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Enhancing Photovoltaic System Electrical Efficiency through Integration of Thermoelectric Generators: A Numerical Investigation

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Abstract— **This paper presents a comprehensive investigation into hybrid photovoltaic thermoelectric generator (HPV-TEG) systems. The focus was on evaluating the impact of the inclusion of TEG in PV panels on PV conversion efficiency, PV temperature regulation, and power generation. A mathematical model based on the energy balance equation of (HPV-TEG) was carried out. The finite difference method (FDM) was employed to numerically solve the developed model. The results showed that incorporating TEG devices in PV systems reduces temperature by 10 K and boosts electrical efficiency by 1.5%. Compared to standalone PV panels Additionally, TEG power output rises with greater solar radiation intensities.**

Keywords— Photovoltaic; thermoelectric generator; HPV-TEG; FDM; Electrical efficiency.

I. INTRODUCTION

One of the main factors influencing the effectiveness and lifespan of photovoltaic systems is the elevated temperature of PV panels [1]-[2]. Improving the efficiency of these systems has emerged as a crucial goal to enhance energy production. To tackle the temperature challenge in PV systems, different cooling approaches have been investigated, including using the thermoelectric generator TEG [3]. TEG takes advantage of the west heat generated by PV panels, converting it into additional energy [4]. Thermoelectric devices can function as both coolers and generators, leveraging the Seebeck effect to transform thermal energy into electrical energy. Depending on the thermoelectric material used and the system configuration, it is noted that integrating thermoelectric generators (TEGs) into PV systems can produce additional electrical energy in the range of 2% to 10% [5].

The inclusion of (TEGs) in photovoltaic systems has recently received greater attention. Bjørk et al.[6] conducted numerical simulations to study the incorporation of TEGs into different types of photovoltaic cells: c-Si, a-Si, indium gallium copper selenide, and CdTe. They found that integrating TEGs into a-Si photovoltaic cells improved overall system performance compared with stand-alone photovoltaic cells. Faddouli et al.[7] analyzed the energy efficiency of a hybrid SWH-TEG system using numerical methods, showing that the hybrid system improved the storage process and generated additional electrical power of around 10.41W. Experimental studies were carried out by Kossyvakis et al.[8] to assess the impact of TEG integration with different thermoelement geometries in polysilicon and DSSC. The results highlighted the improvement in photovoltaic system power output when TEGs with shorter thermoelements were used. Yin et al.[9] conducted a one-day simulation to assess the efficiency of an HPV-TEG system. The authors discovered that by implementing a coupling system with a temperature coefficient (β_{ref}) of 0.002 K-1 and a figure of merit (Z) of 0.004 K-1, the overall performance improved, reaching 16.7% for the system. To boost the overall efficiency of PV systems, and enable electricity generation at night. Naderi et al.[10] carried out a numerical investigation on PV-PCM-TEG, revealing that the inclusion of PCMs with a thermoelectric generator reduced the temperature of the PV system from 74.43°C in standalone PV to 53.72°C in the PV-PCM-TEG system, and enhanced the overall efficiency.

This investigation aims to provide a detailed evaluation of the performance of PV-TEG hybrid systems, examining the effects of integrating TEG into the PV system. To achieve this, a one-dimensional mathematical model using the energy balance equation has been developed. The model enables us to simulate the behavior of PV and HPV-TEG systems. The developed model was solved using FDM and simulated using MATLAB 7.0.1.

II. METHODOLOGY

A. *Hybrid PV-TEG system configuration*

Fig.1 (a), illustrates the HPV-TEG system layout. The PV-TEG consists of a monocrystalline silicon photovoltaic panel with dimensions of 40 (W) × 40 (L) × 3(H) cm its properties are detailed in TABLE I. An aluminum back cover is placed just below the PV panel, with a thermoelectric generator (TEG) module measuring 40 mm × 40 mm placed under the back cover, directly connected. The TEG's hot surface is directly connected to the back cover's surface.

