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Review

Advances in the performance of hybrid photovoltaic-thermoelectric generators: a review

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ABSTRACT

Renewable energy is becoming more apparent as a key solution to climate change, energy challenges, and economic challenges. As a result of the abundance of solar irradiance, photovoltaic power generation remains one of the most promising energy sources. Despite the wide spectrum of solar irradiance, PV solar cells are only able to convert a small part of it into electricity. The remainder of the spectrum is lost as heat waste, which increases the temperature of the PV panels. As the temperature rises, both the efficiency and lifespan of solar PV panels are reduced. To mitigate the aforementioned issue, thermoelectric generators (TEGs) are used in conjunction with solar PV systems. A TEG is a device that converts thermal energy (heat) into electricity based on the thermoelectric effect caused by a temperature gradient across the thermoelectric module. This paper presents an overview of studies on hybrid PV-TEG systems. In addition to hybrid PV-TEG systems, PV and TEG systems are briefly described. PV-TEG systems are compared with individual PV systems in terms of their major operational parameters, including temperature and power generation efficiency. Finally, an update on recent developments in PV-TEG systems is provided.

1. Introduction

Due to the continual depletion of non-renewable resources, such as fossil fuels, and the high demand for electricity, man has had to find alternative sources of energy to meet his energy requirements. In 2024, modern renewables represented 13% of the global total final energy consumption (TFEC) [1]. Modern renewables are categorized as renewable electricity, renewable heat, and Biofuels. Renewable electricity, which contributes more than 7% of energy demands, includes hydropower, wind power, solar photovoltaic (PV), and geothermal. It is also stated that a large growth in renewable energy investment is required compared to the last decade. This shows the importance of research activities in the design and improvement of renewable electricity resources, including solar PV. A direct electrical energy generation system includes PV solar cells, turboelectric generators, piezoelectric generators, and thermoelectric generators (TEGs) [2]. Among the aforementioned systems, solar energy is the most appealing due to its efficiency, sustainability, and environmental friendliness [3]. With dedicated research, solar panels are expected to provide 30%–50% of the nation's electricity by 2050 [4]. In recent years, different processes have been investigated to convert solar energy into thermal, electrical, and chemical energy, and the most successful of these is the use of solar panels to produce electricity. PV cells have several advantages, including the fact that they provide clean, green energy, they have no rotating parts, and they have abundant input energy. A further advantage of PV cells, when compared to other renewable energy sources, is that they have the highest power density [5]. It is predicted that almost 16% of the world's energy requirements directly come from solar PV cells by 2050 [6]. However, solar PV panels with the current technology can convert only a small amount of the incident solar energy, and the remainder is wasted as heat. As a result, the conversion efficiency is low, and excess heat reduces the lifespan of the system [7]. In contrast, TEGs can convert thermal energy into electrical energy. These are electric generators that are environmentally friendly, do not require moving parts, and require very little maintenance. TEGs can be used to convert waste heat from solar cells into electricity in order to make solar PV cells more efficient and generate more power. This idea led to the development of an integrated PV-TEG system. However, combining two systems establishes a more complex system regarding energy transfer considerations as well as conflicting effects on PV cells and TEG modules [8]. High temperatures are harmful to PV cells, both from the standpoint of power generation efficiency and life expectancy, and a high-temperature gradient is required in order to increase the power output of TEG modules. As a result, hybrid PV-TEG systems present an extensive research opportunity for addressing trade-offs and optimizing the PV-TEG systems to achieve higher electrical efficiency than single PV solar panels. Although hybrid PV-TEG systems introduce new challenges, it seems a great solution to increase power generation using solar energy and help providing more sustainable, clean, and reliable electric energy to the global market. The operation of hybrid PV-TEG systems has recently been extensively investigated, and new developments in power generation have also been reported. In this work, we will review numerical and experimental studies that have been conducted on integrating PV and TEG systems in order to achieve increased efficiency. First, the principles and theoretical modeling of both PV cells and TEG modules have been introduced. Next, different approaches to mitigate the waste heat on PV cells are reviewed and compared with temperature reduction in the hybrid system in which the TEGs were utilized. In the end, the outline of challenges and the next steps to improve the hybrid PV-TEG system were directed.

