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Analysis of different Hybrid TEG/TEC Configurations

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Abstract

The growing demand for electricity and the looming environmental crisis are the main challenges to be faced and solved today. This calls for innovative energy conversion systems, for which efficiency and reliability are among the most sought-after features. Thermoelectric generators are devices that can offer partial or complete solutions to these challenges of the new millennium. The advantages of these technologically advanced devices are many: they are environmentally friendly, reliable and have a long service life. Furthermore, by applying thermoelectric generators, it is possible to improve the efficiency of existing systems or meet the electricity demand of different systems with high flexibility. At the same time, their low conversion efficiency has so far prevented their wide application, limiting them mainly to research. However, recent advances in thermoelectric materials and devices are pushing this technology to find its place among state-of-the-art energy conversion systems. This review explores the state of the art in terms of research and solutions already on the market, in order to illustrate a comprehensive and realistic perspective of the PV-TEG/TEC structures.

Keywords: Solar panels; Metal foam; Cooling; Integration; Structural function.

1. Introduction

Today, growing electricity consumption, depletion of fossil fuel deposits, global warming, and environmental problems are among the most difficult challenges facing humanity. The energy sector is now responsible for a large portion of greenhouse gas emissions, and in order to reduce them sharply in the coming years, a huge transition in energy supply and conversion is essential. Toward that goal, most studies conducted have focused primarily on improving the efficiency of existing systems or introducing new systems with greater efficiency and flexibility toward the use of clean and renewable energy sources. In recent decades, the actual development of industries, transportation systems, and human lifestyles have mostly been based on the conversion of chemical energy from fossil fuels into thermal, mechanical, and electrical forms. Despite this, in order to achieve net zero emissions by 2050, the share of electricity generated would have to increase to nearly half of total energy consumption, and most importantly, this electricity would have to be supplied from renewable sources rather than fossil fuels [1]. Moreover, although energy demand is expected to increase, much of this demand can be reduced by improving the energy efficiency of energy systems [2]. The growth in demand and the need to use low-intensity renewable sources such as solar and the advent of new technologies that require access to electricity on board and on a more permanent basis than batteries are some of the reasons that add new dimensions to energy systems. Therefore, energy systems seem to be in urgent need of high-performance devices with new capabilities such as scalability, compatibility, and reliability. As a result, several studies are underway that intend to develop such devices. Among them that has gained much attention in recent decades is the thermoelectric generator (TEG). The TEG can produce an electromotive force through the Seebeck effect when exposed to a temperature difference. TEGs have many advantageous features, such as direct energy conversion, no moving parts, high reliability and scalability.

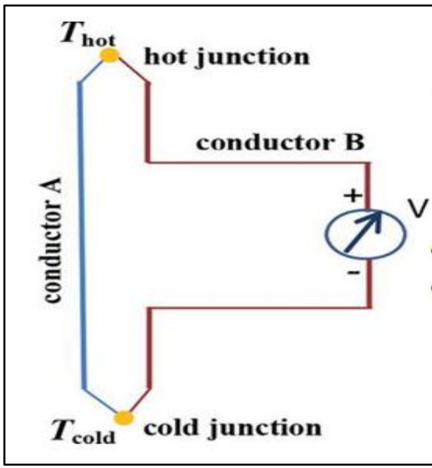
Unfortunately, to date, the low efficiency of TEGs is the most significant obstacle that mainly prevents their large-scale application [3, 4]. However, TEGs are also potentially suitable for many applications where high thermoelectric conversion efficiency is not the main goal. Such applications include, for example, the use of a free heat source (such as waste heat). Although thermoelectric devices are capable of operating in cooling, heating (TEC) and power generation (TEG) modes, the latter is the main focus of this review. Over the past decades, countless research on thermoelectricity has been conducted and review articles have been published illustrating different aspects of the topic. In general, the research conducted on thermoelectricity can be classified into three interdependent areas: (a) Materials Science, which focuses on new thermoelectric materials and the techniques required to improve the performance of existing thermoelectric materials [5-9]; (b) Design of new structures, which focuses on evaluating new solutions to design and improve thermoelectric devices in relation to roles that could fit with the least performance degradation [10-12]; Optimisation techniques for TEG systems, taking into account the needs and characteristics of such applications [13-18]. Research by companies, universities and research centres to date still shows a disconnect in relation to what is available and of interest to the market. This review aims to introduce a comprehensive view of the features of integrated TEG and to recognise the advantages, challenges and restrictions of using this technology. Overall, this review provides a unique and comprehensive view of the integration of solar photovoltaic panels and thermoelectric generators in the context of today's energy market in order to present a clear and realistic perspective, while also presenting innovative solutions for future directions.