Fig.1 (b), illustrates the heat transfer process through the HPV-TEG system and the schematic of the TEG device, TEGs operate as solid-state components. The difference in temperature between TEG sides can result in a generation of electrical power, through the Seebeck effect. When one side of TEG is exposed to the heat and the other side kept cooler, a temperature difference is created across the device leading flow of charge carriers from the hot side to the cold side, generating an electrical current. The integration of TEG into the PV system is due to two reasons, firstly, is to generate additional electrical power via the Seebeck effect improving the power output of the HPV-TEG system, and secondly, reducing the PV panel temperature.
The TEG proprieties are detailed in TABLE II.

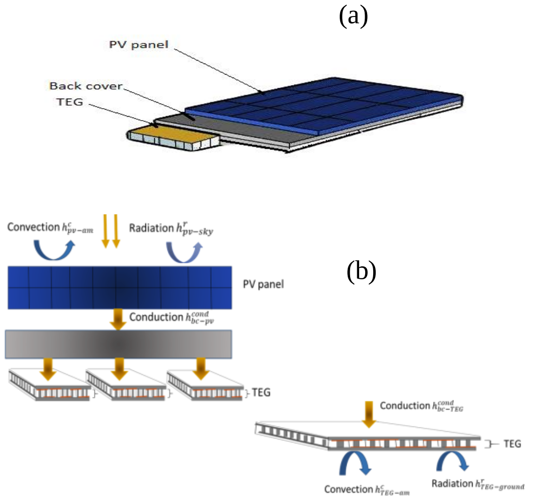

Figure 1. (a) PV-TEG hybrid system configuration, (b) heat transfer mechanism through the hybrid system

TABLE I. PV panel parameters **[11]**.

	Value	**Unite**
solar cell Density	2330	kg/m3
Thermal conductivity of PV panel	130	W/(m k)
Thickness of PV panel	0.03	m
Electrical efficiency	17	%
Absorptiry of PV	0.9	-
Temperature coefficient β_{ref}	0.0045	1/K

TABLE II. TEG proprieties [12].

	Symbole	**Value**	**Unite**
Figure of merit	ZT	0.0085	1/K
TEG Thermal conductivity	k_{TEG}	1.82	W/(mk)
Density of legs	ρ_{TEG}	7700	kg/m³
Seebeck coefficient	Sa	1.83 × 10− 4	V/K
Electrical resistance	R	3.8	Ω
Thermal resistance	Rt	0.85	K/W

B. *Mathematical model*

One-dimensional mathematical models have been developed based on energy balance equations to simulate the heat transfer through the system. The detailed modeling of the system is illustrated below. The developed model was simulated using Matlab software.

- PV panel

The heat is transferred into the PV module by convection between it and the ambient environment, by radiation from the sky, and by conduction between it and the back cover. The governing equation of the PV panel can be written as (1):

$$c_{pv}\rho_{pv}t_{pv}\frac{dT_{PV}}{dt} = h^{r}_{pv-sky}(T_{SKY}-T_{PV}) + h^{c}_{pv-amb}(T_{amb}-T_{PV}) + \alpha CG - CG\eta_{el} + \frac{k_{pv}}{t_{pv}}(T_{B}-T_{PV}) + \frac{1}{dx}\int_{-x}^{x} t_{pv}k_{pv}\frac{dT_{PV}}{dx} \quad (1)$$

Where $c_{pv}, \rho_{pv}, t_{pv}$ Represents the specific heat capacity of the PV panel, the density of PV panels, and the thickness of the PV panel, respectively. h^{r}_{pv-sky}, h^{c}_{pv-amb} denote the radiant and convective heat transfer coefficients,

$T_{sky}, T_{amb}, T_{B}, T_{PV}$ (K) Represents sky temperature $T_{sky} = 0.0375(T_{amb})^{1.5} + 0.35T_{amb}$, ambient temperature, back cover, and PV panel temperatures.

η_{el} is the electrical efficiency of a PV panel expressed by [13]:

$$\eta_{el} = \eta_{ref}(1-\beta_{ref}(T_{PV}-T_{ref})) \qquad (2)$$

η_{ref}, β_{ref} Are the PV panel electrical efficiency 17% and the temperature coefficient 0.0045K^{-1}, respectively.

