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A New Simulation of Photovoltaic and Thermoelectric Generator Hybrid System with a Beam Splitter Cold and Hot Mirror for Low Intensity

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Abstract – *In this study, the simulation of Photovoltaic (PV) and Thermoelectric Generator (TEG) hybrid was developed using a spectrum splitter. The simulation was carried out by using the AM1.5G solar spectrum as a standard for 1 Sun, with a variation of 0.05, 0.1, 0.25, 0.50, and 0.7 Suns. The light spectrum was concentrated by using a Fresnel lens and then transmitted to a spectrum splitter. Spectrum splitter that was used is a hot and cold mirror with dimensions of 50 × 50 mm, which is positioned at the angle of 45^o from the Fresnel lens's direction. Additionally, PV used is a type amorphous Silicon (a-Si) and TEG types of Bismuth telluride (Bi_2Te_3). The simulation result shows that by using a cold mirror, its maximum total power is better than a hot mirror. In addition, the Suns and temperature changes have a significant effect on the output power and efficiency of the hybrid. Particularly at 0.7 suns, 25 °C PV temperature, and 55 °C hot-side temperature of TEG, the power obtained was 0.096 W/m^2, and the efficiency was 50.37% compared to the hot mirror, which is relatively lower, accounted for 0.094 W/m^2 and 48.07%.*

***Keywords**: Light Spectrum, Photovoltaic, Thermoelectric Generator, Output Power, Efficiency*

Nomenclature

PV	Photovoltaic
TEG	Thermoelectric
I-V	Current-Voltage
P-V	Power-Voltage
E_{PV}	Energy passed to PV
E_{TEG}	Energy passed to TEG
F	Spectral Irradiance
λ	Wavelength
I_{ph}	Photocurrent [A]
I_s	Diode current [A]
I_{rs}	Resistance current [A]
I_{sc}	Short circuit current [A]
I_{pv}	Output current PV module [A]
I_{MP}	Maximum power current [A]
V_{pv}	Output voltage PV module [V]
V_{MP}	Maximum power voltage [V]
VOC	Voltage Open Circuit [V]
R_s	Series resistance [Ω]
R_h	Shunt resistance [Ω]
q	Electron charge (1,602 × 10^{-19} C)
k	Boltzman Constant (1,38 × 10^{-23}J)
T	PV temperature [K]
N_s	Number of series cells in the module
N_p	Number of parallel cells in the module
Eg	Energy gap (1.65)
A	Ideality factor = 1
A_{PV}	Surface area PV modules [m^2]
Q_H	Heat absorbed
Q_C	Heat released
T_H	Temperature Hot side
T_C	Temperature Cold side
α	Seebeck coefficient
κ	Thermal conductivity
R	Resistance

I. Introduction

The photon energy is part of the total energy emitted by the sun, which arrives on the Earth. Sunshine in the shape of the electromagnetic wave spectrum can be divided according to its wavelength. Visible light has a wavelength range of 400-700 nm and suitable for the needs of photovoltaic cells (PV) to generate electrical energy [1]. Photons energy absorbed by the PV cells from the solar radiation beam dramatically affects the output power [2]. Various developed methods have been done to improve the energy conversion efficiency in PV, starting from using air and liquid media as a cooler, as well as combining it with the thermoelectric generator (TEG) [3]-[5]. TEG is a technological device that can convert thermal energy into electrical energy based on the Seebeck effect. Heat potential of the solar spectrum at wavelengths above > 700 nm, which is not absorbed by the PV can be used by TEG [6]. The development of a PV-TEG hybrid system to improve efficiency is increasingly popular and has been carried out in two major models of PV-TEG hybrid, both experimental and theoretical [7]-[9]. Vorobiev et al. [10] conducted an

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experiment and simulation to analyze the power and efficiency of the PV-TEG hybrid system, wherein the simulation of the software used in COMSOL Multiphysics 4.4 software (COMSOL Inc. MA, USA). In their research design, the Fresnel lens, which is positioned next to PV, was used to focus the light on TEG. TEG modules were attached below a black painted aluminum plate and mounted on a water-cooled heat sink. Inside the heat sink, fluid circulated thermosiphon.

The results showed that the efficiency of TEG is 2.5-3.5%, while the efficiency of the PV is 10.74%.

