Thermoelectric Element Geometry Optimization for Maximum Hybrid Photovoltaic-Thermoelectric System Efficiency

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Abstract: The geometry of thermoelectric elements in a hybrid Photovoltaic-Thermoelectric (PV-TE) power generation system can influence the conversion efficiency of the hybrid system. Therefore, this study investigates the optimum geometry for maximum conversion efficiency of a hybrid PV-TE uni-couple using Finite Element Method (FEM). COMSOL Multiphysics is used to solve the 3-Dimensional heat transfer equations considering thermoelectric materials with temperature dependent properties. The thermoelectric element geometry area ratio is considered for the range $0.5 \leq R_A \leq 2$. R_A is the cross-sectional area ratio of the thermoelectric element hot and cold junctions (A_H/A_C). Therefore, three different geometric configurations are analysed. Temperature and voltage distributions in the hybrid system for the different configurations considered are presented. Effects of thermoelectric generator (TEG) geometric parameters and load resistance on the hybrid system efficiency are presented. The results show that a hybrid PV-TE system will perform better with symmetrical TEG geometry ($R_A = 1$) however, this is different from the optimum geometry for a TEG only system ($R_A \neq 1$). The influence of solar irradiation and concentration ratio on the hybrid system performance are also studied. Results obtained from this research would influence hybrid PV-TE system designs for obtaining maximum conversion efficiency.

Keywords: PV-TE, FEM, TE Area Ratio, Geometry

1. INTRODUCTION

Renewable energy has received increased research attention because of environmental challenges such as; global warming, increasing energy demand and diminishing oil sources (Erturun et al., 2014). Conventional energy sources have the following disadvantages; creation of noise and exhaust gases, need for constant maintenance and repairs particularly for continuous operation (Kugele et al., 1996). Therefore, renewable energy sources like Photovoltaic (PV) technology offer unique advantages such as; noiseless operation, low maintenance and zero pollution (Ramulu et al., 2014). A thermoelectric generator (TEG) is a solid state device which can convert heat directly into electricity by the Seebeck effect (Wang et al., 2011). Thus, when a TEG is attached to the back of a PV, it will perform a dual function of cooling the PV cell and generating extra electrical energy from the waste heat of the PV cell. (Van Sark, 2011) presented an idealized model for a hybrid PV-TE system and suggested that efficiency improvement of about 50% could be achieved with the development of new TE materials. (Ju et al., 2012) presented a spectrum splitting hybrid PV-TE system using numerical modelling and observed that the cut-off wavelength of the hybrid system is mainly determined by the band gap of the solar cell. (Park et al., 2013) investigated a hybrid PV-TE system using a lossless coupling approach to improve the efficiency of the PV device in the hybrid system by 30%. (Zhu et al., 2016) used optimized thermal management techniques on a thermal concentrated hybrid PV-TE system which achieved peak efficiency of 23% during outdoor testing. (Bjørk and Nielsen, 2015) used an analytical model to determine the performance of hybrid PV-TE systems using different type of PV cells and found that the overall efficiency of the hybrid system can be lower than that of the PV only system. However, (Lamba and Kaushik, 2016) developed a theoretical model for analysing the performance of a concentrated PV-TEG and found that the hybrid system's power output and efficiency increased by 13.26% and 13.37% respectively in comparison with those of PV only system. Furthermore, (Yin et al., 2018) also developed a theoretical model for obtaining the one-day performance of a hybrid PV-TE system and observed a peak efficiency of 16.65%.

In terms of research into TEG geometry, (Li et al., 2017a) studied the influence of geometric size on the performance of hybrid PV-TE systems and found that the overall efficiency increases as cross-sectional area increases. Furthermore, (Hashim et al., 2016) developed a model to determine the optimal geometry of thermoelectric devices in a hybrid PV-TE system. The authors argued that the dimension of the TEG in a hybrid system has a significant influence on the overall power output of the system. (Li et al., 2017b) investigated the optimal geometry of the TEG element in a hybrid PV-TE uni-couple for maximum efficiency. The authors found that the hybrid system's maximum power output occurs when the ratio of area of n- and p-type (A_n/A_p) is symmetrical unlike in the case of a TEG only system.

