A Review of Solar Energy Harvesting Utilising a Photovoltaic–Thermoelectric Integrated Hybrid System

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Abstract. Solar energy has the potential to be converted from light to electricity; however, solar cells can only utilise the short-wavelength portion of the solar spectrum to do this directly. In contrast, long-wavelength portions of the spectrum can be converted to heat inside solar cells, and such heat can be harvested and converted into electricity by means of a thermoelectric generator (TEG). The integration of photovoltaic and thermoelectric hybrid systems has thus attracted a great deal of attention due to these offering the ability to utilise solar energy across the full spectrum, including light and heat. This paper reviews the possibility of integrating photovoltaic (PV) and thermoelectric generators (TEG) in a PV-TEG hybrid system based on examining recent efforts in the field of PV-TEG creation. It also examines the efficiency improvement in PV-TEGs and their applications in recent years, offering a valuable guide for researchers and designers.

Keywords: Solar energy, Solar cell, Thermoelectric, Solar system harvesting

1. Introduction

Renewable energy is currently attracting a great deal of attention due to climate change and pollution issues which require the immediate limitation of fossil fuel use; sources of energy that are competitive with these traditional sources of electricity are thus in great demand. Most renewable energy originates from the sun, which is the dominant source of thermal energy [1]. The sun offers a continuous source of about $1.2 \times 10^5$ terawatts, which is much more than the power consumed globally [2]; however, this solar energy must then be converted into useful forms such as electrical energy or thermal energy.

Photovoltaic devices convert a portion of solar energy into electrical energy, with the rest being transformed into heat inside the photovoltaic cell, reducing the performance of the device; removing heat from photovoltaic cells is thus a crucial issue. A device made from n-type and p-type semiconductors, known as a thermoelectric generator (TEG), can be used to convert the heat to electricity by applying a temperature difference across the cell [3]. TEGs are characterised by being maintenance free, without chemical reactions, having long lifetimes, being reliable, having no emissions or moving parts, and being environmentally friendly. TEG use can also reduce the heat in PVs if both are integrated in a hybrid system. Examining the combination of PVs and TEGs to reduce the temperature of photovoltaic cells to thus enhance
the performance of the PV as well as to generate electricity from both steps is thus an important piece of work.

This review paper presents an attempt to summarise the state of the art in combined photovoltaic and thermoelectric hybrid systems. Overviews of electricity generation in this format are thus presented and the recent challenges to PV-TEG system applications debated. This paper thus offers a range of references for the development and design of PV-TEG hybrid systems for generating electricity

1.1 Photovoltaic cells

There are many types of photovoltaic cells, including Silicon (mono-crystalline, polycrystalline and amorphous), Organic, Dye sensitised, Multi-junction devices, and GaAs (thin film). Each type has limited efficiency, with the highest being seen in Multi-junction devices (InGaPGaAs/InGaAs), which offer about 37.9% conversion under standard conditions [4].

The performance of photovoltaics is significantly affected by temperature increases, as efficiency decreases with temperature increases due to decreases in the open voltage nature of the cells, which is related to the materials and band gaps used. Mono-crystalline and Polycrystalline solar cells offer good efficiency of about 25-28%. However, amorphous silicon, while led affected by increasing temperatures, has a low initial efficiency.

Recently, a third generation of photovoltaic cells, dye sensitised solar cells, have been developed that present different behaviours; importantly, the electric efficiency of these solar cells increases with increasing temperature up to 50 °C before it starts to decrease [5]. This demonstrates that selecting the right photovoltaic cell to integrate with thermoelectric processes is crucial, as the temperature of the photovoltaic will increase and the efficiency with decrease, and there can be no benefit from the integration where the electricity gained from thermoelectric processes does not exceed these loses.

1.2 Thermoelectric

Thermoelectric power sources are characterised by the conversion of heat into electricity [6][7][8]. The working part of a thermoelectric generator is the electron, and thus a TEG produces no noise, is environmentally friendly, and has no moving parts. There are three main phenomena related to TEG: the Seebeck effect, the Peltier effect, and the Thomson Effect [9]. The Seebeck Effect is a method of generating voltage based on temperature variance across two unlike materials connected in parallel and in series, thermally and electrically, respectively [10][11]-[14]. The Peltier Effect is a method of producing difference in temperature through the junction of different semiconductors: one junction absorbs the heat and the other junction rejects the heat by applying an external current [15]. The Thomson Effect is the main phenomenon that appear in all TEG devices, however, and this is the effect of absorption of heat [15].

