2018 International Conference on Smart Grid and Clean Energy Technologies

Performance Evaluation and a New Thermal Model for a Photovoltaic-Thermal Water Collector System

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***Abstract*—A Photovoltaic-thermal (PVT) system is a hybrid solar panel system combining the functionality of solar photovoltaic (PV) and thermal collectors in one system. In Solar PV panel as operating temperature increases, electrical efficiency of panel decreases. In solar PVT panel low temperature fluid, for example water or air is circulated through the heat exchanger placed on back side of PV panel to extract heat from panel and then that heat energy to be utilized for thermal applications. In this way improvement in electrical efficiency is achieved along with heat energy as a by-product. In this paper, a thermal model of a PVT water collector system has been developed. An analytical expression for solar cell temperature, back surface temperature of tedlar, water temperature and an overall thermal efficiency of water collector system has been derived.**

Keywords-Photovoltaic (PV) panel system; renewable energy; solar energy; thermal model; water collector system

Nomenclature

Nomenclature

A	Area, m^2
b	Breadth, m
C	Specific heat, J/kgK
h	Heat transfer coefficient, W/m^2K
pf_1	Penalty factor, no unit
pf_2	Penalty factor, no unit
$I(t)$	Incident solar intensity, W/m^2
K	Thermal conductivity, W/mk
L	Length, m
l	Thickness, m
$\dot{m}$	Mass flow rate, kg/sec
$\dot{Q}_u$	Rate of useful heat transfer, W
t	Time, sec
dx	Elemental length, m
T	Temperature,°C
$U_{w,a}$	An overall heat transfer coefficient from bottom to ambient, W/m^2K
$U_{c,a}$	An overall heat transfer coefficient from solar cell to ambient through top, W/m^2K
$U_{c,bs}$	Conductive heat transfer coefficient from solar cell to water through tedlar, W/m^2K
U_{tT}	An Overall heat transfer coefficient from glass to tedlar through solar cell, W/m^2K

Subscripts

o	Glass to ambient
a	Ambient
bs	Back surface of PV module
c	Solar cell
eff	Effective
g	Glass
w	Water
T	Tedlar
i	Insulation
th	Thermal

Greek letters

α	Absorptivity
β	Packing factor
η	Efficiency
τ	Transmittivity

I. INTRODUCTION

Conventional energy sources like coal, oil and gas have many disadvantages like inadequacy of resources, environmental degradation and harm to the environment. So cheap, obtainable and clean renewable energy resource is needed. Solar energy is congruous alternative. Photovoltaic cells have limited electrical conversion efficiencies, i.e., 10-20% for commercialized silicon cells and around 40% for multi-junction solar cells [1]. The remaining inrush solar radiations are converted into heat and dissipated to the environment. Like this way a lot of solar energy is wasted in the form of heat. Another problem in the solar PV system is effect of temperature on solar cell performance. Solar panel efficiency decreases with the increase in solar cell temperature. Solar cell's open circuit voltage (V_{OC}) is depend on its operating temperature but short circuit current (I_{SC}) is not. For silicon cell, (dV_{OC}/dT) is approximately equal to -2.3 mV/C, which means, that the efficiency of the cell drops by about 0.4% for increase of every one degree Celsius [2]. Fig. 1 shows effect of operating temperature on the output of solar cell.

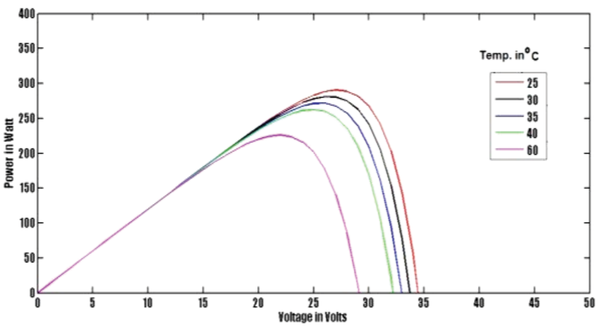

Figure 1. Effect of temperature on the output of solar cell [2].

To reduce the effect of operating temperature cooling of solar cell is necessary. This can be achieved by adding heat-exchanger. A heat-exchanger extracts produced heat to increase electrical efficiency of panel and then to be used for heating applications like water heating, space heating. This system is called as a solar PVT system. In solar PVT system heat extractor is placed on the back side of solar PV panel.