However, this study had not yet shown TEG hybrid PV systems as an integrated unit. Another way of combination for a more integrated PV-TEG, performed with the light spectrum splitting system. Elsarrag et al. [11] conducted simulations and experiments on PV-TEG hybrid in a laboratory scale by using cold mirror as a splitter of visible light (Vis), ultraviolet (UV) for PV, and infrared (IR) for TEG with some variations in the radiation intensity of 0.5, 0.7 and 1.1 Suns. The results showed that the radiation intensity that produces the best efficiency is at 0.7 Sun. They further illustrated that the effect of using cold mirrors is beneficial on cold PV power production at low intensity (<700 W/m^2) with an average temperature of 60^{o}C, and the efficiency of TEG is still low due to the low heat absorbed by the module. Mustofa et al. [12] conducted experimental hybrid PV-TEG using a hot mirror as spectrum splitter, which was mounted on the angle of 45 °C to separate Vis and IR spectrum of artificial suns (xenon, halogen, and incandescent bulbs) used a Fresnel lens to focus. This result only shows the wavelength and radiation on each bulb with an average of 13.85, 15.02, and 29.58 W nm, which is measured in real-time within 60 minutes, while the amount of power divided into PV and TEG is not described in detail. However, Piarah et al. [13], in their research, described the spectral irradiance of artificial suns, which was quite comprehensive. In their research, a hot and cold mirror as a spectrum splitter for Halogen light was used experimentally. The lowest radiation reference used is around 0.05 Sun, which is a small amount compared to sunlight radiation (1 Sun). Since Elsarrag et al [11] got the best result at 0.7 sun at intervals (0.5, 0.7, 0.8 and 1.1 Sun), this study will stimulate a spectrum of solar radiation with several Sun variations from 0.05 to 0.7 (0.05, 0.1, 0.25, 0.5 and 0.7) as spectrum input. This input spectrum variation is important to get the best intensity in the low lights intensity category by using a light spectrum of bulbs close to the solar spectrum, as in the intensity and spectral irradiance the type of bulb that approaches the solar spectrum from the results of Doolittle's study [14].

Not much research has examined the potential for this low spectrum power, especially in the light intensity category of the bulb, which can function as a source of PV and thermal photon energy for TEGs that are converted into electrical energy. Initial investigations by Piarah et al. [13] with a 50 W Halogen bulb had been done. However, only one type of bulb does not provide a general description of the light spectrum of the low-intensity light category. Therefore, this simulation study tries to cover a relatively long interval of low-intensity spectrum from 0.05 to 0.7 sun as mentioned above.

Furthermore, the study of this low spectrum category will later contribute to the characterization of the light spectrum intensity of the light bulb in the indoor scale category, which not only functions as lighting but can also serve as an input source for the re-conversion of electrical energy.

This simulation study begins by putting the PV-TEG hybrid system using a mathematical model (explained in Sections II.1 and II.2) on MATLAB/SIMULINK and its specifications as input (Table I and II). Hence, the replacing of PV and/or TEG modules is done only by changing the specification of the modules used. The selection of the PV module is adjusted to the input of the radiation spectrum or low light intensity and the TEG specifications to the operating temperatures. Besides the PV and TEG module specifications, also the Fresnel Lens, Hot/Cold Mirror specifications, and the variations of the radiation spectrum from 0.05 to 0.7 Sun are included as input to calculate hybrid output power and efficiency.

TABLE I
TYPE OF PV: ASC 4040 SPECIFICATIONS DATA

Components	Parameter	Value
P	Maximum power	0.082 V
V_{MP}	Maximum power voltage	1.85 W
I_{MP}	Maximum power current	0.0443 A
V_{OC}	Open circuit voltage	2.4 A
I_{SC}	Short circuit current	0.0541 A
L×W×H	Dimensions	50×50 mm

TABLE II
TYPE OF TEG: TGM 199-1.4-2.0 SPECIFICATIONS DATA

Components	Parameter	Value
P	Output power	7.3 W
V	Load voltage	5.2 V
I	Current	1.41 A
R	Resistance	3.7 Ω
T_H	Hot site temperature	200 °C
T_C	Cold site temperature	30 °C
L×W×H	Dimensions	40×40×4.4 mm

II. Materials and Methods

Light propagation from source to PV and TEG is shown in Fig. 1. In this simulation, the light spectrum splitters used are Hot Mirror and Cold Mirror type dichroic filter, which split Vis and IR light. These mirrors are placed under the Fresnel lens to form a 45° angle perpendicular to the radiation source and the lens.

Hot and Cold mirror spectrum splitter used are TechSpec AOI cold and hot mirror by the dimensions of 50×50 mm [14], while the PV used is Amplesun 4040 PV commercial Amorphous Silicon (a-Si) thin films [15] and TEG Bismuth Telluride (Bi_2Te_3) types [16]. The light spectrum is concentrated using Fresnel lenses [17] and directed to a hot mirror or cold mirror. The light spectrum that arrives at the hot mirror and the cold mirror will be slotted according to PV and TEG requirements. In the hot mirror, some will be transmitted in the form of Vis to PV, and some others will be reflected in the form of IR to TEG; on the contrary, in the cold mirror, the reflected light is directed to PV and transmitted to TEG.

The light spectrum concentrated by Fresnel lenses is considered to meet the area of hot mirror and cold mirror, while the area of PV and TEG are made equally significant. The light energy arriving at hot and cold mirrors can be expressed in the following equation [18]:

$$E_{PV} = \int_{400\text{ nm}}^{700\text{ nm}} F(\lambda)\,d\lambda \tag{1}$$

$$E_{TEG} = \int_{700\text{ nm}}^{1150\text{ nm}} F(\lambda)\,d\lambda \tag{2}$$

E_{PV} is the amount of energy passed to PV; E_{TEG} is the amount of energy passed to TEG, while F is the spectral irradiance, and λ is the wavelength. AM1.5G spectrum data was used as a reference to estimate the spectrum separation value. The power potential with Suns variation (0.05, 0.1, 0.25 0.5 0.7) is shown in Fig. 2.

