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Series of detail comparison and optimization of thermoelectric element geometry considering the PV effect

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This study investigates the optimum geometry for maximum efficiency of a hybrid PV-TE uni-couple using Finite Element Method. COMSOL Multiphysics is used to solve the 3-Dimensional heat transfer equations considering thermoelectric materials with temperature dependent properties. Two types of thermoelectric element geometry area ratios are considered for the range $0.5 \leq R_A \leq 2$ and $0.5 \leq R_S \leq 2$. Nine different geometric configurations are analysed for two different PV cells. Effects of thermoelectric generator (TEG) geometric parameters, solar irradiation and concentration ratio on the hybrid system efficiency are presented. The results show that a hybrid PV-TE system will perform better with symmetrical TEG geometry ($R_A = R_S = 1$) if a PV temperature coefficient of 0.004/K (Cell B) is used. This is different from the optimum geometry for a TEG only system. However, the optimum geometry of the TEG in a hybrid system will be the same as that of a TEG only system (dissymmetrical i.e. $R_A = R_S \neq 1$) if a PV temperature coefficient of 0.001/K (Cell A) is used. The overall efficiency and TE temperature difference show a decreasing trend as thermoelectric element length and area increase respectively no matter the configuration or temperature coefficient value used. Results obtained from this research would influence hybrid PV-TE system design for obtaining maximum conversion efficiency.

1. Introduction

Alternative energy conversion methods have received increased research attention because of environmental challenges such as; global warming, increasing energy demand and diminishing oil sources [1–3]. Asides the fact that these fossil fuel sources are limited, some other disadvantages include; creation of noise and exhaust gases, need for constant maintenance and repairs particularly for continuous operation [4,5]. Therefore, renewable energy sources like Photovoltaic (PV) technology offer unique advantages such as; noiseless operation, low maintenance and zero pollution [6]. The decrease of PV efficiency due to increasing cell temperature is the main shortcoming of the PV technology [7]. The best efficiency result obtained from a monocrystalline silicon cell is about 18% [8]. This value is quite low therefore, the efficiency of the PV cell needs to increase significantly to increase its comparative advantage over conventional energy sources and to encourage a wider adoption of the technology globally.

Photovoltaic cells utilize only part of the solar spectrum. Therefore, the infrared part of the sunlight which is not used by the PV cell heats up the cell and consequently, reduces the efficiency of the PV cell. Therefore, combining a PV cell which utilizes the visible and ultra-violet part of the sunlight with a Thermoelectric (TE) module which utilizes the infrared part of the sunlight would enable the utilization of the full solar spectrum [9]. The efficient combination of the PV and TE generators would constitute a significant breakthrough in solar energy utilization [10]. Research in the field of hybrid PV-TE has accelerated faster than other hybrid PV technologies [11]. A thermoelectric generator (TEG) is a solid state device which can convert heat directly into electricity by the Seebeck effect [12]. Therefore, the TEG attached to a PV performs a dual function of cooling the PV cell and generating extra electrical energy from the waste heat of the PV cell.

Research in the field of hybrid PV-TE has gained greater attention recently and different methods have been used to investigate the performance of the hybrid system. Van Sark [13] presented an idealized model for a hybrid PV-TE system and suggested that efficiency enhancement of about 50% could be achieved with the development of new TE materials. Ju et al. [14] presented a

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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. [15] 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. [16] used optimized thermal management techniques on a thermal concentrated hybrid PV-TE system which achieved peak efficiency of 23% during outdoor testing. Bjørk et al. [17] 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 et al. [18] 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. [19] 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 addition, Wu et al. [20] presented a theoretical model for determining the performance of glazed/unglazed hybrid PV-TE systems using nanofluid heat sink. The authors observed that nanofluid provides a better performance than water. Likewise, Soltani et al. [21] observed that nanofluid cooling enabled the highest power and efficiency improvements (54.29% and 3.35% respectively) in a hybrid PV-TE system in which five different cooling methods were investigated. To reduce the temperature fluctuations in a hybrid PV-TE system, Zhang et al. [22] developed a novel hybrid system in which the number of TE generator cooled by water could be adjusted by controlling the cycles of water in the cooling blocks. In addition to this, Cui et al. [23] introduced a phase change material (PCM) into a PV-TE system to mitigate temperature fluctuations in the system and observed improved performance. Furthermore, Mahmoudinezhad et al. [24] studied the transient response of a hybrid CPV-TE system and found that the thermal response of the TEG helps stabilize the temperature fluctuation in the hybrid system when solar radiation changes rapidly.

