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Development and performance analysis of solar photovoltaic–thermal (PVT) systems

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Abstract. The photovoltaic–thermal (PVT) systems have been established for providing both electricity and heat using the existing photovoltaic (PV) system set-up. The PVT systems capture panel heat for some useful purpose. It is based on deploying a polymer sheet at the back of the PV panel to accommodate cooling water between the PV panel and the sheet to maximize the contact area between cooling water and panel. The present work compares the performance of a normal PV panel to that of the novel PVT panel. The PVT system is fabricated and experiments are conducted to evaluate electrical and thermal efficiencies. An improvement of 2.17% is observed in the electrical efficiency of the PVT panel in comparison with the normal PV panel. A brief cost analysis along with payback period calculations of the PVT panel is also included.

Keywords. Solar energy; solar–PVT system; overall efficiency.

1. Introduction

For a sustainable future, it is important to establish renewable resources as the primary source of energy. The performance of solar photovoltaic (PV) cell needs to be stable over the wide range of operating conditions. A large fraction of the incident solar energy is rejected in the form of heat. It also results in the raising of the operating temperature of the solar module. Cooling of the solar cell is important for reducing the effects of increased operating temperature; one can achieve this by introducing a heat-exchanger. Keeping the temperature at the optimum level can boost the electrical performance of a module as the heat is extracted for applications like heating water or space heating. This combined structure is called solar photovoltaic–thermal (PVT) panel system [1].

1.1 *Literature survey*

Since the last few decades, numerous studies on the PVT system have been documented. A few notable design approaches of the PVT systems are presented here.

Tiwari and Sodha [2] have proposed a thermal model of a combined photovoltaic and thermal solar (IPVTS) water–air heating system. For the forced circulation of the fluid, an insulated pipe structure is used. Four different configurations are unglazed with Tedlar, glazed with Tedlar, unglazed without Tedler and glazed without Tedlar that are considered. For all configurations other than glazed without Tedlar, it is observed that, as compared with air, characteristic daily efficiency of the IPVTS system is more with water.

Solanki *et al* [3] have studied the performance of a PVT solar heater system with an experimental lab set-up. On a wooden duct the lab testing is set up, which consists of three 75-W PV panels mounted on it. A 12-V, 1.5-A DC fan is installed for the air circulations. The thermal, electrical and overall efficiency of the solar heater obtained at indoor conditions are reported as 42%, 8.4% and 50%, respectively.

An attempt has been made to develop genetic algorithms to maximize the overall energy efficiency of the single-channel PVT system [4]. The optimum values of the parameters like depth of channel, length of the channel and velocity of the fluid flow are found out to maximize the overall efficiency of the PVT system.

Joshi and Dhoble [5], in 2018, have reviewed various PVT systems. It is concluded that the electrical and thermal efficiencies of non-concentrated-type water-based PVT systems are in the range of 10–12% and 50–70%, respectively. They have also mentioned that the heat extraction from the rear surface of the PV panel is advantageous.

It is observed that existing PVT systems rely on forced circulations of fluid through metallic pipes. The

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mechanically attached pipes are designed to maximize the contact area for extracting thermal benefits. Due to gaps in the pipes and non-uniform fluid flow through them because of curvatures, uneven heat signatures are observed. Another significant inference can be deduced that existing thermal collectors have bulky additions that increase overall cost and maintenance. To develop more effective customer-friendly options is the primary motivation for the work presented here.

1.2 *Contribution*

Although the PVT systems are reported by a number of developers in last three decades their commercial realization has been limited [6]. The significant contributions of this work are summarized as follows:

1. The proposed PVT system is built using a lightweight acrylic back sheet keeping the overall system weight low.
2. It uses gravity feed and natural circulation.
3. The system has low capital cost and requires considerably less maintenance, leading to lower operating cost.

2. System description

The PV panels (modules) are made of a variety of different layers depending on the technology used. The PV panel used in the present work is polycrystalline YL300P-35b manufactured by Yingli Solar. This PV module is used to build the PVT panel. The PVT system consists of five main layers: a glass cover, solar cells and EVA, Tedlar, a cooling channel and thermal insulator.