1.3 Integrated photovoltaic and thermoelectric in hybrid systems

The spectrum of solar energy is usually between 280 and 4,000 nm. The part of the solar spectrum with lower energy is doing not contribute to electricity production, but are instead converted into heat in the solar cell. This means that some photovoltaic cells, such as those of thin silicon can only absorb wavelengths of up to 800 nm [4]. The remaining heat does not just decrease efficiency, it also reduces panel lifetime [4].

The influence of temperature on solar cell performance it is due to its effect on the electron holes. Temperature increases present as a voltage drop at the edge of the conduction range and thus creates losses as the electrical transformers are small [16]. In a PV-TEG hybrid system, the PV converts radiation with short wavelengths directly to electricity, while the TEG converts most of the remaining the heat into
electrical energy. As a TEG can generate the electricity in the second stage, it enhances the total electrical energy output of the PV-TEG system [4]. In theory, PV-TEG hybridisation can be accomplished in three ways. One of these is spectral splitting into two systems, one directing a portion of wavelength radiation into PV cells and other sending wavelength radiation into the TEG system. The second way involves integrating the PV system and TEG system into a single system (hybrid system) [17]–[29] using thermal paste in between the segments. The third system proposed in this study connects the PV and TEG thermally by manufacturing the reverse side of PV from metal, which transfers the heat rapidly to the TEG, allowing the ensuing electrical connection to be in series or parallel.

2. Configurations of PV-TEG hybrid systems

2.1. Hybrid PV–TEG system with a spectral beam splitting

Solar spectrum splitting systems have attracted interest due to their complete utilisation of solar energy in a wide wavelength range, as well as their ability to reduce the PV operating temperature. These systems divide the solar spectrum into two areas, the light area and the heat area. The light area is usually used by PV, while the TEG uses the heat area. Based on the separation, the temperature is not increased as in traditional systems in the PV cells. A splitting technique which contains a splitter system, a concentrator system, PV cells, a TEG, and cooling systems, as shown in figure 1 was thus developed by [30] to increase the electrical efficiency of the system and minimise PV temperature.

Several studies have been conducted the influence of solar energy concentration and effect of cooling on PV-TEG hybrid systems [20][24][29]. Ju et al. [30] investigated the performance of a PV type GaAsCoSb3 in a PV-TEG system, with directed lines to follow for layout and the development of the PV-TEG integrated system. The results of the study indicated good electrical performance in the hybrid system under the examined operational conditions, with a low range of temperature, a concentration ratio of solar power of between 550 and 770, and a coefficient of heat transfer (h) between 3000 and 4500 W/m²K. In addition, thermoelectrically generated power was seen to represent around 10% of the system’s overall output power.
An analytical model was presented by Bjørk et al to determine the performance of un-concentrated solar photovoltaic cells within different types of PV cell and TEG cell [20]. The results showed that there was an increase in integrated system efficiency of about 4.5 when TEGs were placed on the back of PVs and for the solar spectrum splitting system. In another study, Yin et al proposed a novel design approach to integrate a concentrated photovoltaic-thermoelectric (CPV-TE) system with a solar spectrum division technique. As indicated in Fig. 2, the new system was simulated and the parameters affecting it, such as operating temperature and wavelength intersection, examined to achieve optimum system efficiency [26].
2.2. Integrated PV-TEG hybrid system

An incorporated photovoltaic- thermoelectric system usually consists of aligned array of the two components of the system. The top component is usually the PV cells, as this absorbs the most shortened wavelength, while the lower component is usually the TEG. The two systems work together to increase output power and to improve system performance. Several researchers have thus examined these integrated systems [3][15-28][30–41].

2.3 Proposed integrated system

A lot of heat waste is generated by the methods of fabrication of the PV-TEG systems discussed above; a new method of integration is thus proposed by the author, which has a level of inherent difficulty that requires the person performing it to have experience manufacturing both photovoltaic and thermoelectric generator. The new idea involves making one side of the photovoltaic cell from the metal then fixing the legs of the thermoelectric section directly to this to reduce heat losses, reduce the temperature of the PV and increase total electricity production.
3. Development of the PV-TEG hybrid system

Lamba and Kaushik advanced a thermodynamic model of a concentrated photovoltaic- thermoelectric generation system to examine system performance with regard to the Seebeck and Thomson effects. The principles of heat transfer by conduction through a device of thermoelectric generation were simulated in MATLAB, and the optimum solar concentration was determined to obtain the maximum output power of the hybrid system. Theoretical investigations highlighted that there was a reduction in the CPV-TEG hybrid system output power, however, as the effect of Thomson phenomenon supposed a steady gradient of temperature through the junctions of TEG [22].

