A study of performance characteristics of hybrid energy harvesting systems based on photo-voltaics and thermoelectrics

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Abstract. The hybrid photovoltaic/thermoelectric generator (PV/TEG) technology is an advanced and efficient technology that combines the power from PV and TEGs to generate sustainable electricity. This hybrid approach optimizes energy output and ensures cleaner power by connecting IoT devices. Comprehensive studies have been conducted in the past to improve the efficiency of TEG modules. Various material parameters of TEG legs, such as the Seebeck coefficient, thermal conductivity, and electrical resistivity, and geometric parameters, including the cross-sectional area, leg size, leg height and the number of leg pairs, influence the TEG characteristic and determine with this the performance of the hybrid system. This work explores the influence of the TEG leg lengths and numbers of TEGs at various weather conditions on the power generation of a hybrid PV/TEG device, using an analytical model verified by experiments. The paper also analyses the performance characteristics of TEGs along with the hybrid PV/TEG system and concludes that the maximum output power from the TEG module in the hybrid PV/TEG model can be achieved by increasing the leg length.

1 Introduction

The demand for increasing clean and sustainable energy sources has driven research towards innovative technologies that efficiently harness renewable energy. In 2023, investments in renewable energy generation in Europe reached US $110 billion, marking a 6 % increase from the previous year [1]. While addressing the scarcity of fossil fuels, renewable energy sources are crucial to satisfying the world's expanding energy needs. The rise in ozone depletion and global warming has led to the shift towards green energy and renewable energy. Solar energy is the most reliable renewable source, harnessing a comprehensive spectrum of irradiation. When transmitting the solar spectrum to the PV panel, there is a heat loss. An energy harvester can perform the activity of utilizing the waste heat. Thermoelectric generators (TEGs) are the most favourable for this kind of application as they can transform waste heat into usable electricity [2]. TEGs are composed of n- and p- type semiconductor materials for the thermoelectric (TE) legs and they work when a temperature difference is

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established at the ends of legs then charge carrier forces flow towards the cold side thus producing the Seebeck voltage across it. Extensive research is being conducted on low energy conversion and maximizing performance in TEGs to increase their electrical output. TEGs have many performance benefits such as having no moving parts, requiring less maintenance, and being highly reliable [3]. However, a major limitation of thermoelectric materials is their low figure of merit (ZT) [3, 4].

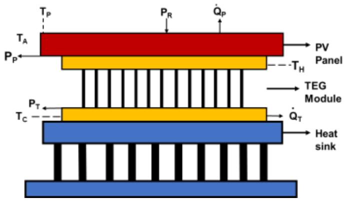
Combining the TEG and PV as a hybrid energy harvesting system improvises the efficiency of the entire system. The first hybrid PV/TEG system was developed in 1987, and the field is growing enormously [5]. Numerous studies are currently ongoing on hybrid PV/TEG combinations. Combining PV and TEG technology has been showing improvements in the past, and they are becoming more practical and reliable energy sources, which efficiently constitutes a breakthrough in solar energy utilization [6]. To improve the performance of TEG, Mirza et al. [6] discussed new methods for optimizing the power output from the hybrid PV/TEG system. They found that the arithmetic optimization algorithm (AOA) works more effectively than other algorithms, achieving an 8% increase in energy output and 99.68% efficiency in power tracking [6]. The feasibility of a hybrid PV/TEG module suggests that integrating a TE module can enhance the performance efficiency of the system by 23 % with a figure of merit value of 0.004 K^{-1} at 300 K for roof-integrated PV/TEG modules [7]. Various studies have indicated that selecting the right PV and TEG types, maintaining optimum temperature on both the hot and cold sides of the TEGs, and reducing internal resistance can enhance the overall system efficiency by 3% to 25% [7, 8]. To increase the performance of TEG, various effects of cooling methods and the parameters have been studied, and their influence on the system's performance was evaluated [9]. Yang et al. found that the concurrent cooling pattern significantly reduces non-uniform temperature distribution, increasing the system's maximum power output [10]. Additionally, Attivissimo discussed a theoretical model for evaluating the performance of the hybrid PV/TEG system, showing that performance and energy conversion parameters are highly dependent on global irradiation and temperature [11]. Babu et al. [12] evaluated the performance characteristics of PV/TEG. They found that the system's performance efficiency is 6% higher than that of standalone PV. A theoretical model was developed by Zhan et al. [13] to analyse the efficiency of concentrating hybrid PV-TE systems and also an evaluation focused on the impact of temperature on the efficiency of hybrid PV/TEG systems and the importance of managing thermal contact resistance [13].