While previous works discussed above have considered the influence of the thermoelectric elements area ratio (A_n/A_p) on the efficiency of the hybrid system there is little study on the influence of the cross sectional area ratio of each thermoelectric element (A_H/A_C) on the efficiency of the hybrid PV-TE system. In addition, some of the previous works have used constant thermoelectric material properties. However, the n- and p-type TE material properties are not the same in real applications and they also depend on temperature (Li et al., 2017b). In fact, the power output and efficiency of a TEG is affected by the temperature dependency of the thermoelectric material properties (Meng et al., 2012). Therefore, this research investigates the optimum geometry for maximum efficiency in a hybrid PV-TE uni-couple. In order to find this optimum geometry, the thermoelectric element geometry area ratio is studied for the range $0.5 \leq R_A \leq 2$. In addition, the investigation is carried out at matched load condition and temperature dependent thermoelectric material properties are used.

2. GEOMETRY DESCRIPTION

The schematic diagrams of the different geometries of the hybrid system simulated are shown in Figure 2 corresponding to the range $0.5 \leq R_A \leq 2$. The system consists of a solar concentrator, PV module, tedlar, and TEG module. The PV module is a Silicon cell and the TEG module consists of Bismuth Telluride thermoelectric elements which are connected electrically in series and thermally in parallel. Solar radiation passes through the solar concentrator and it is impinged on the PV surface. Part of the solar radiation is converted to electricity directly by the PV module, some other part is lost to the environment by radiation and convection (thermal losses) while the remaining heat is transferred to the TEG module through heat conduction. The TEG hot side is attached to the bottom of the PV module and the TEG cold side is attached to a cooling base which is place in ice water to take away the extra energy. Therefore, there is a temperature difference between the hot and cold sides of the TEG and electricity is generated by Seebeck effect.

2.1. Geometric Configurations

The cross-sectional area of the different leg geometries of the thermoelectric generator in the hybrid system considered are shown in Figure 1. Fig. 1a shows the leg geometry for $R_A = 0.5$, Fig. 1b shows the leg geometry for $R_A = 1$ and Fig. 1c shows the leg geometry for $R_A = 2$.

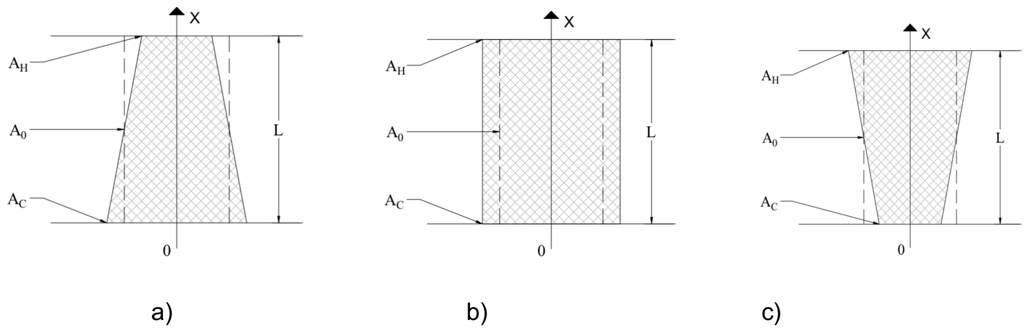

Figure 1: Thermoelectric element geometric configurations for a) $R_A = 0.5$ b) $R_A = 1$ c) $R_A = 2$.

The three different geometric configurations analysed are shown in Figure 2.