The proposed PVT panel layout is shown in figure 1(a). A PVT panel cut view is shown in figure 1(b), which helps to understand construction of the PVT panel. Actual photos of the proposed PVT panel are shown in figure 2.

3. System set-up

In the proposed system, direct surface contact of cooling water with the Tedlar is maintained to improve the heat transfer and to minimize the efficiency loss.

The following are the design consideration accounted for the gap size selection:

- The gap between acrylic sheet and Tedlar plays an important role in the system; bigger the gap, larger the cooling water volume in the channel. However, it puts more load on the back acrylic sheet. Greater load implies more deflection of the sheet, which in turn puts stress on the sealant and the sheet comes off. Hence extra protection is needed for the back sheet, to sustain this excess load, which can lead to unnecessary loading of the panel as well.

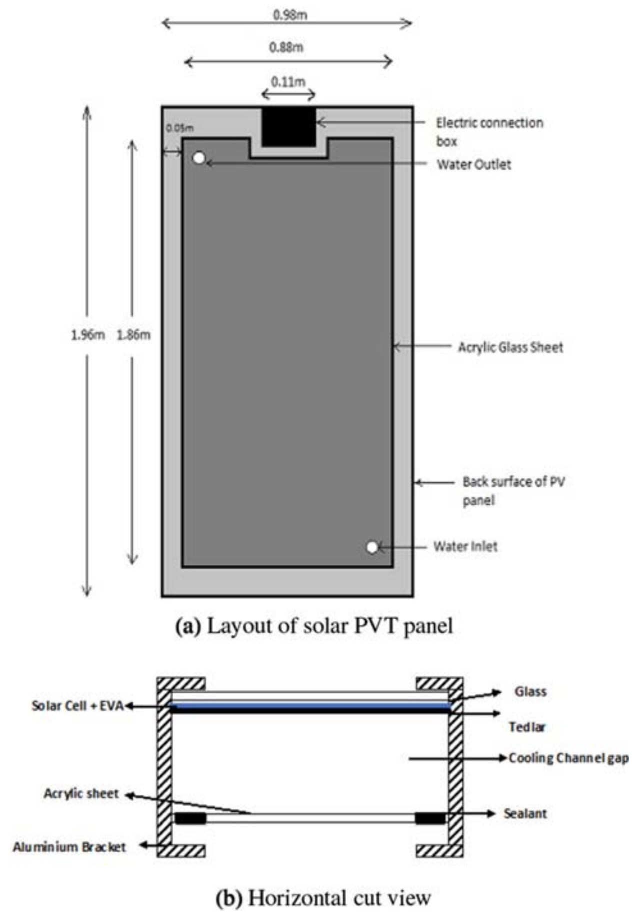

Figure 1. Schematic of PVT panel.

Figure 2. Front and back view of the proposed PVT panel.

- The more water also results in higher cooling of the PV panel. Improvement in electrical performance can be achieved with this modification; however, at the same time, it reduces the outlet temperature of the water. Since we are looking at useful output both in terms of heat and electricity, low temperature water does not serve the purpose; hence it is important to optimize the gap, water quantity and flow rate.
- In the proposed construction of the PVT panel, no extra support is provided to the back of the acrylic sheet as the acrylic sheet is stuck to the Tedlar at the edges with the acrylic base of 2 cm width. With this consideration the gap between Tedlar and acrylic sheet is optimized to 5 mm, which can hold around 8 l of water.
- Any further reduction in the gap of the cooling channel will restrict the water flow rate in the channel. This further leads to increase in operating temperature of the panel and reduction in the electrical output. This is not desirable.

The cooling channel gap was varied according to the panel dimension, epoxy sealant strength and load-bearing capacity of the PV panel holding structure. In the presented model, one aim is to decrease the load on the panel to reduce cost and maintenance issues.

Any pumping system is eliminated from the proposed scheme for two fundamental reasons. Firstly, the pressure exerted on the acrylic sheet can damage it. Though one can use the pump and control flow rate of water through the system, it also increases cost and maintenance issues. Secondly it increases the electricity consumption, defeating the whole purpose of deploying the PVT. In the proposed system, the flow rate is adjusted using a valve attached to the cooling water tank. The tank is connected to the central water system to ensure that the water level in the tank remains constant.