2. PV solar cells

Photovoltaic systems are composed of solar cells made from semiconductors such as monocrystalline silicon, polycrystalline silicon, and thin films made of silicon. PV modules are arrays of photovoltaic cells in parallel and series. They generate power in proportion to the number of PV cells they contain. Solar PV systems have been widely adopted for the generation of electricity in a variety of applications, including building integrated systems, refrigeration, air conditioning, and street lighting [6]. Solar systems may last for an extended period of time, ranging from 25 to one hundred years [9]. PV module temperatures are affected by a wide range of environmental factors, including wind speed, ambient temperature, relative humidity, dew, dust, and solar radiation [10]. Typically, PV cells convert a majority of the visible spectrum and a portion of the infrared spectrum into electricity, as shown in Figure 1 [11], while the remainder of the infrared spectrum ends up being used to heat the PV cells [12]. Even though the PV modules generate abundant amounts of electrical power, the efficiency of the PV modules is in the range of 10-15% as they are able to convert only the visible range of solar irradiation. The remainder of absorbed energy is converted into heat, which raises the temperature of the solar panels, reducing their efficiency and power output and causing them to be damaged [13].

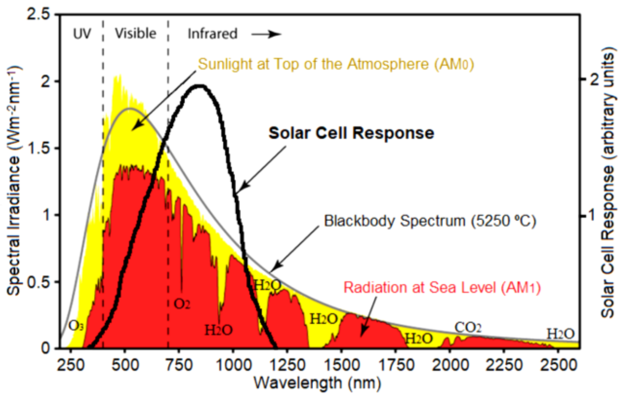

Figure 1. Solar radiation spectrum in comparison with the spectral response of a silicon solar cell [11]

The conversion efficiency of PV panels is maximum when they are operated at temperatures between 25-35°C, and at higher temperatures, the efficiency will drop by 0.25-0.5% as the temperature increases by 1°C depending on the materials used [14]. At average module temperatures of 35.4°C and ambient temperatures of 25.31 °C in Namibia, Temaneh and Mukwekwe [15] observed that a 37.8 kW solar PV system lost at least 3.21% of its rated output power when operating in dry and sunny conditions. The optimal operating temperature for PV cells is 25°C, which ensures high power efficiency and prevents premature aging. Maintaining this temperature is crucial for maintaining high power efficiency.

2.1 PV structure and performance

Through the photovoltaic effect, solar energy is directly converted into electricity in a PV cell. This effect refers to the phenomenon that occurs when materials with semiconductive properties, such as silicon, are subject to sunlight. The schematic of a PV cell structure is shown in Figure 2. The PV cell consists of two layers of semiconductor materials, where the p-n junction is exposed to the sunlight [16].

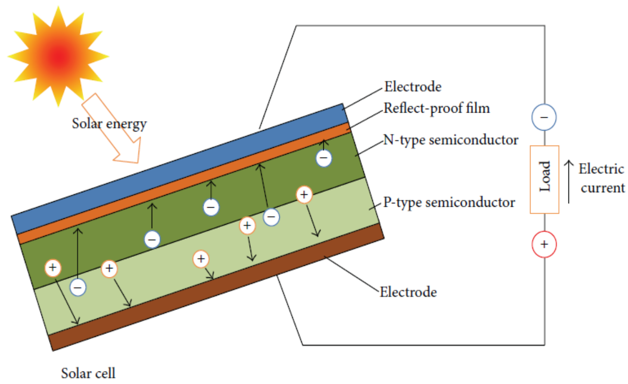

Figure 2. Schematic of a solar cell structure [17]

Figure 3 illustrates the equivalent circuit model for a PV cell [18]. The PV cell behaves as a simple p–n junction diode when there is no exposure to sunlight, where its current equation is given by the Shockley diode equation of

$$I_{sat} = I_0[\exp\left(\frac{eV}{akT}\right) - 1] \quad (1)$$

where, I_0 represents the reverse saturation current, constant e represents the absolute value of the electron's charge which is 1.60217646×10^{-19} C, a is the quality factor of the diode, k is the Boltzmann's constant (-1.380653×10^{-23} J/K), and T represents the junction temperature.