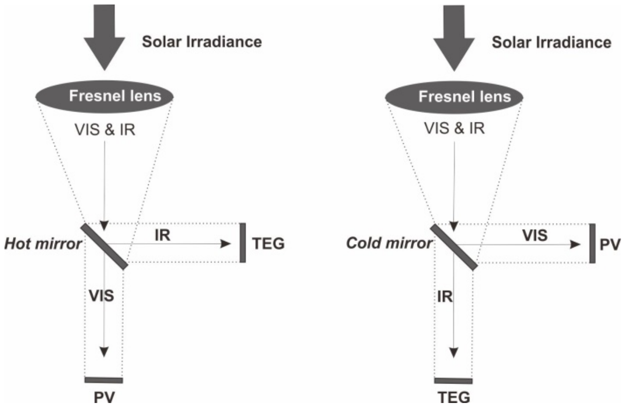


Fig. 1. Scheme of a hybrid PV-TEG system
with hot and cold mirror

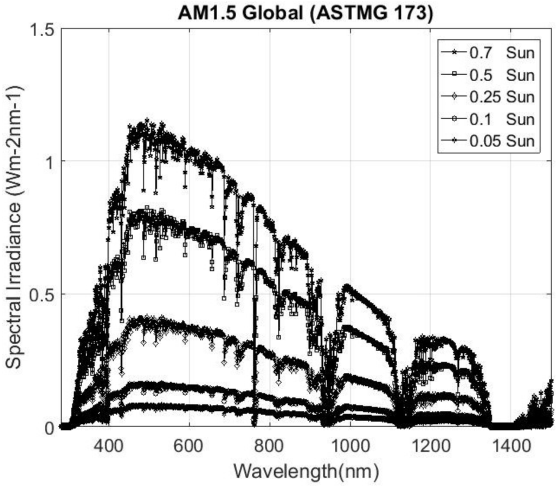


Fig. 2. AM1.5G Suns Spectrum Data (0.7, 0.5, 0.25, 0.1, 0.05)

According to the specifications of the Fresnel lens, only 92% of the light is transmitted to hot/cold mirrors.

Further, the hot mirror specification used in this simulation transmitted 90% of the light to PV, and 95% was reflected to TEG; on the contrary, The cold mirror reflected 95% of light to PV and 90% to TEG.

II.1. PV Mathematical Model

The PV module consists of PV cells that are assembled in series. The absorbed energy will make the electrons to generate electricity. The ideal PV cell is modeled as a single diode circuit, as shown in Fig. 3.

I_{ph} is the current of the photon that is generated, I_s is the diode current, and I_{rs} is the resistance current. Inside the PV cell, R_s is the series resistance, and R_{sh} is the parallel resistance. In the ideal analysis, the resistance value of R_s is considered very small, and R_{sh} is very large.

The mathematical models of PV modules are expressed in equations (3) and (4) [19] below [25]-[29]:

$$I_{pv} = I_{ph} - I_s - I_{rs} \tag{3}$$

$$I_{pv} = N_p I_{ph} - N_p I_s \left[\exp\left(\frac{qV_{pv} + I_{pv}R_s}{N_s kAT}\right) - 1\right] + \\ - \frac{V_{pv} + I_{pv}R_s}{R_h} \tag{4}$$

The maximum power generated from PV can be calculated by the equation:

$$P_{MP} = V_{MP} I_{MP} \tag{5}$$

While the maximum efficiency of PV is expressed as an equation :

$$\eta_{MP} = \frac{I_{MP} V_{MP}}{G A_{pv}} \tag{6}$$

II.2. TEG Mathematical Model

A thermoelectric generator (TEG) is an energy conversion device that can directly convert thermal energy into electrical energy with the working principle of the Seebeck effect.

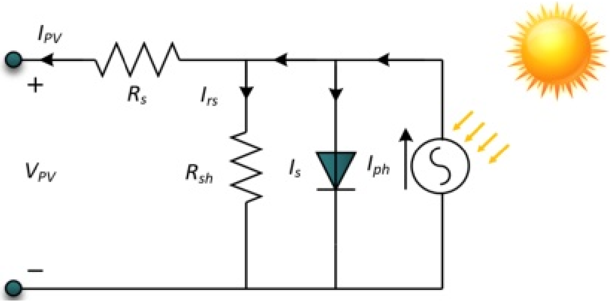


Fig. 3. The PV cell series model is one diode

The temperature difference between the hot side and the cold side of the module generates voltage and flows electric current. The heat absorbed by the hot side Q_H and the cold released by the cold side Q_C is expressed in the equation [20]:

$$Q_H = \alpha I_{TEG} T_H + K\left(T_H - T_C\right) - 0.5RI_{TEG}^2 \tag{7}$$

$$Q_C = \alpha I_{TEG} T_H + K\left(T_H - T_C\right) - 0.5RI_{TEG}^2 \tag{8}$$

where α is the Seebeck coefficient. R is the internal resistance, and K is the thermal conductivity. The output power generated is expressed in the equation:

$$\begin{aligned} P_{TEG} &= V_{TEG} I_{TEG} = Q_H - Q_C = \\ &= \alpha I_{TEG}\left(T_H - T_C\right) - RI_{TEG}^2 \end{aligned} \tag{9}$$

