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Low Sun Spectrum on Simulation of a Thin Film Photovoltaic, Heat Absorber, and Thermoelectric Generator System

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The research presents the simulation results with Matlab on combining of a type of thin-film photovoltaic module (a-Si), a copper plate heat absorber with thermoelectric generators (TEG) utilizing the standard low-sun spectrum AM1.5G at 0.05, 0.06, 0.07, 0.08, 0.09 and 0.1 Sun as a source of radiation. Amorphous silicon is a type of thin-film solar cell that is more suitable for indoor use so that by using a source of low-intensity light radiation from the sun will still generate electrical energy conversion. Spectrum splitting is used as a cold mirror, which reflects the spectrum of light to the a-Si module in the form of photon energy while transmitting to the TEG module the spectrum of near-infrared light radiation in the form of heat. On the hot side of the TEG, a copper plate was placed to accommodate the heat from light radiation to increase convection heat transfer and temperature differences between the hot and cold sides of the TEG. The simulation results show that the highest efficiency of a-Si module is 3.46% achieved at the lowest spectrum of 0.05 Sun, vice versa TEG is at the highest spectrum at 0.1 Sun and 10.05% its efficiency. This low sun spectrum will be a milestone in the utilization of bulb radiation energy in general domestic needs.

Key Words

Thin-film, Low-sun spectrum, Cold mirror splitter

1. Introduction

The characterizations of hybrid of a photovoltaic (PV) module that require photon energy with a thermoelectric generator (TEG) module at the standard of AM1.5G as spectral distribution solar energy radiation source are of concern to researchers to study to achieve optimum PV-TEG electrical energy conversion needs. It is obtained by placing the TEG module under the surface of the PV that functions as a cooler as well as receiving the excess photon energy received by the PV surface. This PV and TEG position can be called a cascade PV and TEG hybrid configuration [1)~3)]. The weakness of this configuration requires a DC electrical energy source on the TEG. Next, the cascade PV-TEG model does not show the splitting of the wavelength spectrum of radiation received by the two modules according to their electrical energy conversion requirements. The solution is to split the wavelength spectrum of the light from the spectrum beam splitter so that the TEG is not attached to the backside of the PV module anymore. Kraemer ***et al.*** [4)], with solar spectrum splitter and Tritt ***et al.*** [5)], with wavelength segregation initiated a review of the concept of spectrum splitting through simulations that utilize AM1.5G spectrum. Some researchers continue this concept [6)~9)] by using a standard spectrum. Ju ***et al.*** [6)] conducted a simulation that split the solar spectrum of a hot mirror type, Jadin ***et al.*** [7)], with hybrid system modeling, unfortunately, did not explain the type of spectrum splitter used. Elsarrag ***et al.*** [8)] investigated the splitting of the solar spectrum with a cold mirror in simulations and experiments. Bierman ***et al.*** [9)] investigated spectrum splitting with hybrid PV and thermal engine modeling using the same principle as PV-

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TEG. Recently, Hariyanto *et al.* [10] also did modeling with a hot mirror as a beam splitter spectrum of the AM1.5D wavelength spectrum of light. The spectrum standard used has not yet put on artificial light, whose spectrum is close to characteristic the sun, namely light bulbs [11]. The type of light bulb referred to by Doolittle [11], such as halogen, mercury, and xenon.

Piarah *et al.* [12] experimentally researched with an experimental 50 Watt Halogen light bulb source. He characterized and compared the use of hot and cold mirror spectrum splitters in a hybrid of the polycrystalline mini PV module with a single in the Bismuth Telluride module type. The results show that hybrid output power is better by using a cold mirror (40% cold mirror > hot mirror). Unfortunately, spectral irradiance only ranges from 0 to 0.06 $W/m^2.nm^{-1}$, so the output power produced is still deficient compared to the specifications of the PV and TEG modules used despite the spectral irradiance of the sun is in the range of 0 to close to 2 $W/m^2/nm$ [13]. Therefore, to reduce errors, costs, and time efficiency in PV-TEG hybrid experiments at below 0.1 Sun spectral irradiance, this study was simulated on the AM1.5G light standard at 0.05, 0.06, 0.07, 0.08, 0.09, 0.09 and 0.1 Sun, It is a spectrum splitter cold mirror that aims to see the characteristics of low sun intensity light. The low intensity of sunlight is a simulation approach to the light spectrum of a bulb that is used indoors for PV needs [14]. Afterward, the results of the simulation will become a milestone in the utilization of bulb radiation energy in general domestic needs. It will not only function as room lighting but also as a source of radiation that can be converted back into electrical energy with the help of PV and TEG technology.