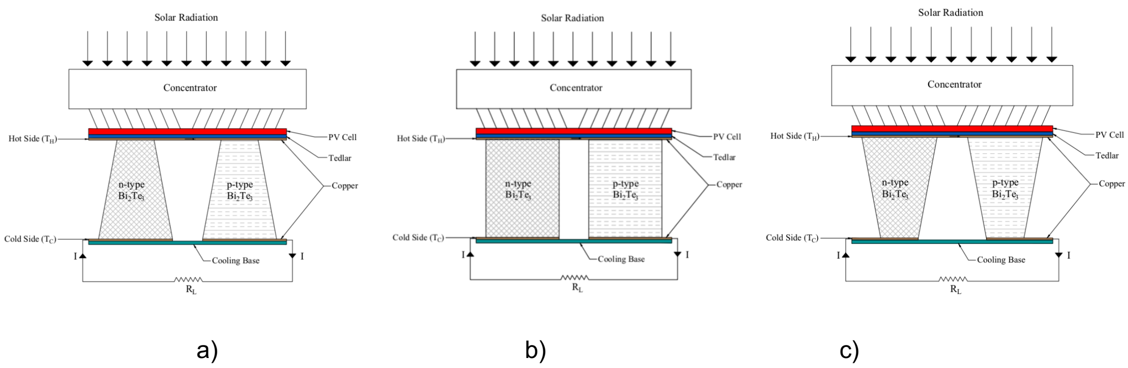

Figure 2: Schematic diagrams of the PV-TE for a) $R_A = 0.5$ b) $R_A = 1$ and c) $R_A = 2$.

3. MODEL DESCRIPTION

3.1. TEG Module

The mathematical equations corresponding to the leg geometries shown in Figure 1 are (Al-Merbati et al., 2013):

$$A(x) = \frac{A_H - A_C}{L_{TE}} x + A_C \quad (1)$$

where A_C is the cross sectional area of the bottom side of the thermoelectric element and A_H is that of the top side. L_{TE} is the height of the thermoelectric element. Therefore, the area ratio can be defined as $R_A = A_H / A_C$. The cross-sectional area of the thermoelectric element can be expressed as:

$$A(x) = A_0 \left[1 + 2\frac{R_A - 1}{R_A + 1}\left(\frac{x}{L} - \frac{1}{2}\right)\right] \quad (2)$$

where A_0 is the cross-sectional area of the uniform thermoelectric element.

3.2. PV Module

The following boundary conditions are applied to the PV module and are used to describe the FEM model.

External heat flux: This is applied at the upper surface of the PV cell and can be expressed as

$$q_0 = CG\alpha_{PV} A_{PV} - E_{PV} A_{PV} \quad (3)$$

The power output of the PV cell per square meter can be expressed as a function of solar irradiation and temperature as shown

$$E_{PV} = CGA_{PV}\eta_{PV}[1 - \varphi_c(T_{PV} - 298)] \quad (4)$$

Convective heat flux: This is applied at the upper surface of the PV cell due to the temperature difference between the upper surface and the ambient. It can be expressed as

$$q_1 = h_{amb}(T_{amb} - T_{PV}) \tag{5}$$

Diffuse surface: The heat transfer due to radiation at the surface of the PV cell can be expressed as

$$q_2 = \varepsilon\sigma_b(T_{amb}^4 - T_{PV}^4) \tag{6}$$

The last boundary condition is applied at the lower surface of the hybrid system. The cold side of the system is placed in ice water to maintain it at a constant temperature of 273K and this can be expressed as

$$T_C = T_0 = 273K \tag{7}$$

3.3. Overall System Performance

The total power output of the PV-TE system is the sum of the power outputs of PV and TEG and can be expressed as

$$P_{PV-TE} = P_{PV} + P_{TE} = E_{PV}A_{PV} + P_{TE} \tag{8}$$

The overall efficiency of the hybrid PV-TE system can be expressed as

$$\eta_{PV-TE} = \frac{P_{PV-TE}}{CGA_{PV}} = \frac{E_{PV}A_{PV} + P_{TE}}{CGA_{PV}} \tag{9}$$

3.4. Modelling Parameters

The Seebeck coefficient, Electrical conductivity and Thermal conductivity of the Bismuth Telluride (Bi_2Te_3) thermoelectric material used are temperature dependent and linearly extrapolated using the equations from (Suzuki et al., 2016) while the geometric parameters used for modelling the hybrid PV-TE system are shown in Table 1.