2. Thermoelectric Effect

Thermoelectric effects are reversible phenomena that lead to direct conversion between thermal and electrical energy [19]. Direct energy conversion is based on the physical transport properties of thermoelectric materials (thermal conductivity, electrical conductivity and Seebeck coefficient) and their energy conversion efficiency in terms of the figure of merit. The main phenomena occurring in a thermoelectric device are the thermoelectric effects (Seebeck, Peltier, Thomson) and the Joule effect.

- When electrical energy is converted into thermal energy, the phenomenon is known as the Peltier effect and its uses are in the fields of heating and cooling. The device used is called a thermoelectric cooler (TEC) [20-22]. In this application, thermoelectric modules can effectively regulate the temperature [23].
- When thermal energy is instead converted into electrical energy, the phenomenon is called the Seebeck effect, with specific uses for power generation. The device used is called a thermoelectric generator (TEG) [24].

The Seebeck effect occurs when a temperature difference across a conductor produces a voltage at its ends. Two separate conductors A and B are connected together to form the junctions of a circuit (Fig. 1). These conductors are connected electrically in series and thermally in parallel. One junction has the hot temperature Th and another the cold temperature Tc, with Th greater than Tc. The Seebeck effect occurs due to thermal diffusion, which causes charge carriers (electrons or holes) to move across (or against) the temperature difference in the conductors.



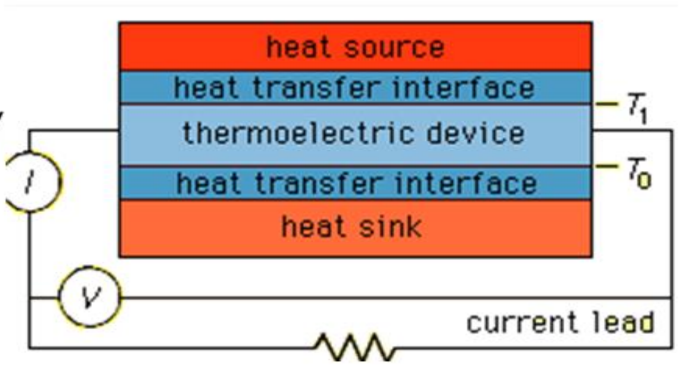


Figure 1. Seebeck effect **Figure-2.** Thermoelectric generator basic configuration

2.1. Thermoelectric Power Generator

Thermoelectric generators comprise the entire class of solid-state devices that convert heat directly into electricity or convert electrical energy into thermal energy for heating or cooling. Such devices are based on thermoelectric effects involving interactions and exchanges between the flow of heat and electricity through solid-state bodies. All thermoelectric power generators have the same basic configuration, as illustrated in Fig. 2. A heat source provides the high temperature, while electricity is provided by a heat source. A heat source supplies the high temperature, while electricity is supplied by a heat source. A heat source provides the high temperature and the heat flows through a thermoelectric converter to a heat sink, which is kept at a lower temperature than the source. The temperature difference across the converter produces direct current (DC) to a load with a terminal voltage (V) and a terminal current (I). There are no intermediate steps involved in energy conversion. Thermoelectric power generation is delineated and identified as direct energy conversion. Another uniqueness of the thermoelectric conversion process is that the direction of the energy flow is reversible. If the load resistor is removed and a DC power supply is substituted, the thermoelectric device can be used to draw heat from the 'heat source' element and lower its temperature. The incoming electrical energy can be converted directly into pumped thermal energy for heating or cooling, or the incoming thermal energy can be converted directly into electrical energy for lighting, operating electrical equipment and other activities. Any thermoelectric device can be used in both modes of operation, although the design of a particular device is usually optimised for its specific purpose. The geometry of thermoelectric generators varies depending on the type of heat source and heat sink, the power required and the intended use (fossil, solar and nuclear energy).