There are numerous ways to enhance the performance of TEGs by modifying their internal structure, including optimizing the size, and shape of the thermoelectric semiconductors etc. Researchers have conducted studies to often analyse and optimize a pair of thermoelectric couples which are most fundamental components of a TEG. The energy conversion efficiency and output of TEGs are influenced by the leg length of thermocouple legs, cross-sectional area, and spacing between the legs. Khalil et al. [14] conducted a study on the performance of various geometries using finite element analysis, finding that the rectangular leg geometry with a 6 mm leg length performed the best. Doraghi et al. [15] compared novel thermoelectric generator leg geometries to traditional rectangular geometry, with the Diamond-shaped leg geometry offering slightly higher voltage output and experiencing less stress. Segmented type TEGs showed significantly better results in power output and conversion efficiency [16].

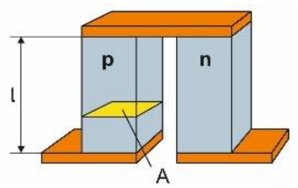
So far, the relationships between the performance-determining parameters of TEGs in combination as a hybrid system with PV components have not been investigated in detail. The research paper addresses this issue and showcases the enhancement of output power generation of hybrid PV/TEG systems through TEGs by modifying leg length and the number of TEGs. An analytical model developed by the authors was employed [17]. that can assess the power generated by both PV and TEG separately and in combination. The paper presents the analyzed results and explains how the considered TEG parameters influence the total power output of the hybrid system.

2 Methodology

The analytical model used for the study on the influence of the dimensions of the thermogenerators and their semiconductor elements (legs) on the power output of a hybrid PV/TEG system under different climatic boundary conditions is described in [17] in detail. It considers the incoming and outgoing heat and energy flows and temperatures as depicted in Fig. 1a. In Fig. 1b the essential dimensions of the semiconductor elements are shown.



(a)



(b)

Fig. 1. Hybrid PV/TEG system, (a) schematic diagram of the system, (b) dimensions of semiconductors.

For the sum of energies entering and leaving the hybrid PV/TEG system, the following correlation was derived [17]:

$$P_R - P_P - P_T - \dot{Q}_P - \dot{Q}_T = 0 \tag{1}$$

with the solar irradiation P_R collected by the PV panel, the electric power P_P provided by the PV panel, the electric power P_T from the TEGs, the thermal loss from the panel front side $\dot{Q}_P$ and thermal loss from the cold side of the TEGs $\dot{Q}_T$.

The parameters of the semiconductor elements of the TEGs, which significantly influence their physical behaviour and thus the power output of the hybrid PV-TEG system, are the Seebeck coefficient α, the thermal resistance R_{te} of a TEG's leg pair and its electrical resistance R_e. These parameters are incorporated into the energy flow $\dot{Q}_T$ from equation (1), for which the following can be applied [17]:

$$\dot{Q}_T = n \cdot N \left(\alpha T_C \cdot I + \frac{T_P - T_C}{R_{te}} + \frac{I^2 R_e}{2} \right) \tag{2}$$

with the number n of TEGs connected to the PV panel back side, the number N of leg pairs of the individual TEG, the current I on the individual TEG, the temperature T_C at the cold side of the TEGs and the PV panel temperature T_P. The parameters R_{te} and R_e are calculated from material characteristics of the semiconductor materials and geometric dimensions of the individual legs, with:

$$R_{te} = \frac{l}{\lambda A} \quad \text{and} \quad R_e = \frac{\rho l}{A} \tag{3}$$

where A is the cross-sectional area of the individual TEG leg, l its length and ρ and λ are the electrical resistivity and thermal conductivity of the semiconductor materials.

The following boundary conditions were applied to simulate the performance of a hybrid PV/TEG energy harvester based on equations (1-3) and the further relationships and simplifying assumptions described in [17]: (a) the use of a monocrystalline PV module with the size of 0.159 m^2, a nominal power output of 30 W and an efficiency of 14.05 % under standard test conditions, and a temperature coefficient of -0.0044 K^{-1}, (b) TEGs with the cross-sectional area of 2673 mm^2 and 72 leg pairs per TEG, a cross section A = 6.76 mm^2 of the individual legs, and the material data according to Table 1, (c) average values for usable solar radiation G and ambient temperature T_A for the year 2020 from the database PVGIS, summarized in Table 2, and (d) a heat transfer coefficient of 2 W/(m^2K) on the front side of the panel and 500 W/(m^2K) on the cold side of the TEGs, which characterise the transfer of heat from the hybrid PV-TEG system to the ambient air.

Table 1. Parameters of the considered thermoelectric materials (average values for the here relevant temperature range) [18, 19].

Specification	**n-type material** $Mg_3Y_{0.02}Sb_{1.5}Bi_{0.5}$	**p-type material** Ag-doped ZnSb
α (V/K)	-0.00015	0.00015
λ (W/(mK))	0.93	1.0
ρ^{-1} (S/m)	55,000	89668.616

Table 2. Climatic boundary conditions.

Location	G (W/m^2)	T_A (K)
Germany (Cologne)	285.583	301.43
Finland (Rovaniemi)	218.344	279.986
Spain (Valencia)	440.403	292.264

The system of equations resulting from the above described principles for determining P_P and P_T was solved iteratively for different leg lengths l between 3 and 4.5 mm and installation locations (Table 2) of the hybrid PV-TEG system using python programming language.