So the voltage equation can be written as follows:

$$V_{TEG} = \alpha\left(T_H - T_C\right) - RI_{TEG} \tag{10}$$

While the voltage in the open circuit is expressed by the equation:

$$V_{CO} = \alpha\left(T_H - T_C\right) \tag{11}$$

Efficiency can be calculated by the equation:

$$\eta_{TEG} = \frac{V_{TEG} I_{TEG}}{Q_H} \tag{12}$$

III. Results and Discussion

The PV and TEG mathematical models have been explained separately in Sections II.1 and II.2. In this section, PV and TEG hybrid were carried out and simulated with several variations of irradiation that arrived at the Fresnel lens, as well as the temperature’s variation of the PV module and TEG hot side. In the simulation conducted, it can show optimal conditions which can produce output power and maximum efficiency. The specifications of lense, mirrors, and modules (PV and TEG) are shown in Tables I-IV.

TABLE III
FRESNEL LENS SPECIFICATIONS DATA

Components	Parameter	Value
L×*W*×*H*	Dimensions	250×135×0.50 mm
	Maximum operating temperature	80 °C
	92% Transmission from	400-1100 nm

TABLE IV
HOT MIRROR SPECIFICATIONS DATA

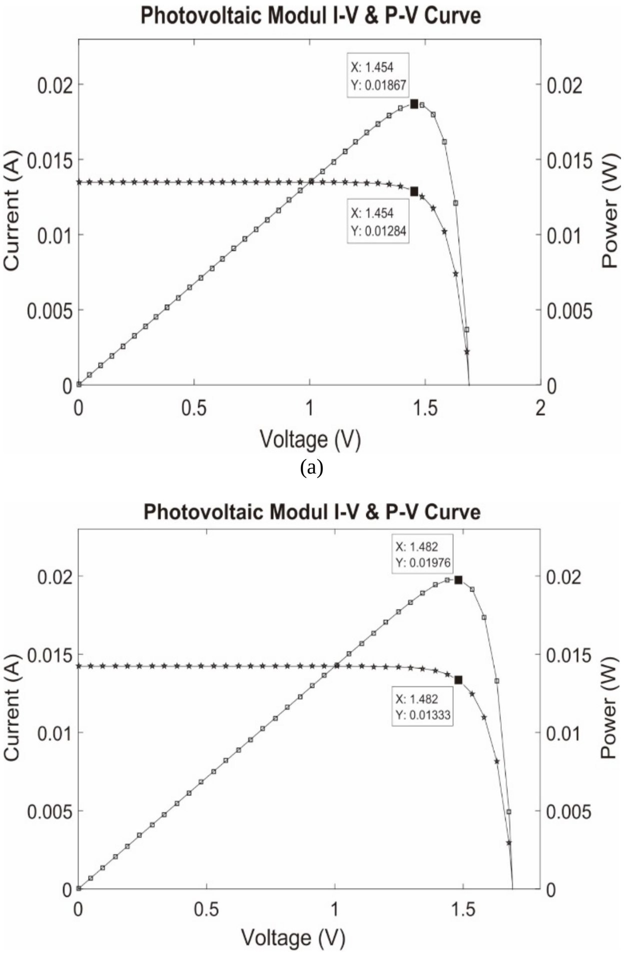
Components	Parameter	Value
L×*W*×*H*	Dimensions	40×40×1 mm
	Angle of incident	45 °C
	>90% Transmission from	400-690 nm
	>95% Reflections from	710-1150 nm

TABLE V
COLD MIRROR SPECIFICATIONS DATA

Components	Parameter	Value
L×*W*×*H*	Dimensions	40×40×1 mm
	Angle of incident	45 °C
	>90% Reflections from	400-690 nm
	>95% Transmission from	710-1150 nm

Simulation results from PV-TEG hybrid show that with the AM1.5G spectrum, the hot mirror transmitting radiation power of 268.470 W/m^2 to PV and reflects 216.159 W/m^2 to TEG. Instead, the cold mirror reflects 283.385 W/m^2 to PV and transmits 204.782 W/m^2 to TEG. The current and output power characteristics as a function of voltage in PV are shown in Figs. 4. Initially, a constant current was followed by an increase in output power, until a specific voltage, both current and power drop dramatically. The optimal power for hot mirror is 0.269 W/m^2 at a voltage of 1.967 V, and the highest current is 0.137 A. For cold mirror, it is 0.285 W/m^2 at 1.967 V and 0.145 A. Calculation of efficiency at the maximum point indicates that using cold mirror is relatively better than hot mirror (62.9% > 62.73%).

These results almost reach the efficiency value (66.3%) that was obtained by Ju et al. [21] that uses a concentrator.