Finite Element Method (FEM) has been applied to the investigation of hybrid PV-TE system performance in the past. Kiflemariam et al. [25] used this method to perform a 2-D simulation of a hybrid PV-TE system and found that higher concentration ratio results in higher power production from the TEG module. Beeri et al. [26] also used this method along with experimental approach to investigate the performance of a PV-TE system and obtained a maximum efficiency of 32% for concentration ratio ≤ 200. More recently, Teffah et al. [27] used this method to investigate the efficiency of a hybrid system consisting of a triple junction solar cell (TJSC), a thermoelectric cooler (TEC) and a TEG. Furthermore, Li et al. [28] also used finite element method to optimise the geometry of the thermoelectric element footprint for maximum power generation in a PV-TE.

Recently, the incorporation of heat pipes into hybrid PV-TE systems have been investigated. Makki et al. [29] investigated a heat pipe based PV-TEG hybrid system and suggested that the system is better used in sunny regions with high operating temperature and low wind speeds. However, temperature independent material properties were used in the research. Furthermore, Li et al. [30] presented a novel PV-TE system based on a flat plate micro-channel heat pipe.

Considering the TEG geometry, Li et al. [31] 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. [32] 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. [33] 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. In addition, Kossyvakis et al. [34] advised the use of thermoelectric devices with shorter thermoelectric elements to obtain improved hybrid PV-TE system performance when operated under sufficient illumination. The authors suggested that this allow less material to be consumed and reduce system cost. These suggestions are in agreement with [35].

The optimized geometry of a TEG only system has been extensively studied in the past [36,37]. However, it is important to find the optimum geometry of the TEG when used in a hybrid PV-TE 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, to the best of our knowledge, there is no 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. A_n/A_p is the area ratio of the n-type and p-type thermoelectric elements while A_H/A_C is the area ratio of the thermoelectric element hot and cold junctions. 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 [33]. In fact, the power output and efficiency of a TEG is affected by the temperature dependency of the thermoelectric material properties [38]. Thus, it is imperative that temperature dependent thermoelectric material properties are used to avoid errors. Furthermore, temperature coefficient affects the efficiency of the PV only system [39]. However, there is limited research on its effect on the geometry and efficiency of the hybrid PV-TE system.

Therefore, this research investigates the optimum geometry for maximum efficiency in a hybrid PV-TE uni-couple. The advantage of using the uni-couple PV-TE model is that computational time can be significantly reduced while still achieving accurate results from which significant optimization activities can be carried out. In order to find this optimum geometry, the two thermoelectric element geometry area ratios are studied for the range $0.5 \leq R_A \leq 2$ and $0.5 \leq R_S \leq 2$. This range is used to investigate the performance of the hybrid PV-TE system because ease of fabrication of the thermoelectric element is considered. Presently, most thermoelectric elements are rectangular or square in shape and the rectangular shape corresponds to the condition $R_A = 1$ in this study. The other two conditions, $R_A = 0.5\ and\ 2$ modify the shape of the thermoelectric element into a trapezoidal shape which can also be fabricated. The goal is to simulate equivalent models which can be fabricated easily. The range $0.5 \leq R_S \leq 2$ controls the cross-sectional area of the thermoelectric elements (n-type and p-type). Also, the chosen range can be fabricated with ease therefore, it is used in the simulations.

In addition, the investigation is carried out at matched load condition and temperature dependent thermoelectric material properties are used. Nonlinearity of thermoelectric material properties used in modelling necessitates the use of computation techniques such as FEM software. The hybrid system is modelled in 3-dimension using COMSOL Multiphysics software and finite element method is used to solve the heat transfer equations. Finite Element Method (FEM) is used because of its Multiphysics simulation capability. Due to recent advancement in its Multiphysics simulation capability, the finite element method has become an attractive method to simulate thermoelectric devices. Furthermore, FEM allows Thomson effects and temperature dependent properties of thermoelectric materials to be easily coupled into the governing equations [40]. Some of the advantages of using finite