- Back cover

The heat is transferred into the back cover by conduction between it and the PV panel, and conduction with the hot side of TEG Fig.1 (b).

The governing equation of the back cover can be written as:

$$c_B\rho_B t_B \frac{dT_B}{dt} = \frac{k_B}{t_B}(T_{pv}-T_B) + \frac{k_B}{t_B}(T_h-T_B) \quad (3)$$
$$+\frac{1}{dx}\int_{-x}^{x} t_B k_B \frac{dT_B}{dx}$$

- TEG hot and cold sides equations can be written as:

- TEG hot side:

$$c_{TEG}\rho_{TEG}t_{TEG}\frac{dT_h}{dt} = \frac{k_{TEG}}{t_{TEG}}(T_B-T_h) + \qquad (4)$$
$$N_{TEG}\ (S_a\ T_h\ I_{TEG} + \frac{(T_h - T_C)}{R_t} - \frac{1}{2}I^2_{TEG}R)$$

- TEG cold side

$$c_{TEG}\rho_{TEG}t_{TEG}\frac{dTc}{dt} = h^r_{c-g}(T_g - T_c) + h^c_{C-amb}(T_{amb}-T_C) \qquad (5)$$
$$+N_{TEG}\ (S_a\ T_C\ I_{TEG} + \frac{(T_h - T_C)}{R_t}) + \frac{1}{2}I^2_{TEG}R)$$

Where N_{TEG}, S_a denote the number of TEG modules and Seebeck coefficient. R_t denote the thermal resistance. Electrical resistivity of TEG represented by R, respectively. T_h, T_c, T_B Denote the TEG hot side temperature, TEG cold side temperature, and the back cover temperature, respectively.

I_{TEG} is the current of the TEG, it can be calculated by[12] :

$$I_{TEG} = \frac{S_a(T_h - T_C)}{2R} \qquad (6)$$

h^r_{c-g}, h^c_{C-amb} Denote the radiant and convective heat transfer coefficients,

III. Results and Discussion

A. Effect of integrating the TEG into the PV system

This section investigates the impact of integrating TEG into a PV system on PV temperature management and electrical efficiency. Fig. 2 (a) shows the PV system temperature variation over time with and without TEG. Solar radiation intensity and ambient temperature are assumed to be constant at 1000 W/m² and 25°C, respectively. In Fig. 2(a), the PV system temperature for the PV-TEG dropped to 345K compared to the temperature of the standalone PV panel, which rose rapidly to 355K. This drop in PV system temperature is attributed to the TEG's capacity to absorb the residual heat from the PV panel.

Fig. 2 (b) illustrates the electrical efficiency of the stand-alone PV panel and the HPV-TEG system. In Fig. 2 (b), the electrical efficiency of the stand-alone PV panel decreased to 12.5% after 60 minutes of operation, while employing the TEG in the PV panel increased its efficiency by 1.5%.