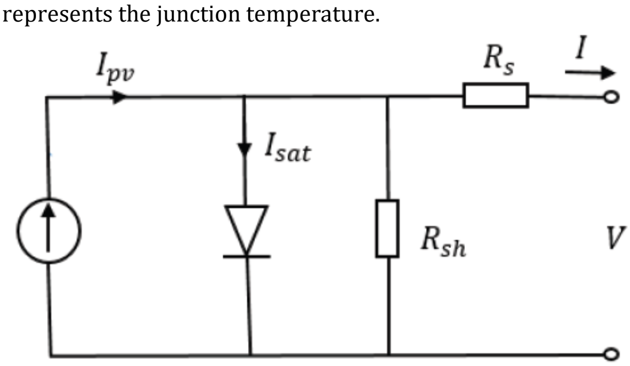

Figure 3. Circuit model of a PV cell [18]

The photovoltaic effect occurs when photons absorb light and form electron-hole pairs across the junction, creating a voltage difference. As a result, charge carriers flow in the external circuit, and a current is generated. This current is called photocurrent (I_{PV}). Using the equivalent circuit, the output current is:

$$I = I_{PV} - I_{sat} = I_{PV} - I_0[\exp\left(\frac{eV}{akT}\right) - 1] \tag{2}$$

An additional resistor R_s is added to the circuit in series with the PV cell to account for losses caused by three factors, namely, contact resistance between the silicon and electrode surfaces, current flow resistance within the silicon, and electrode resistance. Moreover, to include the effect of substantial temperature variation and the leakage current, the shunt resistance, R_{sh}, is added in parallel with the diode. With these additional components, the output current is [16]:

$$I = I_{PV} - I_0\left[\exp\left(\frac{e(V+IR_s)}{akT}\right) - 1\right] - \frac{V+IR_s}{R_{sh}} \tag{3}$$

To determine the short circuit current, I_{sc}, as the highest generated current, the output is shorted and V=0, which results in $I_{sc}= I_{PV}$. The open circuit voltage, V_{oc} is the voltage of the cell when there is no solar exposure, and it is determined when the output current is zero (I=0). In this condition, $I_{PV}=I_{sat}$. Combining all with the current equation, V_{oc} is calculated as [8]:

$$V_{oc} = \frac{kT}{e}\ln\left[\frac{I_{sc}}{I_0} - 1\right] \tag{4}$$

The output power is then calculated by:

$$P = IV \tag{5}$$

The maximum current (I_{mp}) is:

$$I_{mp} = \frac{eV_{mp}}{kT+eV_{mp}}(I_{sc} + I_0) \tag{6}$$

And maximum power is

$$P_{max} = I_{mp}V_{mp} \tag{7}$$

The fill factor (FF) of the cell, which is defined as the maximum possible output power to the actual output power is determined by Equation 8. The fill factor is an important parameter in efficiency calculations and it is determined by the manufacturer.

$$FF = \frac{I_{mp}V_{mp}}{V_{oc}I_{sc}} \tag{8}$$

A PV cell's maximum efficiency is determined by the ratio of maximum generated power to input power:

$$\eta_{PV} = \frac{V_{oc}I_{sc}FF}{P_i} \tag{9}$$

where P_i is the incident solar radiation power.

2.2 Temperature effect on PV cell Operation

The power generation efficiency of solar cells decreases with increasing temperature, which is an important consideration when using these cells. The PV cell efficiency drop by temperature is shown in Figure 4. There are two main approaches to cooling down the PV modules: active and passive methods. Active cooling systems are powered by electricity to operate. Fans and pumps are examples of these systems. Despite this, passive cooling systems do not require electricity to work. Active methods produce a higher efficiency by reducing the temperature up to 30°C, where the electrical efficiency could increase by 22% [20]. They consume power in order to cool down the panels. This is a major concern. However, in the case of passive methods, they do not require any power and cool down the panel by 6°C-20°C with an improvement in electrical efficiency of up to 15.5% [20]. Due to the advantages of energy-free use, much research is being carried out on the use of passive cooling methods such as using fins, cotton wick, phase change materials, heat pipe, selective coating, and liquid immersion [21].