Zhu et al. presented research on developing a traditional PV-TEG system within a closed system to minimise heat losses by convection, as shown in Fig. 3. A thermal absorber made from copper plate was utilised to ensure the highest gradient of temperature through the two TEG module ends. The theoretical results showed a temperature change during the heat flow due to the large transversal thermal resistance in the thermal collector. The results of the study also showed that at $ZT \approx 1$, the CPV-TEG system was more efficient than the simple CPV system. The results also showed that the contribution of the TEG in terms of power generation was enhanced with concentration [34].

Al-Nimr et al. investigated a novel model including an integrated PV-TEG system with a receiver in a cavity that could generate electrical power and hot water simultaneously. Figure 4 presents the detailed structure of the system [43]. The experimental results indicated an enhancement in the electrical characteristics, though the TEG contribution was very low due to load resistance and impedance mismatch.

![Physical model of hybrid PV-TEG](image)
Figure 4. A solar thermal collector novel PV-TEG hybrid system [43].

Lekbir et al. measured temperature and power generation in a PV-TEG in order to confirm the ability of the energy conversion device, with experimental results compared with the theoretical development information from the model. The practical results indicated that the system output electrical power rose as high as 0.12 W [49]. Hybrid PV-TEG system performance integrated with a parabolic trough concentrator was studied by [18] as shown in fig. 5. A mathematical model using heat transfer and electrical equations was utilised to examine the performance of the PV-TEG system, and the results suggested electrical efficiency improvements caused by placing solar cell and thermoelectric modules on the side areas of the absorber tube [42].
Figure 5. Evacuated tube of the hybrid system [18].

Marandi et al. [28] presented an empirical examination of an integrated photovoltaic-thermometric generation hybrid system with a solar cavity-receiver. The module temperature was increased by reducing the heat loss of solar radiation, with the TEG module converting heat directly into electricity using the Seebeck effect via the difference of temperature. The receivers were used to drop the temperature of the PV module, thus producing more output energy. In the laboratory, the device was used under 1,000 W/m$^2$ solar radiation and examined under variation solar irradiance levels throughout the day. The new system’s efficiency increased by up to 21.9% in real conditions in the early morning, though the PV panel’s output power was highly influenced by increasing temperature, with efficiency dropping as the day progressed.

A comparison of photovoltaic only and hybrid photovoltaic-thermoelectric systems was presented by Li et al. [24]. Their system included a heat pipe and three-dimensional numerical simulation following the finite element method was used for analysis. The influences of concentration ratios, ambient temperature, and wind speed in the system were investigated, and the results showed efficiency enhancements of around 61% in the coupled PV-TEG system and heat pipe at working conditions, at an ambient temperature of 313.15 K. Shittu et al. [23] examined the electrical and thermal contact effects on concentrated photovoltaic-thermoelectric generation systems’ performance in 12 dissimilar states within a 3D numerical study. The results suggested that discounting overall resistances at contact area in the hybrid system caused overestimation of the total output power of about 7.6%, while the efficiency was 7.4%.
4. Techniques for cooling

Using cooling systems can increase the total performance of photovoltaic thermoelectric hybrid systems; these are usually applied in two ways: active or passive. In both methods, the performance of the thermal waste system is generally described by the coefficient of heat transfer. Various researchers have actively reported cooling technologies that use air or water due to their high heat transfer coefficients [4], [23], [36], [43-45]. However, a circulating device is essential for active cooling systems, which requires an external power source. This power and the associated additional cost must be taken into account in performance and economic analyses of these systems.

Rodrigo et al [46] and Acar et al [47] examined active cooling using the experimental setup shown in fig. 6 [47], which included a Fresnel lens, PV, TEG and cooling system. The TEG was located in varying locations, and the PV cells and the cold side were cooled with a working liquid. Results during summer testing showed an increase in system efficiency, with voltage increased by 15% and current by 60%.

![Figure 6. Experiment diagram for CPV-TEG [47].](image)

The performance of a PV-TEG associated heat pipe system was examined in [16] and [30]. Mathematical models were developed using elementary heat transfer mechanisms such as conduction, convection, and radiation, and the effect of working conditions such as radiation, wind speed and environment temperature on system efficiency was examined. Under the same operating conditions, the study results indicated increased efficiency as compared to PV panels alone. The results also showed that wind speed had a significant effect.