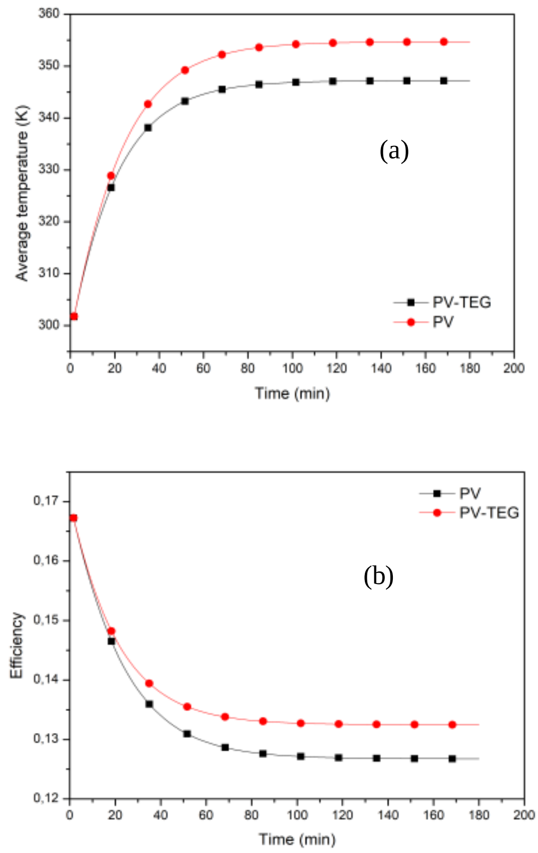

Figure 2. Effect of using TEG on (a) PV panel temperature, (b) electrical efficiency

B. Impact of varied solar radiation intensity on The Temperature and the conversion efficiency of HPV-TEG system

The impact of solar radiation on the HPV-TEG system performance is depicted in Fig. 3.

Four intensities have been tested in this section namely: 400 W/m², 600W/m², 800W/m² and 1000W/m². The results showed that the PV temperature increased as the solar radiation intensity increased, and the photovoltaic temperatures reached 315, 325, 335, and 345 K for the intensities of 400, 600, 800, and 1000 W/m², respectively. This is attributed to the fact that PV panels convert only a fraction of the incident solar irradiation into electricity, with the remainder dissipating as heat and contributing to the elevated PV panel temperature.

An increase in PV panel temperature adversely affects its electrical efficiency. As illustrated in Fig. 3, the electrical efficiency drops when the solar radiation intensities increase and reach 13.3, 14, 14.8, and 15% for 1000, 800, 600, and 400 W/m², respectively.

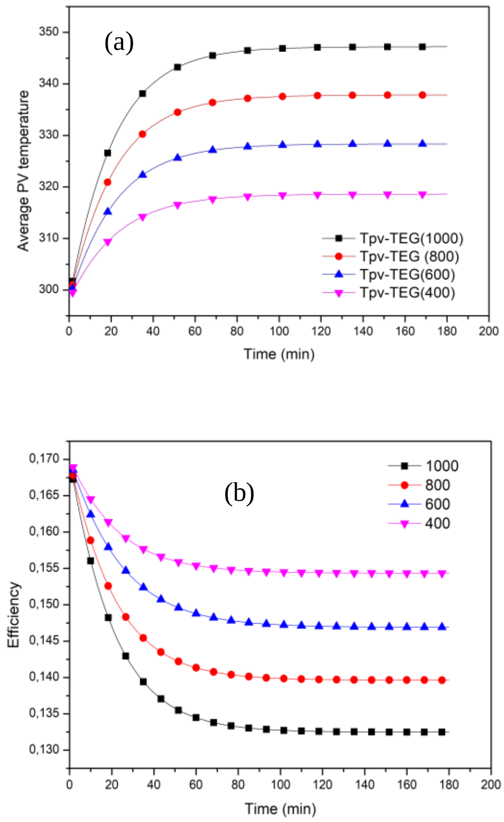

Figure 3. Variation of PV temperature (a), and PV electrical efficiency (b), according to the variation in solar radiation

C. *TEG power output*

A crucial factor influencing the power output of the (TEG) is the presence of a temperature difference (ΔT) between the hot and cold sides.

The power output of TEG can be calculated according to the formula [14]:

$$\mathbf{P_{TEG}} = S_a(T_h - T_C)\mathrm{I_{TEG}} - I_{TEG}^2 R = \frac{Sa^2(T_h - T_C)^2}{4R} \quad (7)$$