The hybrid PV-TEG system simulation study conducted by Piarah *et al.* [15] showed a maximum efficiency of around 7.8%. This efficiency contributions made by PV modules are better than TEG. Their research uses a simulation of the light spectrum at low intensities between 0.05 to 0.7 Sun. However, the resulting hybrid efficiency is still relatively low. This efficiency can be improved by first accommodating the radiation spectrum directed at the TEG module so that the temperature rises before conduction heat transfer occurs to the TEG hot side. The higher the difference in temperature between the hot side and the cold side of the TEG module, the larger the output power of the TEG will increase. Therefore, this simulation study aims to optimize the source of the spectrum of light to PV and especially to TEG with the addition of absorbent plates from copper material that has high heat conductivity. This plate is placed on the hot side and has dimensions according to the surface area of the TEG module. It aims to accommodate the spectrum of radiation in the form of thermal, which is in the spectrum with wavelengths between 700 to 1150 nm. Next the simulated light spectrum covers a fairly larger spectral irradiance variations of 0.05; 0.06; 0.07; 0.08; 0.09, and 0.1 Sun in the low intensity category. 1 Sun means 1000 W/m^2 for solar intensity.

2. Procedures

The simulation of PV-TEG hybrid is available in Fig. 1. This hybrid utilizes the spectral input of the solar energy standard AM1.5G with a low intensity below 0.1 Sun, which nearly close to the spectrum of the bulb in indoor lights, as in Fig. 2. Irradiances are concentrated with a thin Fresnel lens (Fl) form of conical grooves with dimensions of 127 × 127 mm, adequate size 102 mm, focal length 127 mm. In its application, however, the focal point distance will be adjusted to the dimensions of the spectrum splitter that receives lights transmission from Fl to obtain the optimal spectrum [16]. Complete lens specifications are available in Table 1.

When referring to Table 1, Fresnel lens thickness is so thin that loses is less likely to occur during the absorption of the light spectrum. The possibility is only reflected so that the ability to transmit light absorbed is a maximum of 92%. The 92% will be passed down to the spectrum splitter. In this case, a Cold Mirror (CM) is used as one type of beam spectrums to split photon and termal energy. Furthermore, the percentage will be divided in two ways, some are reflected in the PV modules in the wavelength spectrum between 400-690 nm by 95%, and some are transmitted to the TEG module by 90% in the range of 700-1150 nm. However, before being received by the TEG hot side, the beam of light radiation is accommodated first by the absorber plate of copper before being transmitted by convection to the TEG. It aims to

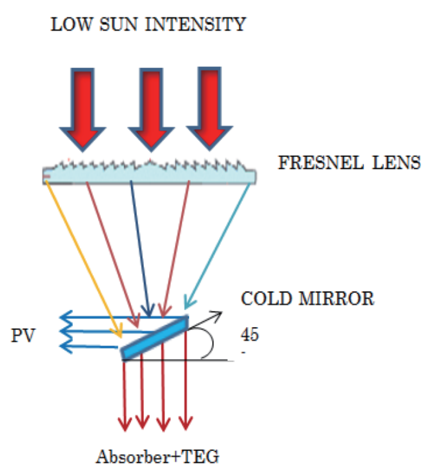

Fig. 1 Hybrid of PV, absorber, and TEG

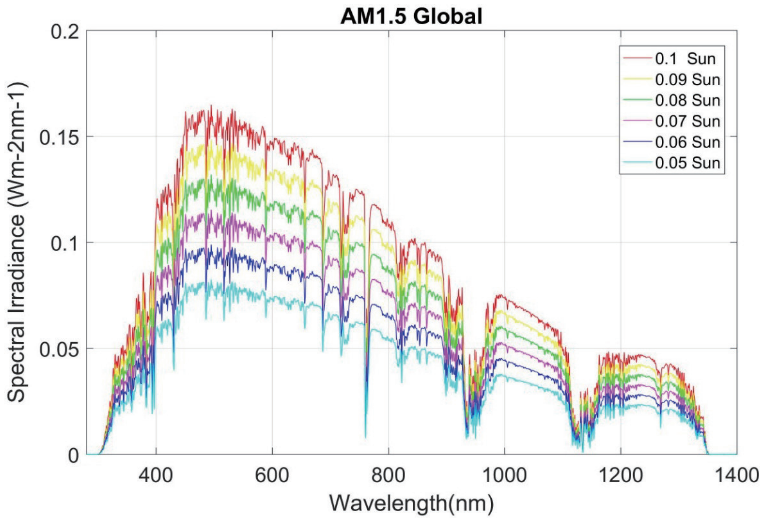

Fig. 2 Spectral irradiance under 0.1 Sun of AM1.5G

Table 1 The spesification of Fresnel lens [16]