Benefits of solar PVT panels:

- As compared to PV more efficient use of the available space on the roof because PVT system allow high yields of energy per square meter.
- Electrical efficiency of panel increases due to reduction in operating temperature of panel.
- This system addresses the majority of building's energy requirement i.e. electricity and heat.

In this paper, we are presenting simulation results of new PVT system. The data refer to a PV system located in Mediterranean climate. They consist of the meteorological data as hourly mean ambient temperature (T_a), hourly mean module temperature (T_m), hourly mean solar irradiance (I) measured on 3 deg. tilted planes and the hourly mean PV power [3]. We are simulating our PVT system based on that data. Our results will show hypothetical case if our system replace by their normal PV panel system in Mediterranean climate.

A. Khelifa *et al*. [4] presented the mathematical model of hybrid photovoltaic thermal system. Their studied system composed of Photovoltaic panel for electricity generation, with thermal system which is used for water heating. This model formed on energy balances equations written for different nodes of the system.

Aste *et al*. [5] proposed a mathematical model for energy simulation of uncovered PVT water collector and the overall experimental performance was discussed. The parameters and factors which are affecting energy performance of uncovered PVT collector are taken into account.

Kulkarni *et al*. [2] made review on research work of convectional flat-plate PVT and concentrating PVT system. The output of their study defined with increasing heat effect in solar cell caused reduction of electrical efficiency. According to their study many researchers concluded that air PVT collectors are less efficient than water. Also concentrator collector's thermal efficiency is good, but high working temperature affects electrical efficiency.

Neha Dimri *et al*. [6] derived a thermal model for semitransparent photovoltaic thermal with thermoelectric cooler (PVT-TEC) collector. T. T. Chow [7] developed dynamic model for a single-glazed flat-plate water heating PVT collector.

Xu Zelin *et al*. [1] developed a model for new design of dual concentration photovoltaic-thermal (CPVT) system. By using dual-purpose liquids such as nanofluids, which having heat transfer characteristics overall system efficiency (electrical+thermal) can be improved. For performance evaluation of thermal and electrical performances of PVT panel mathematical simulation has been developed [8]-[11].

II. System Description

A schematic diagram of a solar PVT system is as shown in Fig. 2. The storage tank is connected with PV module through insulated pipes. A controller is provided between the PVT system and the hot water storage tank. Fig. 3 shows layered diagram of solar PVT system. The description of PV module system used for the study is as shown in the Table I.

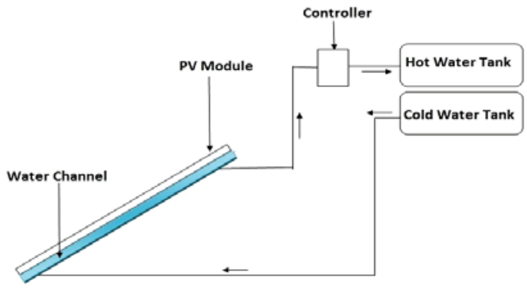

Figure 2. A schematic diagram of the solar PVT system.

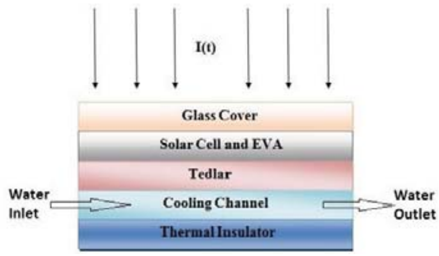

Figure 3. Layer diagram of a solar PVT panel.

TABLE I. Specifications of PV Module

Sr. no.	PV module	specification
1	Type	Poly-crystalline Si
2	Nominal power	250W
3	Open circuit voltage	37.3 V
4	Short circuit current	8.71 A
5	Maximum power voltage	30.2 V
6	Maximum power current	8.30 A

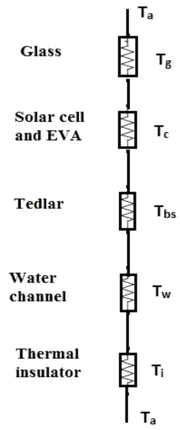

Figure 4. Thermal resistance circuit diagram for PVT water collector system.