(a)

(b)

Figs. 4. Characteristics of I-V and P-V curves for 0.7 Sun: (a) Hot Mirror; (b) Cold Mirror

In TEG, irradiation spectral form does not affect the output power because the TEG output power is only affected by the difference in hot side temperature and the cold side of the module, so that the output characteristics for hot and cold mirrors will be the same as long as the hot and cold side temperature differences are the same. In Figs. 5, the characteristics of the voltage and output power are seen as a function of the current for TEG at hot side temperatures T_H=60 °C and the cold side T_C=30 °C.

As the current increases, it is followed by a decrease in voltage, while the output power forms a parabolic characteristic.

The optimum power produced for hot and cold mirrors has the same value of 0.227 W/m^2 at a voltage of 0.920 V and a current of 0.247 A. From the calculation of the efficiency of TEG, a value of 1.418% is obtained. This result is lower than Ju et al. [21] as they use additional elements of the heat collector and heat sink to increase heat absorption and also by using 1 Sun's irradiance. In this study, the overall maximum efficiency of hybrid PV-TEG using hot mirror was 0.496 W/m^2 and 64.14%, while PV-TEG cold mirrors were 0.512 W/m^2 and 64.31%.

III.1. Irradiation Variations in PV

Figs. 6 and 7 show the simulation results of irradiation variations for PV (0.05, 0.1, 0.25 0.5 and 0.7 Suns) at a standard temperature of 25 °C.

This result shows the sensitivity of changes in irradiation towards the value of the current produced by PV.

The absorbed irradiation intensity value is directly proportional to the value of the current coming out of the PV cell, which is also in line with the results obtained by [18], [19]. For the output power, as shown in Figs. 7, it can be seen that the change in radiation intensity also immensely affected the output power generated. The exciting thing that is shown is the exponential shift in the peak point.

Another thing that is found out in this simulation is the value of the output power by using a cold mirror is higher than the hot mirror.

III.2. Temperature Variations in PV

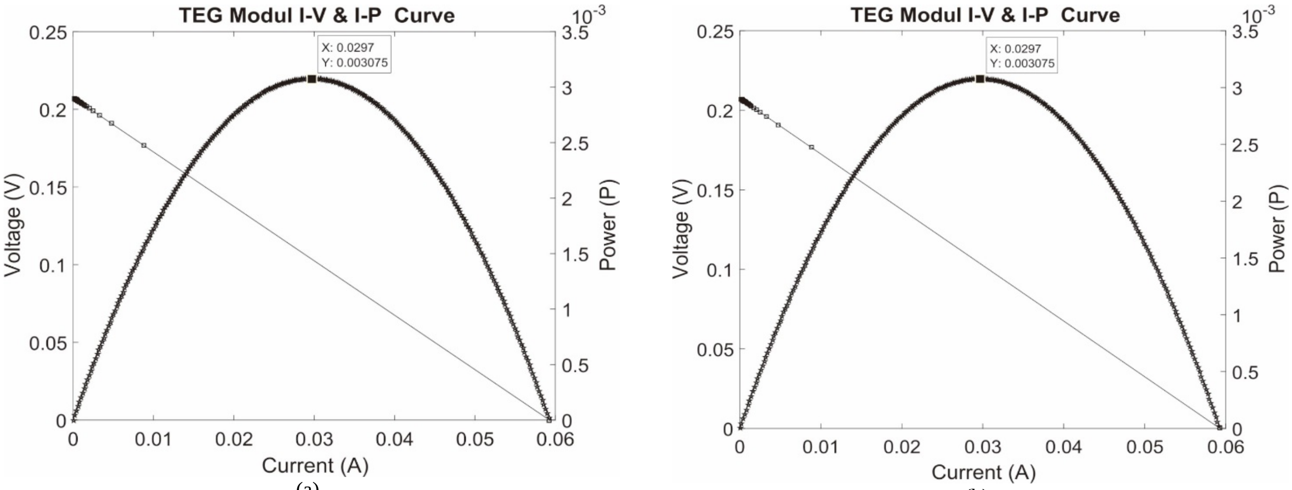
Figs. 8 and 9 show the temperature variations of the PV module from 25 to 45 °C, precisely at 25, 30, 35, 40, and 45 °C at constant intensity 0.7 Sun. The increase in temperature causes an increase in current, on the contrary, a decrease in the voltage. The reduction ratio of voltage is higher than the increasing ratio in current so that the output power decreases. In other words, the increase in PV module temperature will cause the output power to be degraded.

III.3. Temperature Variations in TEG

Figs. 10 and 11 show the effect of temperature changes on I-V currents on TEG.