Dimensional Tolerance		Substrate	Acrylic
(inches)	± 0.05	Thickness Tolerance (%)	± 40
Coating	Uncoated	Operating temp. (° C)	80 (Maximum)
Index of Refraction nd:	1.49	Wavelength Range (nm)	400-1100 nm
Transmission (%)	92 (400-1100nm)		

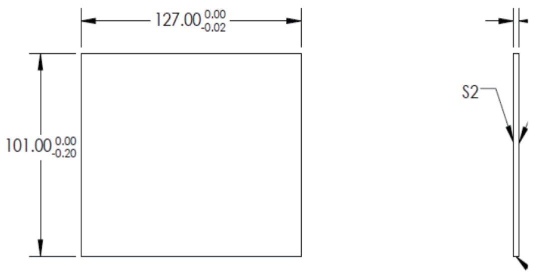

Fig. 3 Cold Mirror [15]

Table 2 The specification of Flexible Film Amorphous Silicon PV [17]

Parameter	Value
Peak Power	1 W
Voltage	6 V
Current	0.16 A
Working temperature	-15 °C - 60 °C

Table 3 The specification of Thermoelectric Generator (Bi_2Te_3)

Parameter	Value
Voltage open circuit	4.8 V
Current	0.66 A
Resistance	2.4 Ω
Hot side temperature	100 °C
Dimensions	40 × 40 × 3.4 mm

gather lights into heat for TEG material requirements.

The CM dimension, as shown in Fig. 3 with a size of 101 × 127 mm at a thickness tolerance of +0.0 and -0.2 mm, a thickness of 3.3 mm, which is positioned at an angle of 45° below Fl. The dimension of the CM adjusts the beam of light that is transmitted by Fl. It is one of the causes of the results of the research of Piarah *et al*. 12), where the total radiation transmitted by Fl is not fully absorbed optimally by CM because it only has dimensions of 50 × 50 mm so that in this simulation the dimensions are enlarged [15].

The reflected light beam is directed to the thin-film solar cell with the specifications in Table 2 and the TEG module in Table 3.

3. Results and Discussion

Table 4 shows the results of the low sun spectrum simulation after passing through the Fresnel lens and the spectrum transmitted to the TEG module and reflected the PV by Cold Mirror. As seen in the table, the total spectral power reflected is higher (169.05 W/m^2) in the form of photon energy compared to that transmitted to the TEG module (126.90 W/m^2) in the form of heat energy. This reflected power is in line with the results of the research of Piarah *et al*. [15] at spectrum intervals between 0.05 and 0.7 Sun, except those transmitted to TEG. The transmitted light spectrum is accommodated first by the copper plate as a heat absorber to increase the conversion of light to heat

Table 4 Irradiances of AM1.5G on low Sun spectrum

Spectrum AM.1.5G	Full spectrm 250-1500 nm (W/m^2)	Reflection 400-700nm to PV (W/m^2)	Transmission 700-1150nm to copper plate+TEG (W/m^2)
0.1	89.79	37.57	28.20
0.09	80.82	33.81	25.38
0.08	71.84	30.05	22.56
0.07	62.86	26.30	19.74
0.06	53.88	22.54	16.92
0.05	44.90	18.78	14.10

Table 5 The efficiency of PV Module on low Sun spectrum under 0.1 Sun AM1.5G

Spectrum AM1.5 G	Reflection 400-700 nm to PV (W/m^2)	Current (A)	Voltage (V)	Power (W)	Apv	Pin	η_{PV} (%)
0.1	37.57	0.006	4.25	0.03	0.02	0.75	3.33
0.09	33.81	0.005	4.24	0.02	0.02	0.68	3.11
0.08	30.05	0.005	4.23	0.02	0.02	0.60	3.33
0.07	26.30	0.004	4.22	0.02	0.02	0.53	3.42
0.06	22.54	0.004	4.22	0.02	0.02	0.45	3.33
0.05	18.78	0.003	4.21	0.01	0.02	0.38	3.46

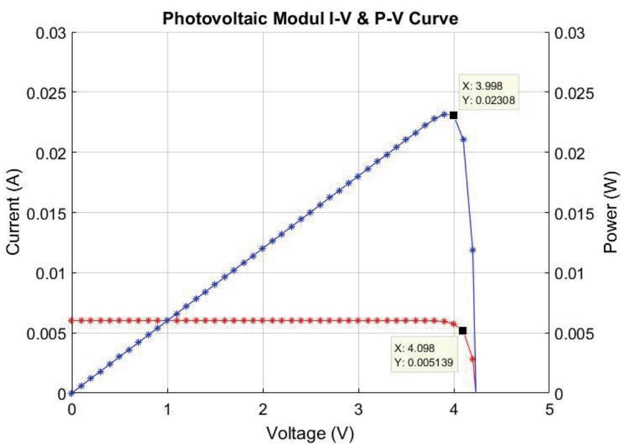

Fig. 4 Simulation of PV in I=f (V) and P=f (V)

and by convection heat transfer to the hot side of the TEG module.