Table 1: Parameters used in hybrid PV-TE model

Parameters	Symbol	Value
Area of PV	A_{PV}	0.0001 m^2
Thickness of PV	H_{PV}	0.0003 m
Thickness of tedlar	H_{ted}	0.000175 m
Thickness of copper	H_{cu}	0.0001 m^2
Area of TE element	A_{TE}	0.000014 m^2
Height of TE element	L_{TE}	0.005 m
Heat transfer coefficient	h_{amb}	5 $Wm^{-2}K^{-1}$
Absorptivity of PV	α_{PV}	0.9
Emissivity of PV	ε_{PV}	0.8
Ambient temperature	T_{amb}	298 K
Solar irradiation	G	1000 W/m^2
Concentration ratio	c	5
Wind velocity	u_w	1 m/s
PV efficiency at standard test conditions (STC)	η_{PV}	15%
Temperature coefficient	φ_{PV}	0.004 K^{-1}

4. RESULTS AND DISCUSSION

COMSOL Multiphysics software is used to analyse the performance of each of the geometrical configurations. Different temperature and voltage distributions are obtained for each geometrical configuration as the load resistance (R_L) attached to the TEG is changed to find its optimum value for maximum hybrid system power output and efficiency. The temperature and voltage distributions corresponding to the maximum efficiency obtained are shown in Figure 3 for $R_A = 1$.

a) b)

Figure 3: a) Temperature distribution and b) Voltage distribution for $R_A = 1$

4.1. Geometry Area Ratio

The geometry of the thermoelectric elements in a hybrid PV-TE system influence the overall performance of the system which is measured in terms of its overall power output and conversion efficiency.

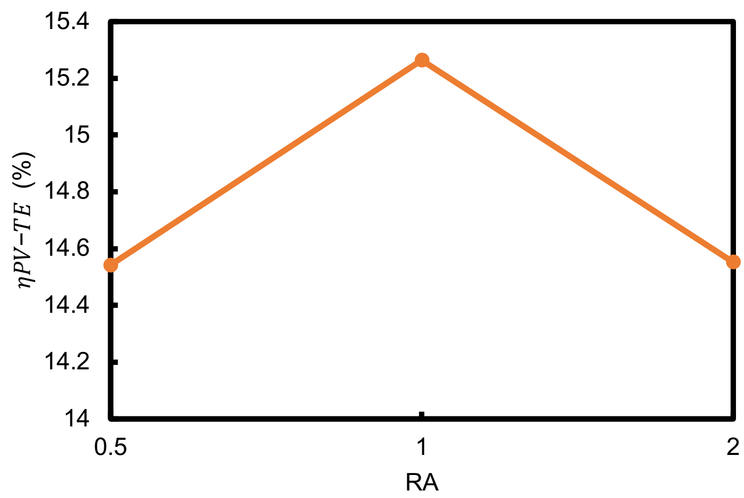

Figure 4: Overall hybrid system efficiency variation with geometry area ratios

Figure 4 shows that the optimum geometry for the thermoelectric element in the hybrid PV-TE system is symmetrical i.e. $R_A = 1$. In essence, the optimum geometry of the TEG in the hybrid system is not the same as its geometry in a TEG only system. (Al-Merbati et al., 2013) found the optimum geometry of the thermoelectric elements in a TEG only system to be dissymmetrical $(R_A \neq 1)$.

4.2. Geometric Parameters

The thermoelectric element geometric parameters such as height and area can affect the maximum efficiency of the hybrid system. The effects of these geometric parameters on the overall hybrid system efficiency are shown in Figure 5 for $R_A = 1$.