3. The PV-TEG/TEC Structure

Several hybrid PV-TEG systems have recently been developed to effectively utilise the broad spectral region of solar energy and improve the efficiency of PV components and the integrated TEG system. In this chapter, we review some of the most popular structures based on the integration of PV and TEG elements subjected to normal and concentrated light. In the first analysis, we discuss PV-TEC. The purpose of the TEC is to cool the PV to increase its efficiency. The most popular structure on the market and in the literature is a sandwich structure with direct coupling, as shown in Figure 3 [25]. The TEC element is placed between the PV and a heat sink. The cold side of the TEC is in contact with the PV, while its hot side is connected to the heat sink. Power for the TEC is supplied by a second panel

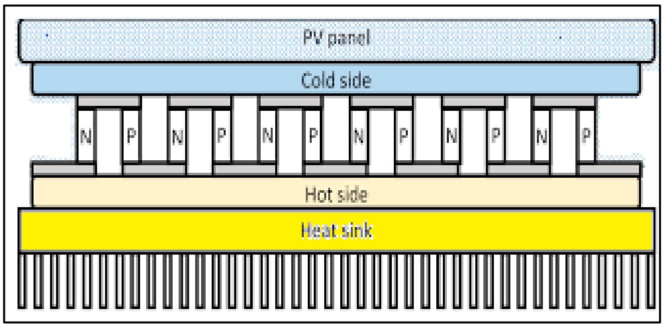


Figure-3. Photovoltaic–thermoelectric cooler (PV-TEC) structure

The second structure is the PV-TEG (Figure 4). The TEG is used to cool the PV by absorbing heat from the PV cells and converting part of it into electricity (electrical cogeneration) and transferring the rest to a heat sink. The advantage of this structure is the electrical cogeneration of the TEG but the cooling efficiency is lower than in the PV-TEC configuration. The heat sink can be passive (aluminium heat sink) or active (water [25, 26] or nanofluids [27]).

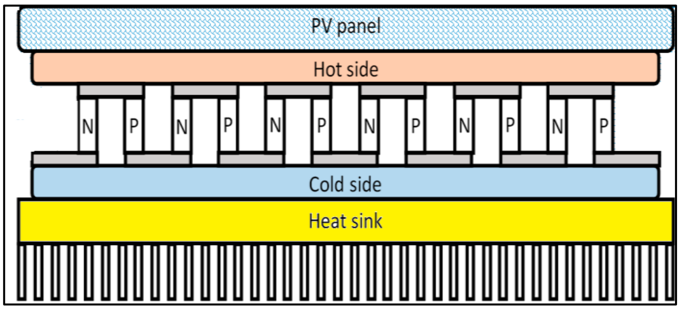


Figure-4. PV–thermoelectric generator (PV-TEG) structure

The third is presented in Figure 5 and consists of three active components also embedded in a sandwich structure (PV-TEG-T). In this apparatus, the heat sink is replaced by a thermal collector to add the generation of thermal energy to electrical energy. Indirectly coupled structures with a distributed or mixed structure have been analysed in the literature. The fourth structure is the PV-TEG distributed structure, shown in Figure 6. Actually, it is a mixed structure involving heat pipes or a microchannel heat pipe system (MCHP) consisting of two parts: a part with an evaporator function that is directly coupled with the PV, extracting waste heat from the PV, and a part with a condenser function that is directly coupled with the TEG, conducting heat to the hot side of the TEG [28-30].

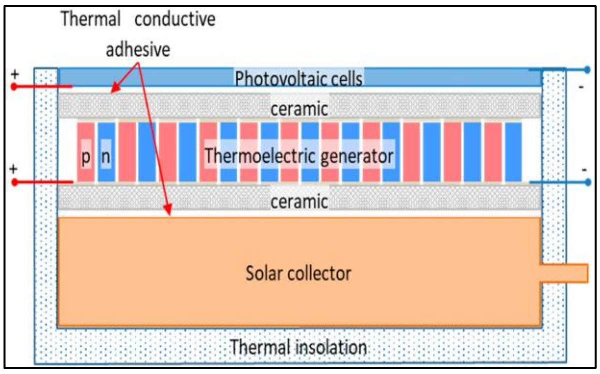


Figure--5. PV-TEG-T structure from Cotfas and Cotfas [31]

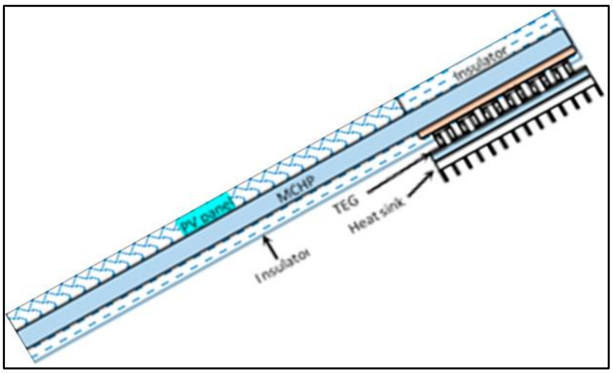


Figure 6. PV-TEG with micro-channel heat pipe from Makki, *et al.* [29]

The fifth structure analysed in the literature is based on the separation of the light spectrum into two parts, long and short wavelengths, using a beam splitter (BS) in concentrated sunlight, as shown in Figure 7. The shorter wavelengths are concentrated on Pvs, while the longer wavelengths are concentrated on TEGs.