III. Thermal Model

Thermal resistance circuit diagram for PVT water collector system is as shown in Fig. 4.

Following assumptions are made in order to write energy balance equation of photovoltaic module:

The glass cover is at uniform temperature due to no temperature gradients along thickness of glass.

The transmittivity of EVA is about 100%.

In the solar cell and PV module the Ohmic losses are negligible.

A. For Solar Cells of PV Module

The energy balance equation for solar cells of PV module can be written as

$$\begin{bmatrix}\text{The rate of input}\\ \text{energy available}\\ \text{on PV module}\end{bmatrix} - \begin{bmatrix}\text{Rate of electrical}\\ \text{energy generated}\\ \text{by PV module}\end{bmatrix} = \begin{bmatrix}\text{Thermal energy loss}\\ \text{from top surface of}\\ \text{cell to ambient}\end{bmatrix} + \begin{bmatrix}\text{Thermal energy loss}\\ \text{from cell to back}\\ \text{surface of tedlar}\end{bmatrix}$$

$$\begin{aligned}&\tau_g[\alpha_c\beta_c+\alpha_T(1-\beta_c)]I(t)bdx-\eta_c\beta_c I(t)bdx\\ &=[U_{c,a}(T_c-T_a)+U_c,b_s(T_c-T_{bs})]bdx\end{aligned} \qquad (1)$$

From (1), the expression for solar cell temperature is

$$T_c=\frac{[\tau_g[\alpha_c\beta_c+\alpha_T(1-\beta_c)]-\alpha_c\beta_c]I(t)+U_{c,a}T_a+U_{c,bs}T_{bs}}{U_{c,a}+U_{c,bs}} \qquad (2)$$

B. For the Back Surface of Tedlar

The energy balance equation for the back surface of tedlar of PV module can be written as:

$$\begin{bmatrix}\text{Rate of thermal energy}\\ \text{transfer from cell to}\\ \text{back surface of tedlar}\end{bmatrix} = \begin{bmatrix}\text{Rate of thermal energy}\\ \text{transfer from back sur-}\\ \text{face of tedlar to water}\end{bmatrix}$$

$$U_{c,bs}(T_c-T_{bs})bdx=U_{bs,w}(T_{bs}-T_w)bdx \qquad (3)$$

Using (2) and (3), the expression for back surface temperature of PV module can be obtained as

$$T_{bs}=\frac{pf_1[(\alpha\tau)_{eff}I(t)+U_{c,a}T_a]+U_{bs,w}T_w}{U_{tT}+U_{bs,w}} \qquad (4)$$

C. For Water below Tedlar

The energy balance equation for water below tedlar of PV module can be written as

$$\begin{bmatrix}\text{Rate of thermal}\\ \text{energytransferred}\\ \text{from back side of}\\ \text{tedlar to water}\end{bmatrix} = \begin{bmatrix}\text{Rate of}\\ \text{thermal}\\ \text{energy carried}\\ \text{by water}\end{bmatrix} + \begin{bmatrix}\text{Rate of thermal}\\ \text{energy loss}\\ \text{from water}\\ \text{to ambient}\end{bmatrix}$$

$$\dot{m}_w C_w\frac{dT_w}{dx}+U_{w,a}(T_w-T_a)bdx=U_{bs,w}(T_{bs}-T_w)bdx \qquad (5)$$

Using (2), (4) and (5) and initial condition, i.e. $T_w|_{x=0}=T_{w0}$, the expression for water temperature can be obtained as

$$\begin{aligned}T_w=&\left[\frac{\sum_{pf_1}^{pf_2}(\alpha\tau)_{eff}I(t)}{U_L}+T_a\right]\left[1-\exp\left(\frac{-U_LA_c}{\dot{m}_w C_w}\right)\right]\\ &+T_{w0}\exp\left(\frac{-U_LA_c}{\dot{m}_w C_w}\right)\end{aligned} \qquad (6)$$