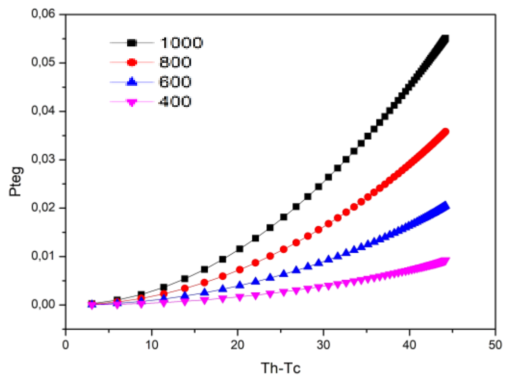

Figure 4. The power output of TEG under varied solar radiation intensity

Fig.4 represents the variation in TEG power generation output under varied solar radiation intensity. As shown in Fig. 4, the increase in the temperature difference between the hot and the cold sides of TEG $(T_h - T_C)$ leads to a noteworthy improvement in thermoelectric performance. At 1000 W/m², TEG output power peaks at 0.05 W. Decreasing solar radiation intensity results in a reduction in TEG power output, with values of 0.035 W, 0.015 W, and 0.005 W recorded for 800, 600, and 400 (W/m²), respectively. Nevertheless, the power output of TEG units is significantly lower than the electrical output of photovoltaic panels.

Poor productivity and materials failure at high-temperature operations are considered the main obstacles affecting the effectiveness of the application of TEG to residual heat recovery.

D. *Effect of the number of TEG module used on PV performance*

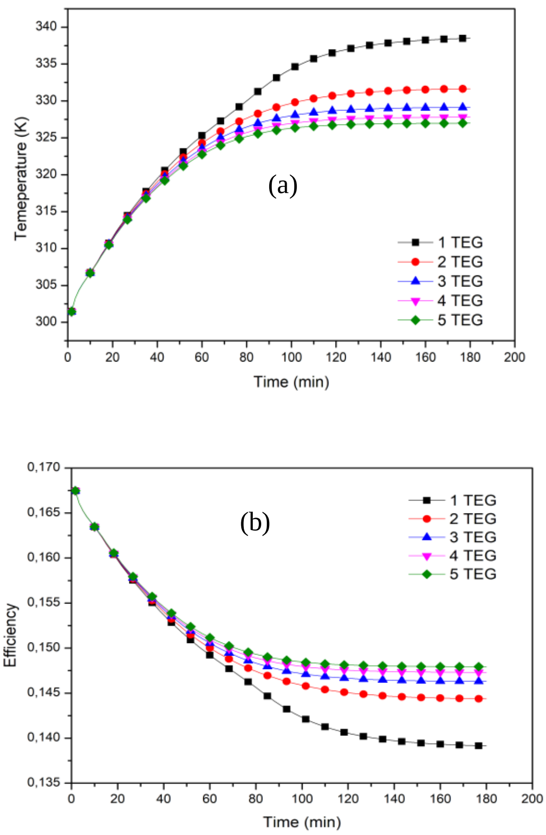

Figure 5. Impact of the Number of TEG modules used on (a) PV temperature, (b) electrical efficiency

Fig. 5 shows the effect of the number of TEG employed in the hybrid system, on the PV temperature Fig. 5(a) and the efficiency of the PV panel Fig. 5(b).

Increasing the number of TEGs can result in a decrease in the system's temperature Thus, numerous TEGs can help to absorb the heat from the back cover leading to a decline in the system temperature. The electrical efficiency is enhanced by increasing the number of TEG units used, as depicted in Fig. 5(b).

IV. Conclusion

We have studied the effect of incorporating TEG into the PV system in this investigation. The key findings of this investigation are summarized as follows:

- The incorporation of TEG with the PV system decreased the PV average temperature by 10 K and improved the PV conversion efficiency by 1.5% compared to the standalone PV panel.
- Increased solar radiation intensities lead to higher PV average temperatures, with a 10 K increase for every 200 W/m² rise in solar radiation. Although this negatively affects PV conversion efficiency, it increases the temperature difference between the TEG hot and cold sides, improving TEG output and conversion efficiency.
- The power output of TEG units is significantly lower than the electrical output of photovoltaic panels.
- Increasing the number of TEG modules used reduced PV temperature and improved electrical efficiency.
- The low productivity of the TEG at higher temperatures is a limitation of this technology when applied to West heat recovery.

Despite TEG's effectiveness in improving PV efficiency, it suffers from low productivity due to the small temperature difference between the hot and cold sides of TEG. Future research will aim to enhance PV-TEG efficiency by integrating phase change material into the system.

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