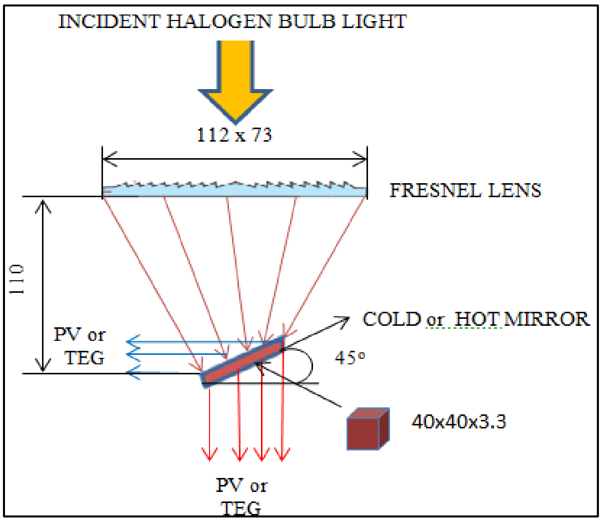


Figure-7. PV-TEG indirectly coupled structure with beam splitter from Piarah, *et al.* [32]

Eskandar, *et al.* [33], performed a performance analysis of a new model of a PV-TEGs photovoltaic system enhanced with flat-plate reflectors. The energy produced by the system is hot water flowing in rectangular-section aluminium tubes connected to the cold surfaces of TEGs in series. The results showed that the difference in electrical energy produced by the PV module and the TEGs due to the presence and absence of reflectors is 1095.448 (kJ) and 80.874 (kJ), respectively. Furthermore, the daily thermal efficiency of the system was about 42%. Amirhooshang, *et al.* [34], proposed an experimental investigation of a PV/T system containing a TEG section between a water heat exchanger and an air heat sink, The study proposes a new arrangement of the integrated PV/T-TEG system using water and air cooling to improve the performance of PV modules in hot regions. The system applies TEGs between the water heat exchanger and the air heat sink, instead of between the PV module and the cooling fluid. This avoids the uneven cooling associated with directly connecting the TEGs to the back side of the PV. The proposed system was tested in four different climates in Iran and compared with PV-TEG and PV alone. The results showed that the proposed system reduced the surface temperature of the PV by 23%, increased the electrical power output by more than 15%, and improved the electrical efficiency of the PV by about 3%. The average total energy efficiency was 55.6% and the maximum thermal efficiency was about 20%, which are satisfactory values for the non-focused TEG-based PV/T system. In contrast, Xin, *et al.* [35] present a detailed performance analysis of a new concentrated system consisting of a photovoltaic/thermal module (PV/T) with phase change material (PCM) and a solar thermal collector (ST) with thermoelectric generators (TEG) connected in series. In addition to acquiring considerable electrical energy, more high-temperature thermal energy is also obtained. In this system, the PV/T module generates both photoelectric energy and low-temperature thermal energy, while secondary heated water and secondary thermoelectric production are obtained through the ST module and the TEG on the ST. Theoretical investigations show that the system consisting of the PV/T module and the ST module in series (PV/T-ST) performs well in terms of thermal performance and overall performance. During all-day operation, compared to the PV/T-PV/T system, the final temperature of the water tank in the PV/T-ST system is approximately 5°C higher. Furthermore, the electrical efficiency and thermal efficiency are 10.65% and 65.22% respectively at 12:30 p.m. when using the 1.1 m2 Fresnel lens. The TEG converts part of the thermal energy into electrical energy, increasing the amount of high-level energy by approximately 321.53 kJ during the day.