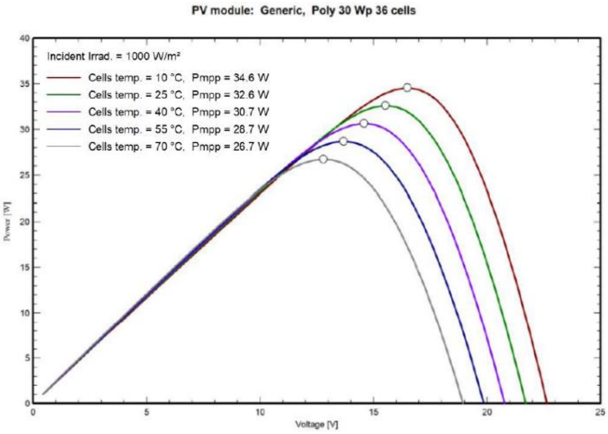

Figure 4. Effect of cell temperature on the output power of a PV cell [19]

To evaluate the effectiveness of the fins as a means of cooling the solar PV modules, numerous experiments were conducted. To utilize the fines as a heat sink, experiments were conducted where the fins were attached with glue to the back of PV panels (Figure 5). A comparative experiment was performed on PV panels by Amr et al. [22] with and without fins-cooling to determine how operating temperature affects output voltage, current, and power. There were 9 fins, each with a different cross-sectional area, attached at 50 mm intervals to restrict airflow to improve heat transfer. As a result of fin cooling, the panel's operating temperature dropped significantly, about 4.2% (4-5°C), resulting in an output power improvement of 5.5%. In another study by Chen et al. [23], fins were glued to the PV panel to cool the system with natural ventilation, and results were compared with PV panels without fins under different experimental conditions. Under various experimental conditions, PV panels with fines had an average electrical efficiency of 0.3–1.8% higher than PV panels without fins. The average output power generated by PV panels with fines increased by 1.8–11.8% compared to PV panels alone.

Cotton wicks have been shown to be an effective method of cooling solar panels in several research studies. In a study by Rejon et al. [25], wicks, which are made up of Martin clothing (Figure 6), are used with water cooling that is covered by the finned heat sink. This method is used instead of an active water-cooling system that requires electric energy to run the water pump. In these experiments, the temperature of the panel is roughly observed to be between 35°C and 47 °C during the water cooling with cotton wicks, and the electric efficiency is found to be a maximum of 15.4%. They concluded that water cooling with cotton wicks can be considered the most effective, environmentally acceptable, simple to use, and cost-efficient compared to natural air cooling with fins and forced air cooling with fins.

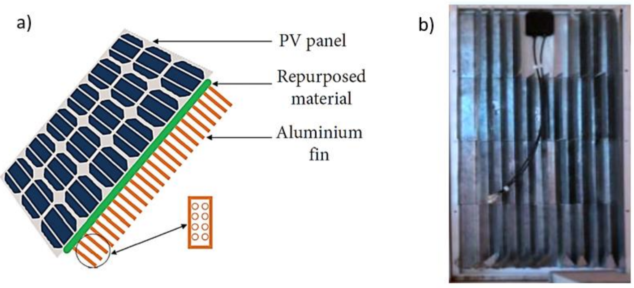

Figure 5. Using fins under the PV module to cool down the module's temperature a) schematic structure [24], b) experimental setup [23]

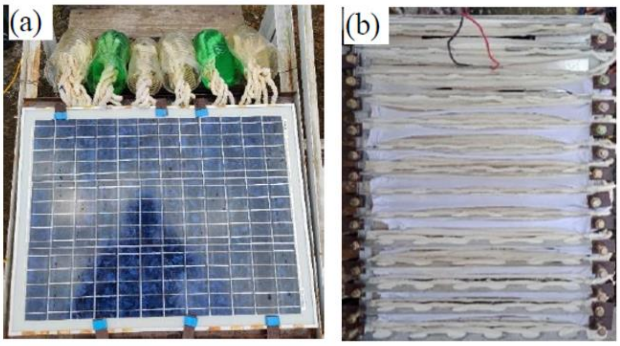

Figure 6. Cotton wicks covering the finned heat sink for water cooling: (a) top view and (b) backside view of the PV module [25]

A comparative experimental study was conducted by Muhammad Azahari et al. [26] to compare the effect of two passive cooling systems of cotton wicks with water and aluminum fins. As compared to the control PV module, the finned module produced an average output increase of 2.67%, and the cotton wick module produced an average output increase of 3.94%.