3.1 Module of PV

It appears that the spectral irradiance at 0.05 Sun, the smallest power input generates the highest efficiency, 3.46% more than 0.04 compared with the 0.07 Sun irradiance (Table 5). It shows that although the spectral irradiance and the small power in the wavelength spectrum of 400-700 nm, the efficiency is still high. The power generated is still far greater than the power in the study of Piarah *et al.* [12]. It is due to the simulated assumption that there is no radiation energy loses other than following the FL and CM transmission specifications.

Fig. 4 shows the simulation results using the 0.1 AM1.5G spectrums input, which has passed the Fl and CM of 37.5672 W/m^2. The maximum output power obtained is 0.023 W, with a voltage of 4.098 V and a current of 0.005 A.

3.2 Module of TEG

The simulation results in Table 6 on the TEG module as a result of the lights transmission of low sun spectrum after CM depicts the temperature changes on the hot side TEG from 70 to 120 °C to a 40 °C with a constant temperature on the cold side. Optimum power is achieved at an 80 °C delta temperature between the hot and cold sides of the TEG module. This large temperature ratio indicates that the copper plate absorbs light into heat well before being transferred by convection to the TEG hot side. As a result, the TEG module efficiency also displays an increase in a trend like its output power (Fig. 5).

Fig. 6 presents the simulation results on the temperature of a TEG hot side, TH = 70 °C and the cold side of the module, TC = 40 °C. The maximum output power obtained is 0.1107 W, with a voltage of 1.241 V and a current of 0.354 A.

In short, as depicted in Table 7, the highest efficiency

Table 6 Simulation of TEG module on low Sun spectrum under 0.1 Sun AM1.5G

TH(°C)	TC(°C)	Current (A)	Voltage (V)	Power (W)
70	40	0.355	1.238	0.110
80	40	0.474	1.654	0.196
90	40	0.592	2.068	0.307
100	40	0.711	2.481	0.442
110	40	0.830	2.895	0.602
120	40	0.948	3.308	0.787

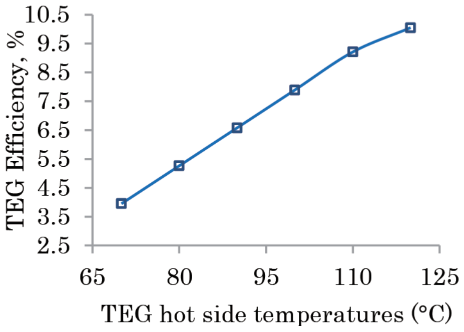

Fig. 5 The efficiency of the TEG module

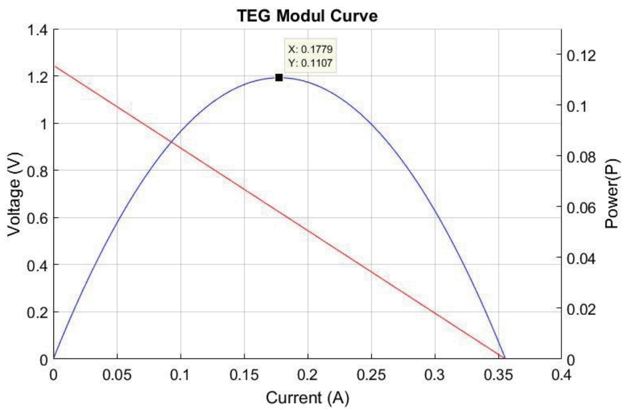

Fig. 6 Simulation result of TH = 70°C and TC = 40°C on the TEG module

Table 7 The efficiency of PV-TEG hybrid

Spectrum AM1.5 G	$\eta_{PV\text{-}TEG}$ (%)
0.1	13.38
0.09	12.31
0.08	11.22
0.07	10.00
0.06	8.59
0.05	7.41

achieved at 0.1 Sun low sun spectrum input of 13.38%. This high value is the contribution of the simulation on TEG as a result of the effectiveness of copper heat absorbent because the highest efficiency of the PV module is obtained in the lowest spectrum of 0.05 Sun. The results of this simulation also prove that the efficiency of the hybrid PV-TEG system produced (10%) is higher with the addition of copper plates on the TEG hot side compared to the efficiency of the simulation results conducted by Piarah *et al.* [15] at 7.8% in the same of light spectrum at 0.07 Sun.

4. Conclusion

It can be concluded that even in the low Sun spectrum, the photon energy produced is enough to generate electrical energy or output power in the PV module. Likewise, the output power generated by the TEG module increases with the addition of a heat absorber plate. It is consistent with the results of the study of Ju *et al.* [6], only they did not display the type of light spectrum splitter in their PV-TEG hybrid system.

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