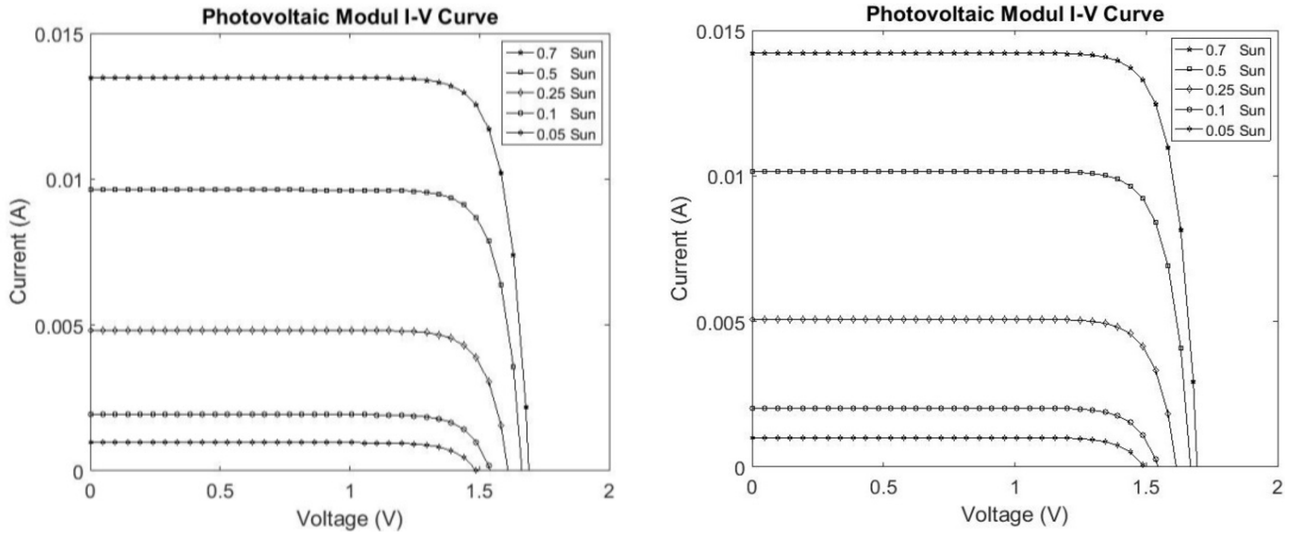
The hot side temperature varied from 60 to 120 °C, precisely at 60, 80, 100, and 120 °C, where the cold side temperature T_C as made constant at 30 °C. It appears that the increase in hot side temperature greatly influences the value of current (I), voltage (V), and output power (P) that comes out of TEG. Current and voltage are inversely proportional, while power forms parabolas with increasing current.

An increase in temperature causes an increase in output power, where the maximum point shifts exponentially. Increasing the temperature from 60 °C to 120 °C causes an increase in power from 0.227 W/m^2 to 2.050 W/m^2 and an efficiency of 1.418 to 3.178%.



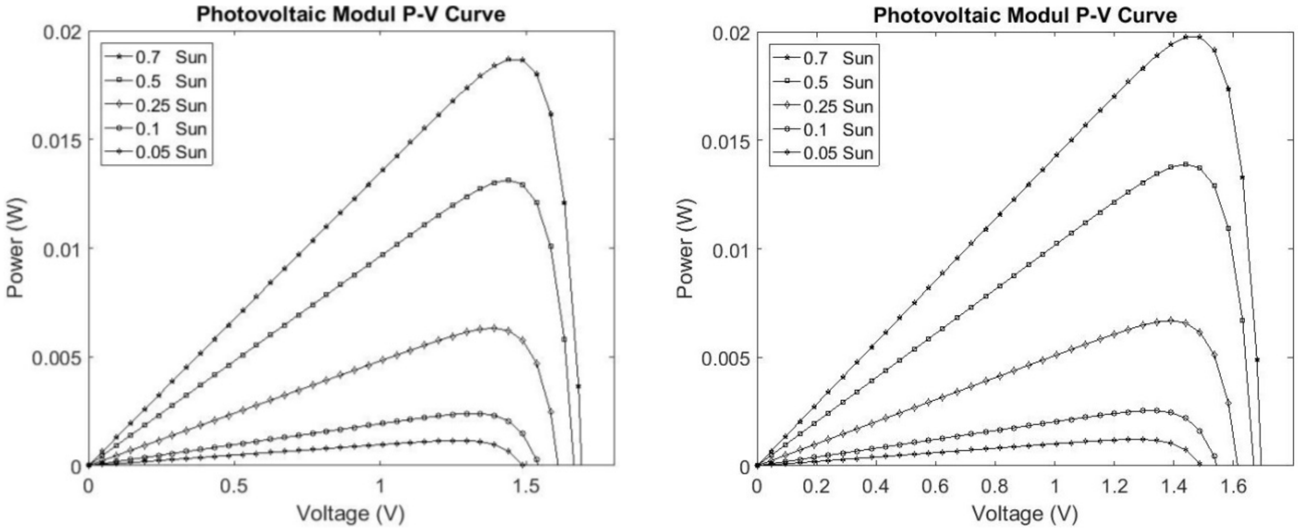
(a) (b)

Figs. 5. Characteristics of I-V and I-P curves in TEG for T_H = 35 °C and T_C = 30 °C: (a) Hot Mirror; (b) Cold Mirror