The average water temperature over the length of water channel below PV module is obtained as

$$\begin{aligned}\overline{T}_w=&\left[\frac{\sum_{pf_1}^{pf_2}(\alpha\tau)_{eff}I(t)}{U_L}+T_a\right]\left[1-\frac{1-\exp\left(\frac{-U_LA_c}{\dot{m}_w C_w}\right)}{\frac{U_LA_c}{\dot{m}_w C_w}}\right]\\ &+T_{w0}\frac{\dot{m}_w C_w}{U_LA_c}\left(1-\exp\left(\frac{-U_LA_c}{\dot{m}_w C_w}\right)\right)\end{aligned} \qquad (7)$$

The rate of useful thermal energy is given as

$$\begin{aligned}\dot{Q}_u=&\frac{\dot{m}_w C_w}{U_L}\left\{\sum_{pf_1}^{pf_2}(\alpha\tau)_{eff}I(t)+U_L\left(T_a-T_0\right)\right\}\times\\ &\left(1-\exp\left(\frac{-U_LA_c}{\dot{m}_w C_w}\right)\right)\end{aligned} \qquad (8)$$

The thermal efficiency is given as

$$\eta_{th}=\frac{\dot{Q}_u}{A_cI(t)} \qquad (9)$$

The temperature dependent electrical efficiency of solar cell is calculated from the following relation[12], [13]:

$$\eta_c=\eta_{ref}[1-\beta_{ref}(T_c-T_{ref})] \qquad (10)$$

where η_{ref} is an electrical efficiency of the module at the reference temperature, and T_{ref} at solar radiation of 1000 W/m2. The temperature coefficient, β_{ref}, having value of about 0.004 K^{-1}, for crystalline silicon modules [14]. The quantities η_{ref} and β_{ref} are normally given by manufacturer. The actual value of temperature coefficient, β_{ref}, in particular, depends on the PV material as well as T_{ref}. It is given by the ratio [12]

$$\beta_{ref}=\frac{1}{T_0-T_{ref}} \qquad (11)$$

in which T_0 is the (high) temperature at which the PV module's electrical efficiency drop to zero [15].

The overall efficiency of PVT system is given as

$$\eta=\eta_c+\eta_{th} \qquad (12)$$

G. N. Tiwari *et al*. [16] has obtained an expression for solar cell temperature of PV panel module as

$$T_c = \frac{[\tau_g(\alpha_c\beta_c + (1-\beta_c)\alpha_T) - \eta_c\beta_c]I(t)}{U_t + U_T} + T_a \quad (13)$$

In the above equations from (1)-(10), the related heat transfer coefficients and other unknown parameters are defined as follows:

$$(\alpha\tau)_{eff} = \tau_g[\alpha_c\beta_c + \alpha_T(1-\beta_c)] - \eta_c\beta_c$$

$$pf_1 = \frac{U_{c,bs}}{U_{c,a} + U_{c,bs}}, \quad pf_2 = \frac{U_{bs,w}}{U_{tT} + U_{bs,w}}$$

$$U_{tT} = \frac{U_{c,bs}U_{c,a}}{U_{c,a} + U_{c,bs}}, \quad U_{tw} = \frac{U_{tT}U_{bs,w}}{U_{tT} + U_{bs,w}}$$

$$U_L = U_{tw} + U_{w,a}, \quad A_c = b_L$$

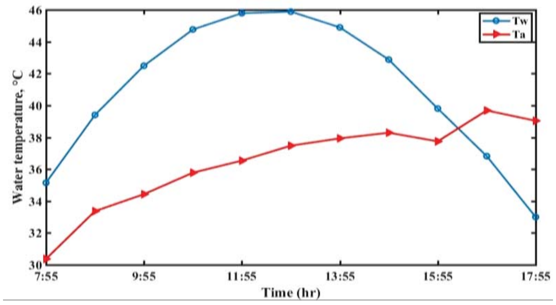

Figure 5. Water temperature with comparison of ambient temperature for a typical day of summer.

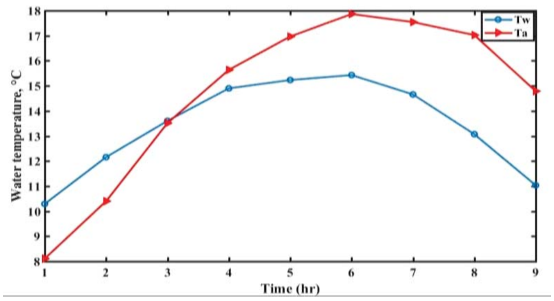

Figure 6. Water temperature with comparison of ambient temperature for a typical day of winter.

