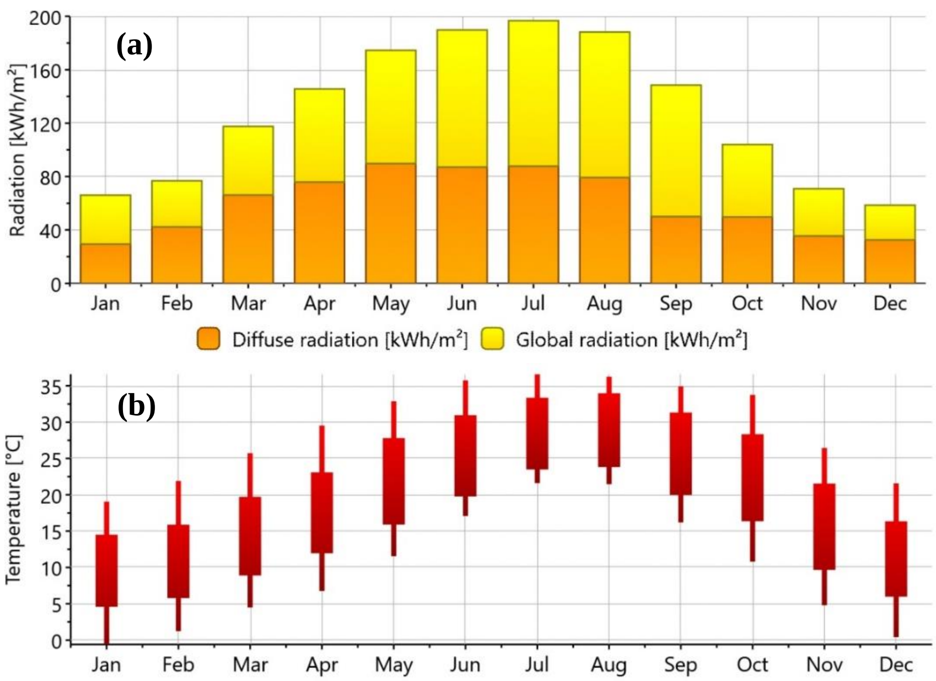

Fig. 2. (a) Monthly average global radiation over the period of 1991−2010; (b) Monthly average ambient temperature over the period of 2000−2009 [5]

Module characteristics of PV at reference conditions affect directly the performance. The PVT with module specifications given in Table 1 was taken into account for the simulation.

Table 1. Technical specifications of Excell PV-T 300W

Cell type	mc-Si
Module dimensions	1672×950×60 mm
Number of cells	60 (6×10)
Number of riser tubes	7
Length of flow path	1445 mm
Riser inner diameter	7.1 mm
Riser outer diameter	8 mm
Header inner diameter	16.6 mm
Header outer diameter	18 mm
Maximum power point voltage (Vmp)	34.30 V
Maximum power point current (Imp)	9.62 A
Open circuit voltage (Voc)	41.67 V
Short circuit current (Isc)	10.17 A
Nominal operating cell temperature, NOCT	36.9 °C

Temperature dependence of Voc	−0.104 V/°C
Temperature dependence of Isc	0.005 A/°C
Temperature dependence of Pmp	−0.314 %/°C

After describing the physical characteristics of the PV module, the annual system simulation can be done parametrically to find the optimum tilt angle which provides the maximum delivered electricity. It was obtained to be 32° for the location interested. To tilt the PVT at an angle of 32° as seen Fig. 3, a protractor or an inklinometer can be used but to tilt the PVT accurately, opposite and adjacent sides should be calculated using the Pythagoras theorem and the length of the solar panel stand legs should be manufactured on this.


Fig. 3. Tilt angle calculation for installation

2.2. Electric Load Management

SAM also has the capability of drawing current-voltage curves with irradiance change. If maximum power point tracking (MPPT) algorithm is implemented in PV inverter, it continuously adjusts the impedance seen by the solar array to keep the PV system operating at, or close to, the peak power point of the PV panel under varying conditions, like changing solar irradiance, temperature, and load. If it is not implemented, a constant load or rheostat shown in Fig. 3 can be used where more than one stage will be useful to satisfy the proper load arrangement. Note that under constant electric load, the voltage difference should be close to Vmp otherwise, the electricity produced will reduce with increasing current across the rheostat.