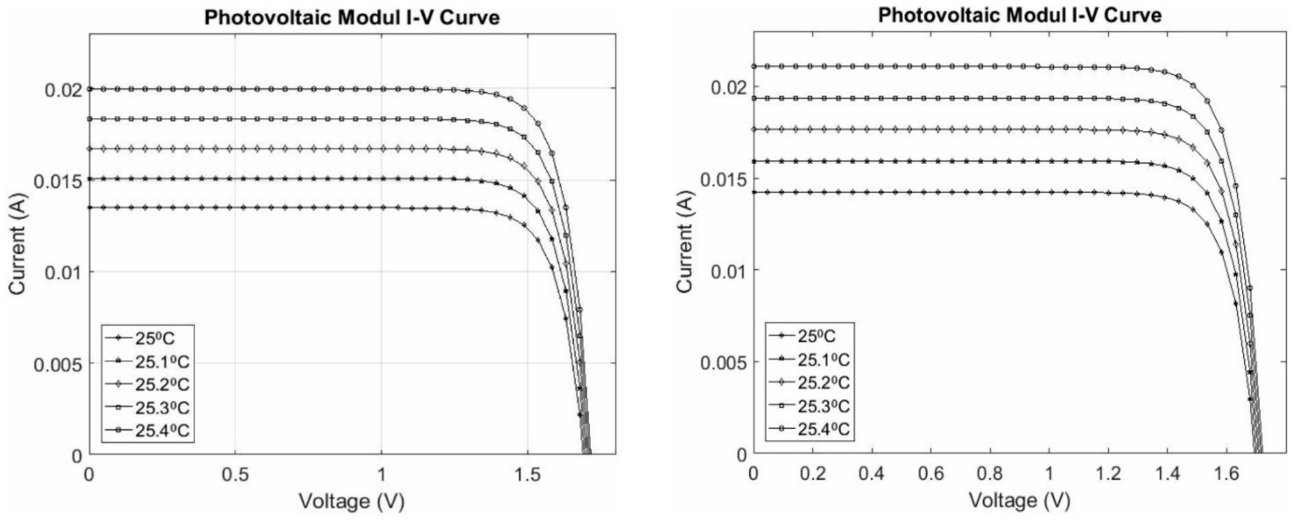
(a) (b)

Figs. 6. I-V radiation change curve: (a) Hot Mirror; (b) Cold Mirror



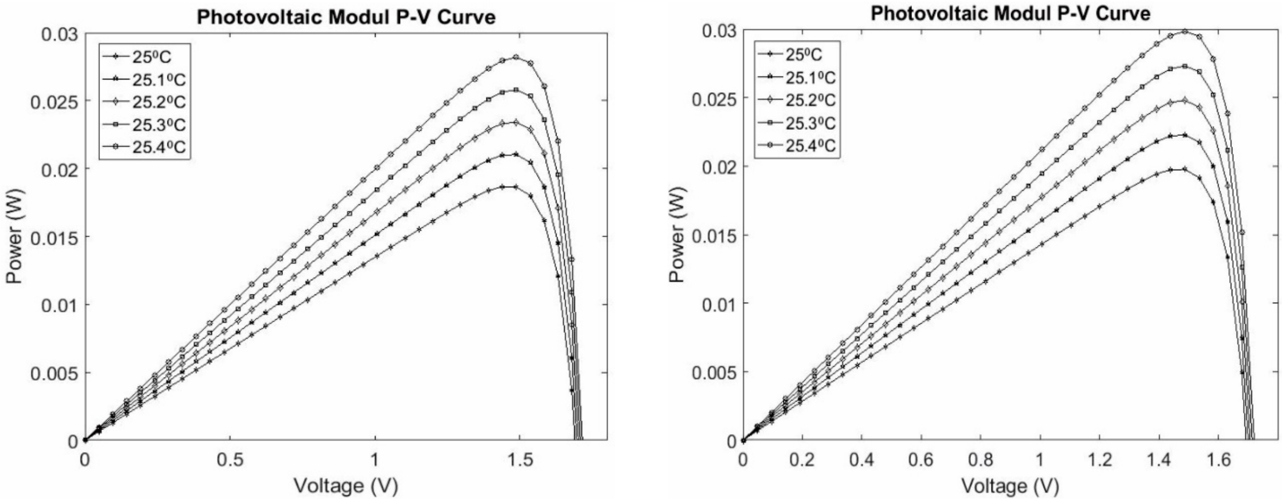
(a) (b)