It should be noted that the permissible temperatures for the components of the hybrid system were not taken into account in this study. In practice, these are particularly important for smaller numbers of TEGs.

3 Results and discussion

Fig. 2 shows P_P and P_T as a result of the simulation carried out for the different locations and semiconductor dimensions of the TEGs as a function of the number n of TEGs applied. It is evident that in all cases considered, a larger l leads to a higher power output P_T of the TEGs and a reduction in the power output P_P of the PV module. However, the influence of l on P_T is significantly higher than on P_P. For example, P_T changes by 24 % and P_P only by 7 % in the example of 5 TEGs applied for a system installed in Valencia, Spain, when l is changed from 3 to 4.5 mm. Furthermore, the influence of l increases when higher solar irradiation prevails. It is also evident in all cases that the use of a small number n leads to higher P_T-values but low P_P-values and, conversely, high numbers of n increase the value of P_P slightly but lead to small P_T-values. Irrespective of the influence of l, under the assumptions made here, the achievable increase in P_P is significantly higher in areas with high solar irradiation through the hybridisation of PV and TEGs than in those with low irradiation.

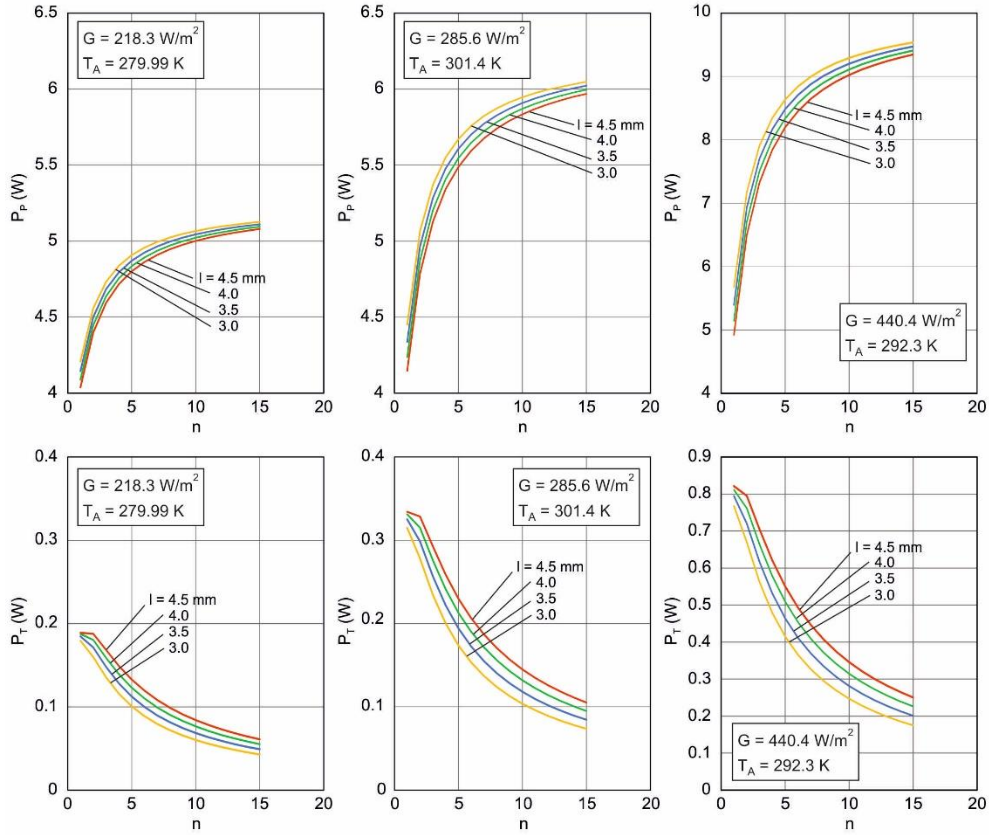


Fig. 2. Simulation results of power output P_P and P_T for different leg-length and installation locations of the hybrid PV/TEG system.

To summarise, in areas with strong solar radiation, l has a more significant effect on the change in P_P and P_T than in areas with less radiation. The design of l can also influence whether the output of the PV is increased or the output of the TEGs. Overall, however, the use of TEGs as a hybrid system can achieve a higher power output than pure PV technology.

4 Conclusion

This research work presents an evaluation study of the performance output power of a hybrid PV/TEG system based on varying geometrical properties. The results, based on weather data from three European cities with different temperature and solar irradiation ranges, revealed that the power output of the PV device and the TEGs can be specifically influenced by the leg length of the TEGs and the total number of TEG modules used. Higher solar radiation increases the effect of the investigated parameters. Further analysis will be conducted to improve the system by changing other important parameters, such as a change in distance between legs, cross-section area of TEG legs, and geometrical shapes, and how these parameters influence the performance of the TEG module and impact the results on the hybrid system.

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