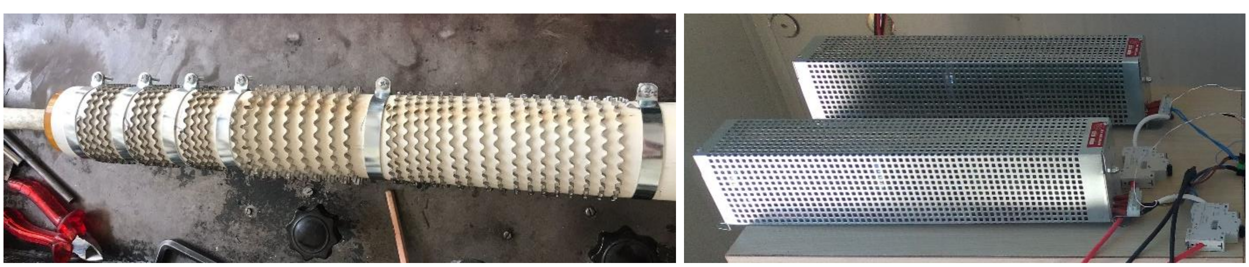
Fig. 3. Rheostat structure (on the left), ready to use rheostat for electric load management

2.3. Working Fluid Circulation

In liquid-based PVTs, a working fluid is used, water is a widely used liquid in PVT applications. the determination of the optimum liquid flow rate is essential to reach the highest electric output since the pump consumes electricity for fluid circulation. For this reason, the use of a frequency-controlled pump [6] will be useful to control the flow rate and see the net electricity production i.e., the difference between the PVT power production and the pump power consumption.

The maximum electrical efficiency of the PV module, $\eta_{e,\max}$ can be calculated using

$$\eta_{e,\max} = \frac{V_{mp} I_{mp}}{I_T A_m} \tag{3}$$

where the numerator parameters are defined in Table 1. I_T is the total or global incident irradiance in W/m^2 and A_m is the module area in m^2.

The nominal maximum power point rating at standard test condition can be found as 20.78% for the given specifications in Table 1. This result agrees well with the efficiency value presented in Fig. 4. This means that the rest of the total absorbed radiation by the PV i.e., 79.22% can be converted into thermal energy which lowers the electrical efficiency due to the increasing stagnation temperature of the PV during operation but can contribute to the overall efficiency of the PVT. That is why the PVT is preferred in place of PV.

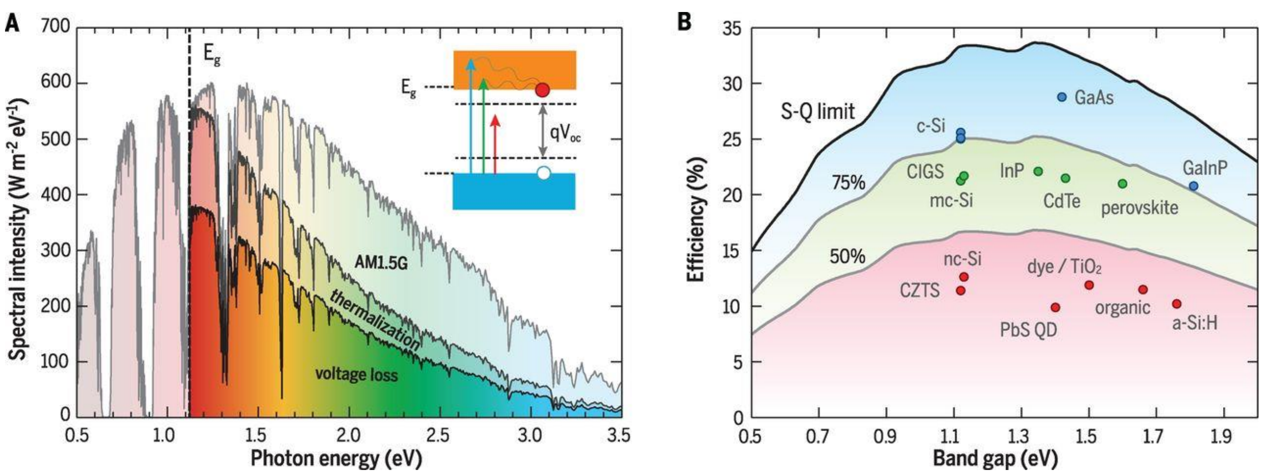

Fig. 4. PV materials and present efficiencies [7]