Figs. 7. P-V radiation change curve: (a) Hot Mirror; (b) Cold Mirror



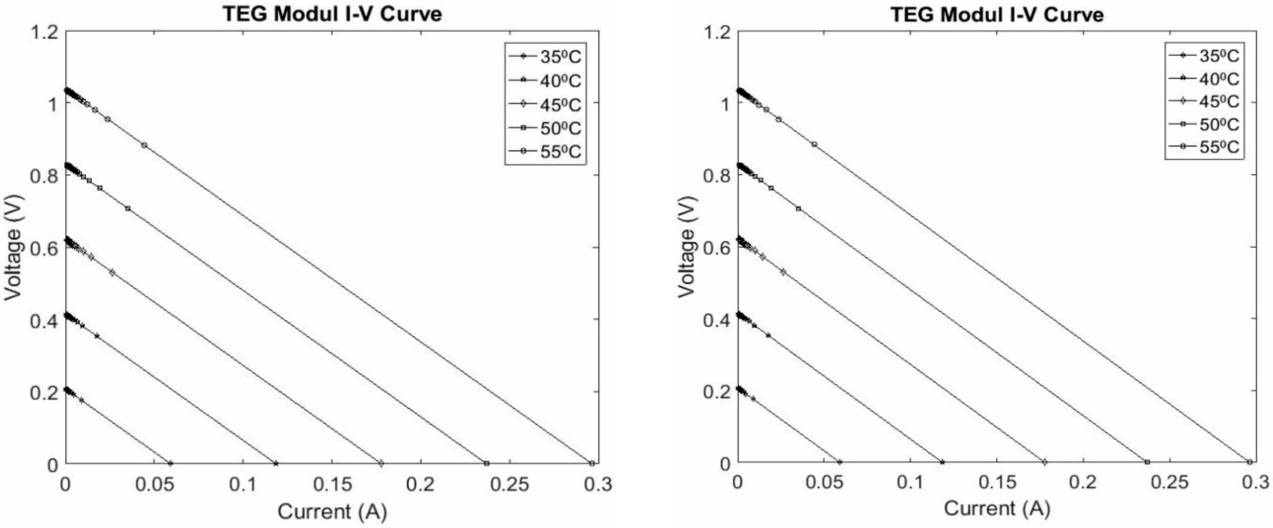
(a) (b)

Figs. 8. I-V temperature change curve: (a) Hot Mirror; (b) Cold Mirror



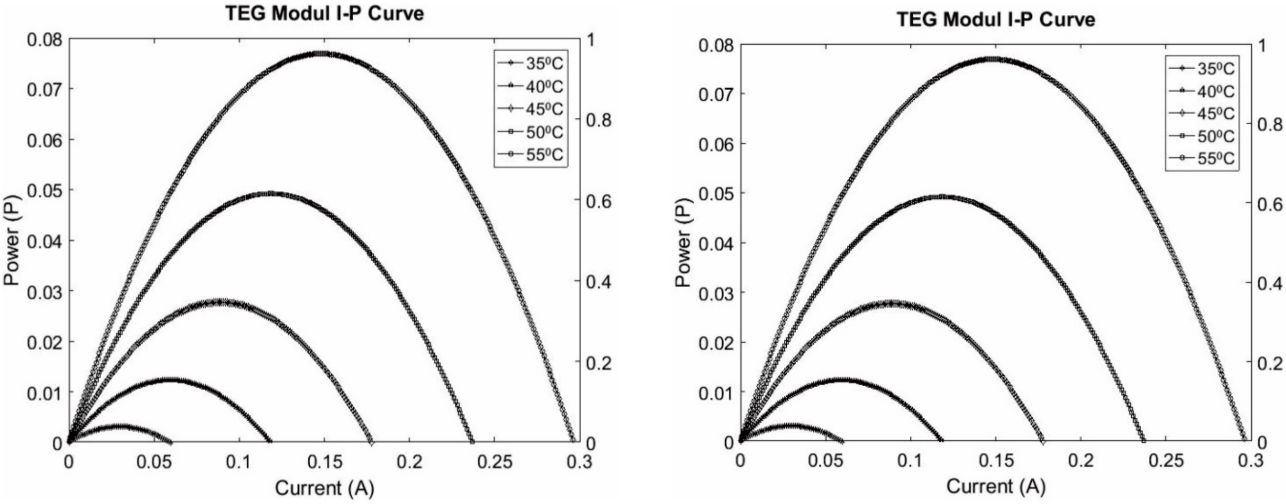
(a) (b)

Figs. 9. P-V temperature change curve: (a) Hot Mirror; (b) Cold Mirror



(a) (b)

Figs. 10. I-V temperature change curve in TEG: (a) Hot Mirror; (b) Cold Mirror



(a) (b)

Figs. 11. I-P temperature change curve in TEG: (a) Hot Mirror; (b) Cold Mirror

IV. Conclusion

The PV-TEG hybrid system simulation results using hot and cold mirrors have different results. Using a cold mirror shows better results than a hot mirror. This is because the magnitude of spectrum power per square (283,385 W/m^2) reflected by the cold mirror to the PV is higher than the spectrum power transmitted by the hot mirror (268,470 W/ m^2) to the PV. The simulation results also show that the variation of irradiation and temperature in PV dramatically affects the power output and efficiency. An increase in irradiation causes parameters such as current and voltage to increase, but an increase in temperature in PV can also cause parameters such as current and voltage to decrease so that the output power and efficiency decreases. Whereas in TEG, a very influential aspect is the difference between the hot side and the cold side temperature. An increase in temperature in the TEG results in an increase in current and voltage so that the output power and efficiency increase. The maximum power per square generated by a hot mirror on a hybrid PV-TEG system is 0.094 W/m^2 and the efficiency is 48.07%, while with a cold mirror TEG is 0.096 W/m^2 and efficiency is 50.37% on the 0.7 Sun spectrum, with a PV temperature of 25 °C on the hot side of TEG 55 °C. A further review is needed by installing air cooling to maintain temperature stability in both PV and TEG modules leading to an increase in output power and efficiency.

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