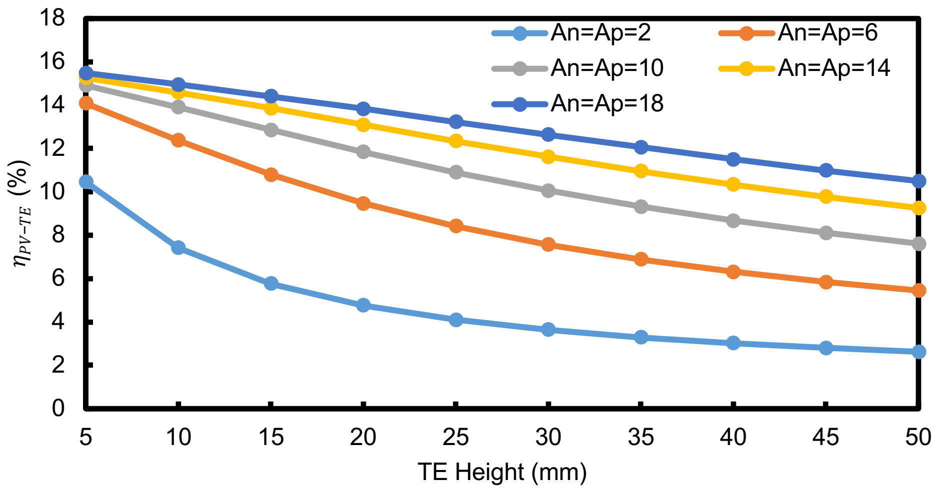

Figure 5: Overall hybrid system efficiency variation with TE height and area for $R_A = 1$.

It can be seen from Figure 5 that the hybrid system efficiency shows a decreasing trend as the thermoelectric element height increases and an increasing trend as the thermoelectric element area increases. This implies that maximum hybrid system efficiency can be obtained using some specific geometry parameters.

4.3. Irradiation

The solar irradiance value and concentration ratio determine the amount of heat flux at the surface of the PV cell and consequently, the performance of the hybrid PV-TE system. The effect of solar irradiance and concentration ratio on the performance of the hybrid system is investigated when $A_{TE} = 14mm^2$, $L_{TE} = 5mm$, $R_A = 1$. These conditions are chosen because they provide the optimum hybrid system performance based on the findings presented earlier.

Figure 6 shows the variation of PV-TE efficiency with solar irradiance. It can be seen that the hybrid system efficiency shows a decreasing trend as solar irradiance increases. This is because the PV module temperature increases with increase in solar irradiance and this affects the overall efficiency of the hybrid system. Therefore, the efficiency curve of the hybrid PV-TE system will follow the same trend as that of the PV system.

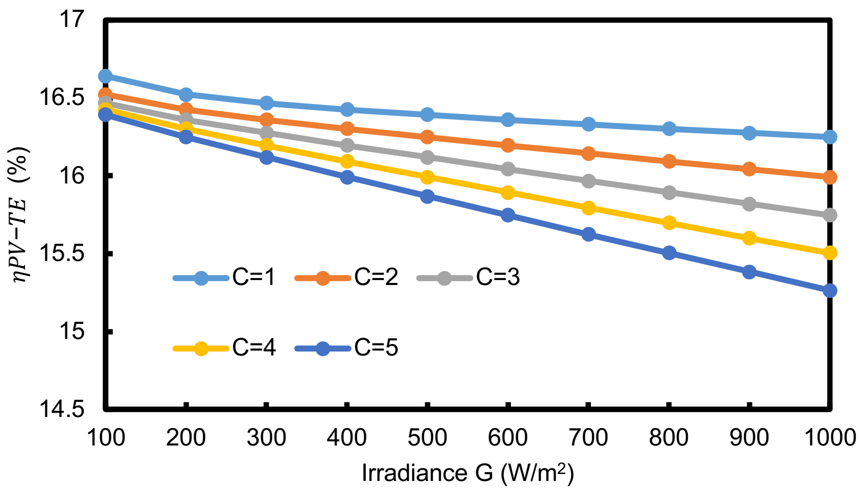

Figure 6: Variation of hybrid PV-TE efficiency with solar irradiance at different concentration ratio.