4. Results and discussion

The experimental set-up of a new solar–PVT hybrid system is developed and tested at Pune, India. A PV panel system of same rating is also installed alongside the PVT system to compare the performances of the arrangements. LM-35 sensors are used for the temperature measurement of the backside of the PV (Tedlar) and PVT panel, and DS18B20 temperature sensors are used for outlet water temperature. For the irradiance data a BH1750 sensor is used, which is calibrated with the standard pyranometer output. All the electrical parameters and other sensor data are logged using an Arduino Mega 2560. An ACS 712 sensor is used for the current measurements.

Summarized experimental results of PVT system for a typical summer day are as shown in table 1. Comparison of results for PVT and PV systems is shown in table 2. These results are for an average value of parameters. Here, t is time of the day, T_w and T_a are water and ambient temperatures, I is solar irradiance and η_{elec} and η_{th} are electrical and thermal efficiencies, respectively.

Table 1. Summarized experimental results of PVT system for a typical day of summer.

t (h)	$I\,(\mathrm{W/m^2})$	$T_a\,(^\circ\mathrm{C})$	$T_w\,(^\circ\mathrm{C})$	$\eta_{elec}\,(\%)$	$\eta_{th}\,(\%)$
8	472.47	30.37	32.74	14.70	43.60
9	659.82	34.32	43.65	13.76	45.12
10	807.10	36.03	48.27	13.45	43.19
11	906.81	37.78	51.67	13.22	42.79
12	947.58	39.04	53.79	13.10	42.85
13	955.35	42.07	53.99	12.99	44.77
14	867.72	41.50	51.83	13.14	45.38
15	832.58	40.20	48.15	13.39	46.74
16	560.37	38.74	43.45	13.71	49.90

Table 2. Comparison results of PVT system with PV system during summer.

Parameter	For PVT system	For PV system
$T_w(^\circ\mathrm{C})$	47.50	–
$\eta_{elec}(\%)$	13.50	11.33
$\eta_{th}(\%)$	44.92	–
$\eta(\%)$	58.42	11.33

In comparison with the typical systems presented in [7] [8], the proposed system costs 75% less in terms of construction cost per Watt due to the exclusion of metallic structures, pumping system and thermal back insulation[8]. The maintenance expenses also reduced in the proposed system.

4.1 *Discussion*

The solar PV and PVT panel both harvest the energy from solar radiation. To compare the performance of the PVT panel to that of the normal PV panel an Energy Harvesting Factor (EHF) is calculated. The formula for EHF for the proposed PVT panel is given in equation (1):

$$\mathrm{EHF} = \frac{\text{total energy harvested by PVT panel (electrical + thermal)}}{\text{total energy harvested by PV panel}}. \tag{1}$$

One may argue that it is inappropriate to add the thermal and the electrical energy to calculate the overall energy output; however, here we are interested in the total useful energy extracted from the solar radiation from both PV and PVT systems. Hence, it is fair to add the thermal and electrical output for the PVT panel as it produces both energies together. To find out EHF for the proposed system one needs to calculate ratio of areas under the curves of PVT panel outputs (electrical + thermal) and PV panel output. The EHF for the PVT panel is 6.6, which states that the useful energy harvested by the proposed PVT panel is 6.6 times that of the normal PV panel for the same input parameters. This factor justifies the use of PVT over a normal PV panel. To analyse the performance of the solar PVT system and for a comparative study of theoretical output with the experimental thermal efficiency, a plot of thermal efficiency versus reduced temperature $\grave{T}$ (in meter square °C per Watt) is shown in figure 3.

$$\grave{T} = \frac{T_i - T_a}{I} \tag{2}$$

where T_i is inlet water temperature, which is fixed for the calculation at 30°C, T_a is the ambient temperature and I is the incident solar radiation. Figure 3 shows experimental thermal efficiency plotted against the reduced temperature of $\grave{T}$, which indicates that the thermal efficiency varies linearly with the difference between the input and ambient temperature. The negative values can be explained by the fact that during the day, the ambient temperature is higher than the water input temperature.