Phase Change Material (PCM) has been used to cool down the PV panels as a passive cooling method (Figure 7). A PCM is a material that stores latent heat. Thermal energy is stored and controlled by these materials as they absorb and release heat during phase changes. It has been found that PCM is one of the most effective PV cooling systems [27]. Zhao et al. [28] simulated experiments to investigate the effect of different PCMs as well as their thickness on cooling PV modules. Based on their study, PCMs were able to drop the temperature of the system by up to 25 °C, resulting in an increase of 11% in output power over PV modules alone. Waqas et al. [29] reviewed the PV-PCM technology and concluded that using PCM, PV panel peak temperatures can be reduced by up to 20 °C, which results in an increase of about 5% in electrical conversion efficiency. They have also mentioned that the average amount of PCM required to reduce the temperature of PV by one degree during peak hours is 2.6 kilograms per square meter. There have been several technological challenges, such as high costs and a lack of appropriate PCMs, which have prevented the PV-PCM cooling system from being commercially viable to date [30].

In a recent study, Hindi et al. [31] studied the effect of PCM and combined Fin-PCM passive cooling on PV modules. Compared to PV modules without passive cooling, PV-Fin-PCM and PV-Fin demonstrated an increase in electrical conversion efficiency of 15.2% and 14.7%, respectively, while the average temperature decreased by approximately 27.2% and 9.6%. This resulted in power output increase by 23.1% in PV-Fin-PCM panels and 16.8% in PV-Fin panels. Utilizing thermoelectric generators (TEGs) is the latest addition to passive cooling techniques. In a hybrid PV-TEG system, the waste heat generated by PV cells is used not only to cool down the PV cells but also to generate power. After introducing the structure and functions of TEG, a review and discussion of hybrid PV-TEG systems developed over the years are presented.

Figure 7. Encapsulated PCMs are installed at the back of the PV panel

3. Thermoelectric generators (TEG)

In thermoelectric generators, electricity is generated using the thermoelectric (Seebeck) effect. In this effect, temperature gradients generate voltages between two sides of a material. This phenomenon has been discovered to be more prevalent in metals and semiconductor alloys, resulting in the development of TEG technology. Essentially, a thermoelectric generator consists of a thermocouple whose elements are n-type and p-type, arranged and connected electrically in series but thermally in parallel. There are three basic sections of a typical TEG module: a hot side, a cold side, and thermoelectric materials. As shown in Figure 8, when heat is applied to one side of the TEG (hot side), the charge carriers, namely electrons in n-type and holes in p-type legs, gain energy and move to the other side (cold side) resulting in a voltage between the two ends of the thermocouple [32-34]. In a wide range of applications, TEGs are used to generate power for systems with low power requirements, such as micropower generation and wearable sensors [35].

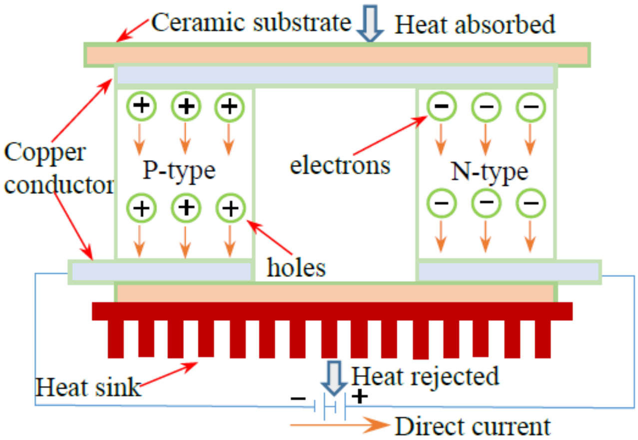

Figure 8. Operation concept of a TEG module [32]