The variation of power outputs from the PV, TEG and PV-TE systems with concentration ratio when $G = 1000\ W/m^2$ is shown in Figure 7. It is obvious that the PV provides the greater percentage of the total hybrid system power output. The contribution of the TEG is very small compared to that of the PV in terms of power output

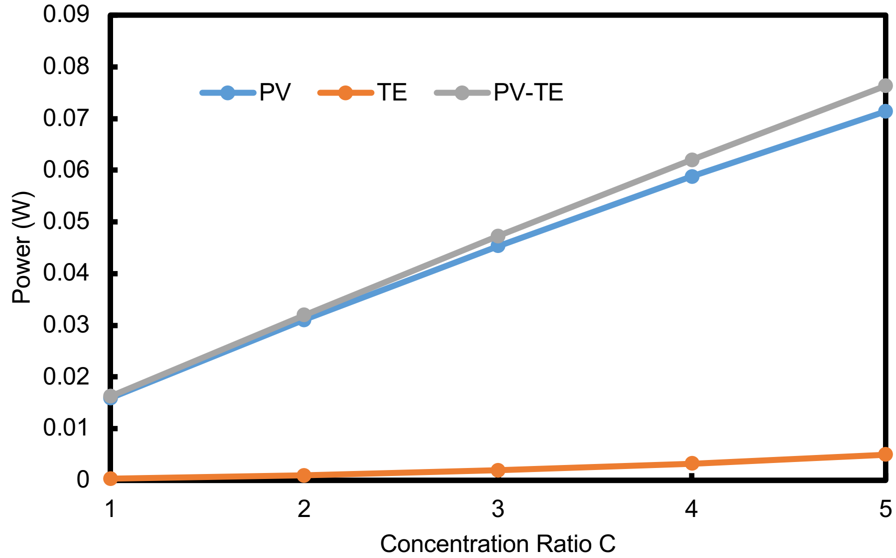

Figure 7: Variation of power outputs of PV, TEG and hybrid PV-TEG system with concentration for $G = 1000\ W/m^2$.

5. CONCLUSION

The optimum geometry of a thermoelectric element in a hybrid PV-TE system has been investigated in this research using finite element method. The thermoelectric element area geometry was investigated for the range $0.5 \leq R_A \leq 2$. Ra is the cross-sectional area ratio of the thermoelectric element hot and cold junctions (A_H/A_C). It was found that the hybrid PV-TE system performs better with symmetrical TEG geometry ($R_A = 1$) however, this is different from the optimum geometry for a TEG only system $(R_A \neq 1)$. In general, thermoelectric element with shorter heights and higher cross sectional area should be used to obtain maximum hybrid system efficiency. It was found that low concentration ratio produce high overall hybrid system efficiency and this is due to the low PV temperatures corresponding to such low concentration ratio. Furthermore, it was found that the PV provides the greater percentage of the total hybrid system power output. Finally, the hybrid system efficiency showed a decreasing trend as solar irradiance increased.

6. ACKNOWLEDGMENT

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Nomenclature

A	Area, m^2	***Greek Symbols***	
C	Concentration ratio	α	Absorptivity
C_P	Specific heat capacity, $J/(kg \cdot K)$	φ	PV temperature coefficient, K^{-1}
E_{PV}	Power output of PV per square meter, W/m^2	η	Efficiency
G	Solar irradiance, W/m^2	η_{ref}	Efficiency of PV cell under standard test conditions
h_{amb}	Convective heat transfer coefficient on outer surface, $W/(m^2 \cdot K)$	ε	Emissivity
k	Thermal conductivity, $W/(m \cdot K)$	σ	Electrical conductivity, S/m
L	Height, m	ρ	Density, kgm^{-3}
P	Power output, W	***Subscripts***	
q_0	Heat flux, W/m^2	n	n-type
R_A	Cross-sectional area ratio of TE hot and cold junctions	C	Cold side
R_L	Load resistance on TEG, Ω	H	Hot side
S	Seebeck coefficient of TE module, V/K	p	p-type

T	Temperature, K	***Abbreviations***	
ΔT	Temperature difference, K	PV	Photovoltaic
	$\Delta T = T_H - T_C$		
u_w	Wind velocity, m/s	TE	Thermoelectric