IV. Results and Discussion

For the present study the data refer to a PV system located in Mediterranean Climate. They consist of the meteorological data as hourly mean ambient temperature (T_a), hourly mean module temperature, hourly mean solar irradiance measured on 3 deg. tilted planes (I) and the hourly mean PV power [3]. This data and data from Table II have been used to evaluate the hourly variation of the solar cell temperature (T_c), back surface temperature of tedlar (T_{bs}) and water temperature (T_w) from (1)-(7). The overall efficiency of PVT panel has been evaluated from (12). The hourly variation of water temperature with comparison of ambient temperature during summer and winter is as shown in Fig. 5 and Fig. 6, respectively. The maximum water temperature obtained for typical day of summer and winter is about 45.88°C at 12:55 and 15°C at 12:54, respectively.

TABLE II. Values of Design Parameters of PVT Water Collector

Parameters	Value	Parameters	Value
L	1.2 m	l_c	0.0003 m
b	0.54 m	l_i	0.05 m
C_w	4190 J/kgK	Pf_1	0.8772
h_0	9.5 W/m^2K	Pf_2	0.9920
h_T	1000 W/m^2K	U_b	0.6246 W/m^2K
h_i	5.8 W/m^2K	U_t	9.2368 W/m^2K
K_i	0.035 W/mK	U_T	66 W/m^2K
K_T	0.033 W/mK	U_L	8.6623 W/m^2K
K_g	1W/mK	U_{tT}	8.1028 W/m^2K
l_g	0.003 m	U_{tw}	8.0376 W/m^2K
l_T	0.0005 m	α_T	0.50

The hourly variation of solar cell temperature with and without flow of water i.e. for PVT and PV system during typical day of summer is as shown in Fig. 7. The maximum solar cell temperature obtained for PVT and PV system during typical day of summer is about 54°C and 64°C, respectively. Similarly the hourly variation of solar cell temperature for PVT and PV system during typical day of winter is as shown in Fig. 8. The hourly variation of back surface temperature of tedlar of PV module for summer and winter is as shown in Fig. 9 and Fig. 10, respectively.

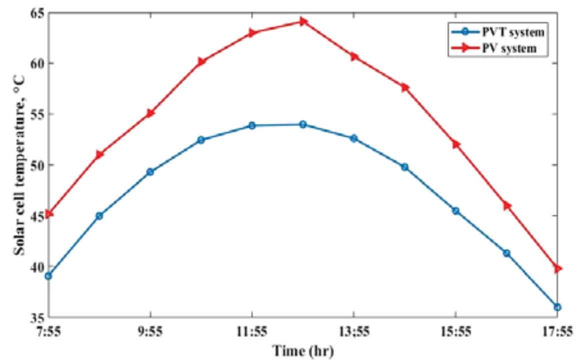

Figure 7. Solar cell temperature for a typical day of summer.

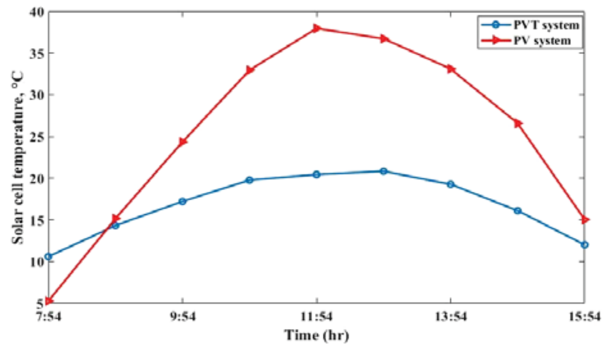

Figure 8. Solar cell temperature for a typical day of winter.

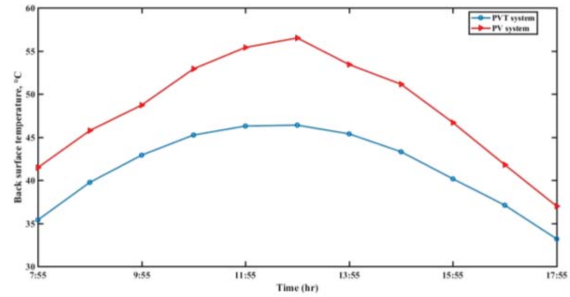

Figure 9. Back surface temperature of tedlar of PV module for a typical day of summer.