The TEG generates voltage based on the Seebeck effect, in which the magnitude of the generated voltage difference depends on the thermoelectric material and the temperature gradient. The Seebeck coefficient (S) for the thermoelectric material is defined as:

$$S = \frac{\Delta V}{\Delta T} \text{ (V/K)} \quad (10)$$

where ΔV is the voltage difference generated between the junctions (V) and ΔT is the temperature gradient between the hot and cold sides of the module (K). The maximum efficiency of the energy conversion at a given temperature, T (K), in the material, is calculated by the dimensionless figure of merit (ZT) by:

$$ZT = \frac{S^2\sigma}{k}T = \frac{S^2}{k\rho}T \quad (11)$$

where σ is the electrical conductivity (Sm^{-1}), and k is the thermal conductivity (W/m-K). The equation in terms of electrical resistivity (ρ), which is the inverse of conductivity, is also given in Equation 11.
The maximum efficiency of a TEG, is calculated as [32].

$$\eta_{max} = \frac{\Delta T}{T_h}\left(\frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_c}{T_h}}\right) \quad (12)$$

T_h and T_c represent the hot side and cold side temperatures, respectively. The output power at maximum efficiency (η_{max}) is determined by [8]:

$$P(\eta_{max}) = \frac{n\times\sqrt{1+ZT}}{R}\left(\frac{S\times\Delta T}{\sqrt{1+ZT}}\right) \quad (13)$$

where R is the total equivalent internal resistance of the thermocouples, and is calculated by:

$$R = \frac{n\times 2\xi\times L}{A} + R_a \quad (14)$$

where n is the number of thermocouples connected in series, ξ is the electrical resistivity for both p-type and n-type semiconductors (ohms-meter), L and A are the length and area of each thermocouple, and R_a is thermal contact resistance.

4. Hybrid PV-TEG system

4.1 Output power and efficiency

A thermoelectric device has been investigated for the purpose of cooling PV cells and producing electricity from waste heat [36]. The use of thermoelectric generators integrated with PV modules not only helps to cool the PV module but also generates electric power. The total power of a hybrid PV-TEG system is the total power generated by the individual systems:

$$P_{PV-TEG} = P_{PV} + P_{TEG} \quad (15)$$

The theoretical overall conversion efficiency is the sum of the individual efficiencies [34]:

$$\eta_{PV-TEG} = \eta_{PV} + \eta_{TEG} \quad (16)$$

In theory, a hybrid PV-TEG system produces higher energy by about 10% in comparison to a PV solar cell, but this is dependent on several factors including geometry, connections, and material of the TEGs that are used [37]. The initial promise of hybrid PV-TEG systems is confirmed by several theoretical and experimental studies [8, 10, 35-38]. There are two ways to develop a hybrid PV-TEG system. One approach is the spectral splitting method, which divides the solar spectrum into two parts and directs them to PV and TEG modules separately.

4.2 Hybrid PV-TEG system configurations

In the spectral splitting approach, solar irradiation is divided into two portions:1-visible and part of the infrared spectrum that can be converted directly to electricity by PV cells; 2- the rest of the spectrum that is converted to heat. In this way, the PV's temperature is not heated. As in this case, the spectrum is not split. This technique is schematically shown in Figure 9. It uses a beam splitter system, a concentrator, and a heat sink [38]. The most widely studied method involves using TEGs directly attached to PV panels to generate electricity and reduce temperature by using the heat generated by the panels. As shown in Figure 10, the TEGs are pasted to the back of the PV panels using thermal glue from one side and are electrically connected in series. Integrated PV and TEG systems contribute to enhancing the output power and efficiency of the overall system. There have been extensive studies on hybrid PV-TEG systems looking into different aspects of the hybrid system's performance. Investigations were made to find out the optimum working conditions of a hybrid PV-TEG model based on the influence of various factors, such as the structure of the overall system, thermal resistance, the concentration ratio of the module, and the cooling system.

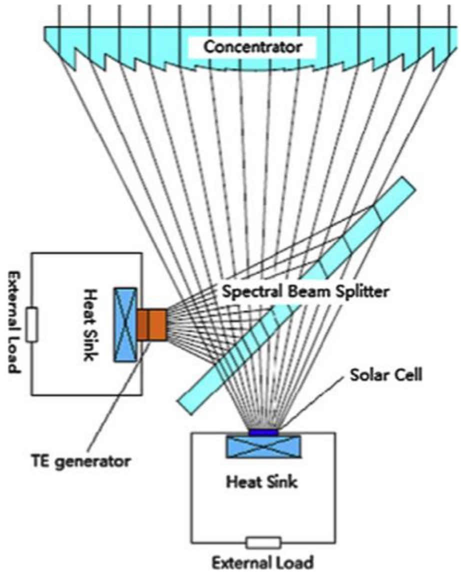

Figure 9. Hybrid PV-TEG system using beam splitting technique [38]