Figure 3 plot is very important; even the standard experimental tests on the thermal collectors take into account the variation of the instantaneous thermal efficiency as a function of reduced temperature to determine the performance of thermal collectors [9].

4.2 *Cost analysis*

The proposed system can be implemented with external modifications in the existing PV panel. For calculating payback period only the cost of modification is taken into account. The cost of the PV panel is excluded from the calculations. The following assumptions are made to simplify the payback period calculation.

- The components cost are dynamic; hence, for present calculation, the additional cost considered is Indian Rupees (INR) 9000, including two tanks, pipes and acrylic back sheet.
- Inlet water temperature is assumed to be constant at 30°C.
- Maintenance cost is negligible and is excluded from the calculations.

The flow rate of water is kept at 0.01 kg/s; hence, in 9 working hours, total amount of water collected will be 324 l. The average water temperature in a day is 47.50°C (see table 2). The details of the payback period calculations based on electrical heating are provided in the table 3.

Table 3. Cost payback calculations.

Sr. no.	Parameter	Value
1	Flow rate (l/h)	36
2	Working hour	9
3	Mass of water collected per day (kg)	324
4	Inlet water temperature (°C)	30
5	Avg. outlet water temperature (°C)	47.5
6	Thermal energy generated per day (MJ)	23.814
7	Equivalent electrical energy (kWh)	6.61
8	Assumed heater efficiency (%)	80
9	Total electrical energy consumed (kWh)	8.26
10	Unit cost of electricity (INR)	6.5
11	Cost payback period (days)	168

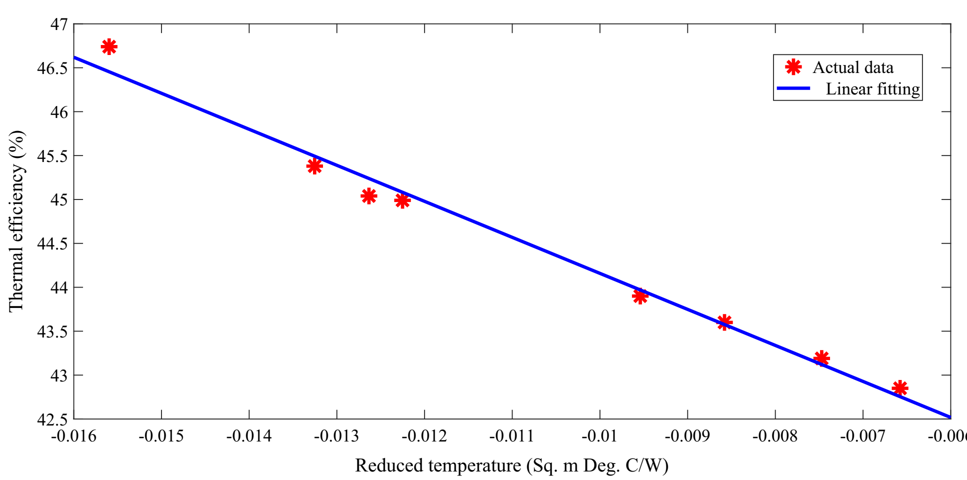

Figure 3. Thermal efficiency according to the reduced temperature.

Table 3 calculations suggest that a total of 168 sunny days are required to recover additional costs invested in the proposed PVT panel.

5. Conclusion

In this paper, the design and development of a novel PVT panel is presented. The proposed system is found to be of low cost, requiring minimal maintenance and having simplicity in design. Some concluding remarks are made as follows:

(i) The proposed PVT system shows explicit improvement (2.17%) in the electrical efficiency as compared with that of PV.

(ii) An average overall efficiency of PVT water collector obtained for a typical summer day is 58.42% (thermal + electrical), which is considerably high when compared with an electrical output of a normal PV system (11.33%) under the same conditions.

(v) For the proposed PVT system, the payback period for the incremental cost over the PV panel is 168 days.

The proposed PVT system can be very easily replicated as well as expanded for large area power plants. It has a potential to make large positive impact on useful energy extraction from solar power plants.

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