4. Innovative PV_TEG Structure

An innovative TEG cooling system (Figure 8b), which is rather different from the state-of-the-art configuration (Figure 8a), could prove to be one that technically and productively enables a significant simplification of the solar cell cooling technology and thermoelectric conversion by Seebeck effect, by integrating the heat exchanger with the thermoelectric converter. In the integrated system, described by Fabbri *et al.*, [36, 37], the heat exchanger also acts as a carrier for the cells. The main innovative aspects of the technology concern the integration between the heat exchanger and the thermoelectric generator, the independence between heat exchange efficiency and thermoelectric generation efficiency, as only a portion of the heat removed from the panel passes through the thermocouples, and the use of a joint system to make the electrical contacts, resulting in simplified construction and installation. Furthermore, the apparatus can be realised according to a modular structure so that it can be easily adapted to different sizes of photovoltaic panels. Finally, the apparatus not only serves to cool the solar panel and increase its efficiency, but also has the advantage, when mounted on the roof, of acting as a thermal insulator. The core of the TEG/heat sink module consists of P- and N-doped thermoelectric legs joined together by press-fit joints, so that thermocouples are more compact and easier to construct and assemble. In addition, the integrated TEG cooling system serves as a support for the solar panel. Moreover, thanks to its modularity, it can be adapted to different requirements.

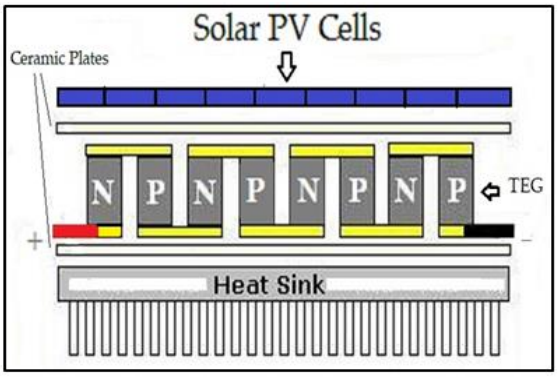


Fig-8A. State of the art PV-TEG module from Fabbri [36]

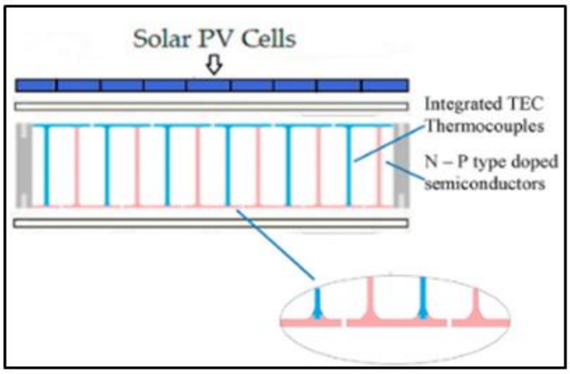


Fig-8B. Integrated PV_TEG apparatus from Fabbri [36]

A reference geometrical configuration of the cooling system suitable for practical applications was identified, with respect to which the effect of changing certain parameters was investigated. For a standard photovoltaic panel of 100 x 125 cm the proposed cooling system allows an increase of almost 15% of the electrical power converted by the cells. Moreover, the exploited Seebeck effect provides an electrical power (ranging from 61.2 to 71.2 W in the studied cases) that is respectively 10.9 and 1.33 times the power required for forced ventilation.

6. Conclusions

One of the main and challenging technological advances that can simultaneously harness electrical and thermal energy and increase overall performance while also utilising renewable resources is the integration of hybrid PV-TEG systems. In this review, several PV-TEG hybrid configurations were analysed. PV-TEG systems provide a wide-range solar radiation harvesting mechanism based on the potential of PV generators and TEGs for power generation. Thermal contact resistance between PV and TEG and between TEG and heat sink reduces the efficiency of the PV-TEG system by producing excessive PV temperatures. This problem can be partially avoided by adding a sheet between the PV and the TEG. In general, the cold side of the TEG is cooled using various techniques to maintain a large temperature difference in the TEG. Furthermore, the concentration ratio, figure of merit, temperature coefficient and heat transfer coefficient are all factors that influence the efficiency of the integrated PV-TEG system. The various approaches taken by recent studies to improve the performance of the coupled system were also examined. Based on the preliminary analysis, the current review found that increasing the concentration ratio improves the efficiency of the TEG and thus increases its contribution to the hybrid system. This, however, is only possible with an effective heat sink that is well integrated into the PV-TEG system such as the one proposed by Fabbri [37], which also acts as a support for the PV cells. Temperature variations controlled by the PV to TEG can also significantly improve the overall efficiency.

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