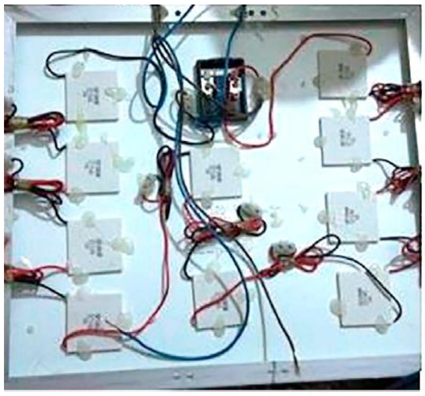

Figure 10. Hybrid PV-TEG system [36]

4.3 Studies on hybrid PV-TEG system

In a numerical study by Kohan et al. [39], the number of TEGs varied, and it was found that the performance of a PV-TEG hybrid system was proportional to the number of TEGs used in that system. Sark et al. [40] modeled the hybrid system in which the TEGs are directly attached to the PV panel. They studied the hybrid system using annual irradiation and temperature profiles of two different locations, the Netherlands (Utrecht) and Spain (Malaga). It is expected to have a 14.7% increase in efficiency in Utrecht and an 11% increase in Malaga within one year compared to the conventional PV system. In experiments using the direct integrated PV-TEG system by Khan et al. [36], a boost in both power and efficiency produced by PV-TEG over PV alone was reported. The temperature of the PV-TEG system was reduced by 5.5% compared to that of the PV system. Also, an overall increase in the average output power and average efficiency was 19% and 17%, respectively, compared to the conventional PV module. Zhang et al. [41] developed a theoretical model to study the performance of the hybrid PV-TEG system using different types of PV material, including crystalline silicon PV (c-Si PV), polysilicon thin-film PV (p-Si TFPV), polymer PV, and copper indium gallium selenide PV (CIGS PV). Their model analysis showed that the thermal contact resistance should be reduced to be in the range of 20-100 mm^2 K/W in order to mitigate its drawback on the enhanced efficiency of the hybrid system. They concluded that the CIGS PV results in the highest efficiency, but the cost of this type of PV is high, especially for commercialized systems. Using the optimum solar concentration ratio of 12 and optimum heat transfer coefficient of about 1000 W/Km^2, the polymer silicon p-Si TFPV provides the optimum structure to achieve high efficiency in concentrated PV-TEG systems. They have also recommended the use of polymer PV when the system does not use the concentrator. Zhang et al. [42] designed and developed a novel PV-TEG system to improve power generation and efficiency. In this system, in order to make a compact and direct connection between PV and TEG modules, the ceramic plate on top of the TEGs was removed, and a thin insulation alumina layer was deposited on the back of the PV panel to prevent electrical contact. The experiments on this novel system showed an improvement of the output power of PV by about 14.9% compared to the PV alone when a 15 °C water cooling was used. Furthermore, it has also been found that the output power increases when the alumina layer is thinner. Using an alumina layer with a thickness of 16.1 mm, the PV-TEG hybrid device produced 7.56% more power than when the system used the 18.8 mm thick alumina layer.

4.4 Cooling methods for hybrid PV-TEG systems

As the efficiency of the TEG operation increases by the temperature gradient between the hot and cold sides, a suitable cooling method helps to provide sufficient cooling of the cold side, increasing the overall efficiency and output power of the PV panels while the lifetime of the PV panels is extended. The most common cooling method for TEGs is using heat sinks attached to the cold side of the TEGs using thermal glues (Figure 11) [43, 44]. In a theoretical analysis by Babu et al. [45] in which the hybrid PV-TEG system was cooled down by heat sinks connected to the TEGS, the output energy and the electrical efficiency of the system improved by 5% and 6%, respectively, compared to the standalone PV system. An experiment conducted by Gopinath et al. [44] compared the cooling effects of graphite sheet and heat sink attached to the back of the TEGs. The heat sink cooling approach proved to be a more effective solution as it provided a voltage gain of up to 1.78 times greater than TEG alone by increasing the temperature gradient from 3.92 °C to 5.96 °C.