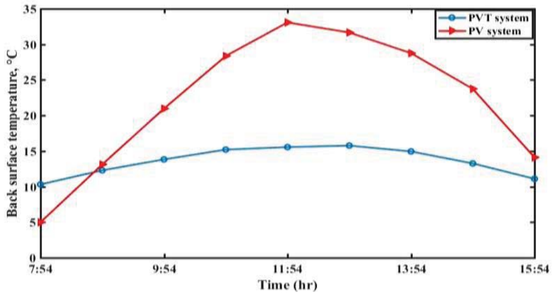

Figure 10. Back surface temperature of tedlar of PV module for a typical day of winter.

The electrical efficiency of PVT and PV panel has been evaluated from (10). Fig. 11 and Fig. 12 shows the electrical efficiency of PVT and PV system for a typical day of summer and winter, respectively.

Fig. 13 and Fig. 14 show the overall efficiency of PVT and PV system for a typical day of summer and winter, respectively.

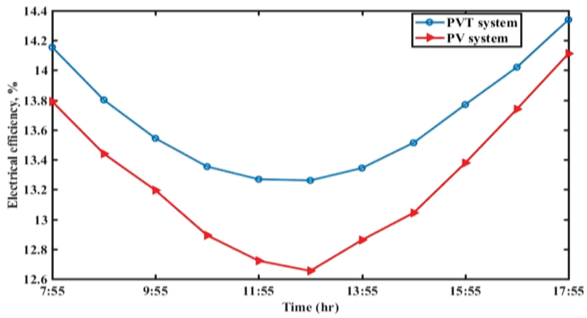

Figure 11. Electrical efficiency for a typical day of summer.

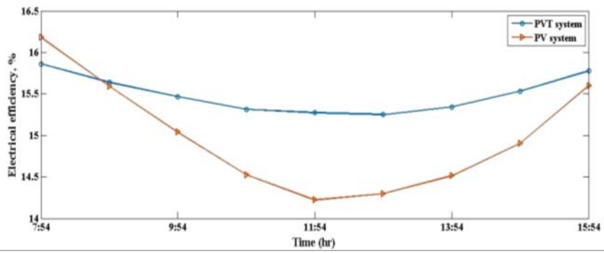

Figure 12. Electrical efficiency for a typical day of winter.

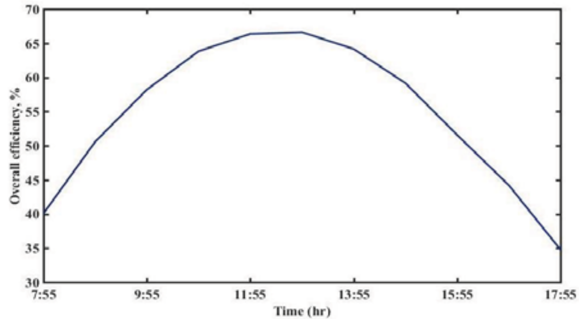

Figure 13. Overall efficiency for a typical day of summer.

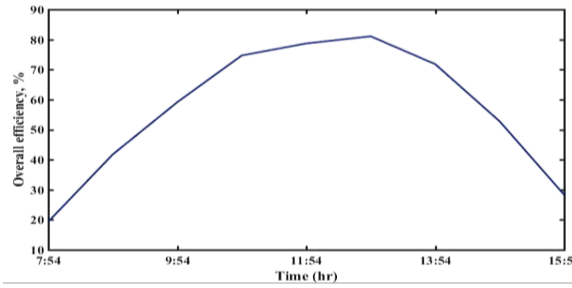

Figure 14. Overall efficiency for a typical day of winter.

V. Conclusion

In this paper the performance evaluation of a PVT water collector was carried out. A novel simulation model for PVT water collector is proposed to calculate the thermal and electrical parameters. The following conclusions are drawn, based on present study:

1) The solar cell temperature of PVT system is less than PV system.
2) Increasing the solar radiation intensity, PVT system gives better electrical efficiency as compared to PV system.
3) The overall efficiency of PVT water collector obtained for a typical day of summer and winter is about 66% and 80%, respectively, which is always greater than electrical efficiency of PV module.

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