2.4. Thermal Energy Storage

For performance tests, thermal energy storage (TES) tank/s is needed as shown in Fig. 5 since the outlet temperature of the heated working fluid in the PVT will raise with instantly absorbed radiation. The rejected heat will increase the TES temperature for this reason it should work as a heat exchanger that facilitates the exchange of heat between the hot and cold fluids while keeping them from mixing. This is important for testing the PVT performance since the inlet fluid temperature of the PVT must be kept constant. The volume of the hot water tank and the serpentine length should be as much as possible but their costs need to be considered. If they are enlarged, controlling the inlet temperature will be easy otherwise a proportional integral derivative (PID) controlled electric heater is needed to keep the inlet fluid temperature stable [8, 9]. The instantly discharged heat being absorbed by the PVT must be rejected to the cooling medium i.e. hot water tank where the water is stagnant in the tank where the tape water should be entered steadily to keep the tank temperature at ambient temperature.


Fig. 5. Cold storage tank (upper), hot storage tank (bottom)

2.5. Thermal Expansion Tank

In the experimental setup, a thermal expansion tank (TET) is needed to provide a space for the working fluid due to volume change when heated from ambient temperature to normal operating temperature. It is usually installed before the pump suction to provide a positive pressure head, and also to vent moisture, non-condensable and any low boiling components. The TET should be sized to hold about 25% of the fluid volume as it is cold and have no more than 75% of the fluid volume as the system is at its maximum operating temperature [10].

2.6. Measurement Devices

Various measurement instruments are essential to test the PVT. The following instruments are needed to analyze the PVT performance:

- The voltage across the terminals of the PVT and the current generated by the PVT.
- A pyranometer to measure the global radiation on the tilted surface.
- An anemometer to measure the wind speed on the tilted surface.
- Temperature detectors for the inlet and exit fluid temperatures of the PVT and hot water tank.
- A flowmeter to measure the flow rate of the fluid passing through the PVT piping.
- Temperature detector for measuring the ambient temperature.

2.7. Data Acquisition

The measurements of voltage and current are essential for the instant measuring of electricity. For this, a data acquisition (DAQ) card and an interface software are needed for instant signal processing and data storage, respectively. Many commercial DAQ devices may not measure both absolute voltage and current signals coming from the PVT in this case calibration is needed to measure actual physical quantities. If the DAQ card only measures voltage input like [11], a current sensor can be the cheap choice for converting current into a voltage signal during the measurement of electrical parameters as shown in Fig. 6.

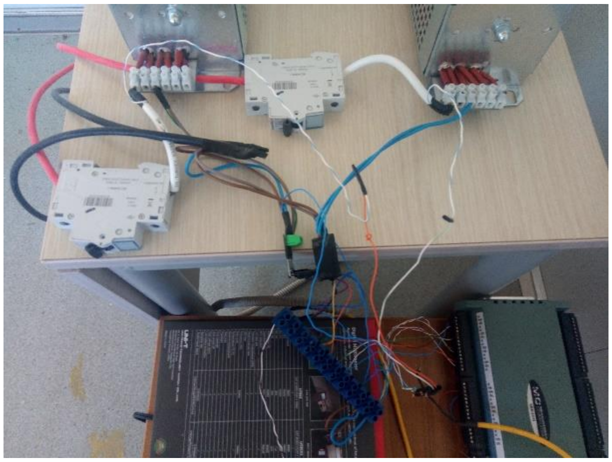

Fig. 6. Current sensor and connections with the DAQ card

3. CONCLUSION

The PVT hybrid collector is a promising technology particularly for domestic and industrial applications. Various studies were performed in the literature to improve their efficiency and different experimental setups were proposed to test them. To test the system performance, the experimental setup should be installed suitably and care must be exercised how an accurate setup is accomplished to measure parameters. This paper suggests a methodology and shows the critical points that should be considered and justified before testing the setup. Some points seem to be fundamental but many researchers overlook these points and set an inaccurate test facility that may not give reasonable results. On the other hand, in some research papers, it is not easy to find the technical specifications of the test setup. New researchers in the field may have problems with the basics of PVT installation and testing instruments.

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