Darkwa et al. developed a mathematical model to extend the theory of incorporating a PCM thermoelectric device into the PV module to improve performance. ANSYS FLUENT was used to perform numerical analysis of a system that included a PV, TEG and PCM. Various parameters such as thickness, conductivity, and temperature of phase change were investigated [38]. Another study by Cui et al. examined the use of phase change materials between a PV and a TEG to regulate system temperature oscillation due to solar radiation, as shown in fig. 7. A mathematical model was presented to verify the efficiency of the system and the feasibility of utilizing various types of photovoltaic cells such as crystalline solar cells, single junction GaAs, and GaInP/In GaAs/Ge. Optimisation of the PV, PCM and TEG system temperature was found to depend on the liquefying degree of the phase change material. The results showed that the optimal operating...
temperature of the PV-PCM-TEG was approximately 330 K and the enhancement in total efficiency was about 1% as compared to PV alone and PV-TEG. The best performance was seen in the GaAs PV cell [48].

An experimentally study was performed by Tengfei et al to examine the concentrated photovoltaic-phase change material-thermoelectric hybrid system in comparison with a CPV. The new system presented favourable results, and the study showed that the thermal contact resistance at the interface causes the highest deviations of temperature within the PV cell and thermoelectric generation [50].

Yin-Ershuai et al. performed an experimental study examining the thermic strength impact within concentrated photovoltaic-phase change material-thermoelectric hybrid systems, as shown in fig. 8. In that study, dilatable graphite, frothed copper, and paraffin were used to reduce thermic impedance and develop thermal accessibility. An empirical study was thus conducted between three groups of CPV, TEG and PCM systems utilising diverse paraffin PCM platelets to check the influence of thermic impedance at contact areas and heat opposition on the heat-extracting unit. The results indicated the hybrid system showed better performance than the system without PCM [39].
5. Optimisation and development of hybrid PV-TEG devices

Combining PV with TEG will increase the PV operating temperature due to the new thermal resistance produced via the TEG; optimisation of the integrated PV-TEG system is thus fundamental and an exchange between the waste heat from the PV and energy obtained from the TEG is required. Researchers have conducted numerous theoretical and experimental investigations into improving PV-TEG, including optimising TEG engineering for a specific region of the PV. The results showed that the size of TEG is very important to hybrid systems as it can increase or decrease the total power generated from the hybrid system and can render integration useless [43].

Wellars et al. proposed a hybrid PV-thermoelectric system based on a new experimental model, which could function as the standard mode for an integrated solar system. The model consisted of a photoelectric panel, a focused irradiation lens, a Bi2Te3 thermoelectric generation, and a water-cooling unit linked within the same optical plane, as indicated in fig. 10. Model performance and influencing parameters were then examined theoretically and experimentally [40].

Figure 8. Schematic diagram of system structure including CPV, TEG, and PCM [39].
6. Future ideas

Several new ideas have emerged in this work as a result of reviewing papers on state of art of the PV-TEG hybrid systems. The following ideas have either not been investigated yet or represent rich areas of research that require further investigation:

- Hybrid systems with special types of PV: for example, one side of the PV may be made from a metal that would facilitate transfer of heat between the PV and TEG and increase the total efficiency of the hybrid system.
- Optimisation of the TEG area for large area PVs.
- Using vacuumed systems to accurately determine heat losses.
- Using efficient cooling systems to withdraw heat from the other side of the TEG.
- Increasing the solar intensity on the PV to increase both the light on the PV and the heat in the TEG.
- Selecting the proper type of PV cells for hybrid systems.
- Using nanotechnology in fabrication, both for main materials and for cooling systems.
- Outdoor experiments.
- Cost analysis, based on the potential expense of hybrid systems.
- Ensuring that the figure of merit (ZT) for the TEG is in an acceptable range.
7. Conclusions

Integrating photovoltaic cells with a thermoelectric generator in a hybrid system has attracted many researchers’ attention; both splitter and tandem systems have been investigated in the search for the right solution to accessing the wide spectrum of solar energy. In this paper, a comprehensive review of such PV-TEG hybrid systems was offered.

The review highlighted that several parameters directly influence the design and performance of PV-TEG hybrid systems, including the efficiency of the photovoltaic cell, the figure of merit (ZT) of the TEG, the operating temperature of the PV, the thermal resistance between the PV and the TEG, and solar radiation levels. Most existing studies on PV-TEG have been theoretical or simulation and few have been done under experimental or outdoor conditions. More experimental investigation, including in varying weather conditions during the day and the year, is thus required. Most theoretical studies were also one-dimensional, and further 3D research is required to develop an understanding of the behaviours of the proposed PV-TEG hybrid systems more fully. Photovoltaic-thermoelectric hybrid systems are also more costly as compared with PV, and studies in this area are thus advised.

This paper also proposed a novel idea for future attempts, which consists of sticking the TEG legs directly to the PV based on manufacturing a PV with a metal cathode or anode to facilitate this. This system should increase the heat transfer between the PV and TEG, reduce the PV operating temperature, and increase the total efficiency of the hybrid system.

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