Cooling with air, wick, and water circulation on hybrid PV-TEG systems was investigated by Chandan et al. [21] (Figure 12). According to their experimental results, PV surface temperature decreased by 7% (≈4°C), 47% (≈30°C), and 22% (≈14°C) when the system was cooled by air, water, and wick, respectively. Taking into account the cumulative output energy and the cooling system requirements, wick-based cooling was found to be the most efficient and effective cooling method. The flat plate heat pipe is another method of cooling used in hybrid PV-TEG systems. An example of the use of flat plate heat pipes is reported by Li et al. [46]. The PV modules in this novel PV-TEG system were attached to the top of a Micro Combined Heat and Power (MCHP) system, whereas the TEG modules were mounted to the condenser layer (Figure 13). By means of the heat exchanger, the heat is transported to the MCHP. In the heat exchanger, condensation occurs due to evaporation, which releases heat and passes it to the TEG, which in turn creates a temperature gradient and generates electricity. Heat sinks are used to cool TEGs. This system is found to have a 14.0% higher electrical efficiency than a PV module alone.

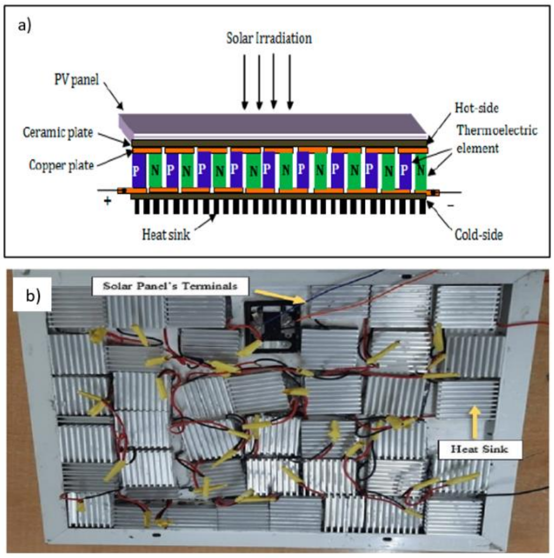

Figure 11. Hybrid PV-TEG configuration with heat sinks thermal glued to the cold side of the TEGs: a) schematic [43], b) physical system [44]

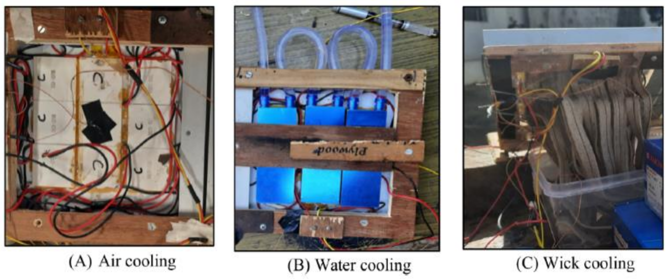

Figure 12. Three different cooling techniques are employed on PV and PV-TEG systems [21]

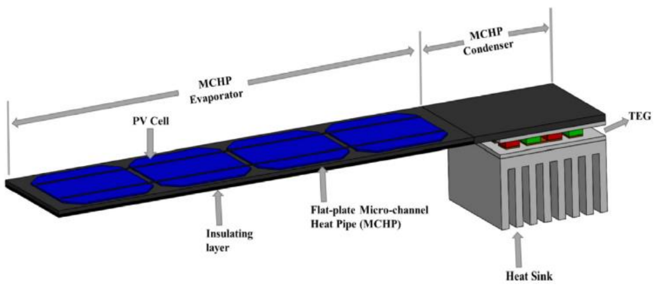

Figure 13. PV-TEG-MCHP configuration [7]

Using the three-dimensional finite element method, Shittu et al. [47] conducted a numerical analysis of PV, PV-TEG, and PV-TEG-heat pipe systems utilizing concentrator systems. The PV-TEG-heat pipe efficiency was found to be 1.47% higher than the PV-TEG and 61.01% higher than the PV at an optimum solar concentration ratio of 6. PV-TEG-heat pipes were recommended for highly concentrated systems due to their superior performance. They concluded that hybrid systems can also be negatively affected by ineffective TEGs cooling. Using PCMs as passive cooling methods were also used in hybrid PV-TEG systems in several studies [48, 49]. Motiei et al. [48] developed two-dimensional modeling of the PV-TEG-PCM system in which PCM was attached to the cold plate of the TEGs as shown in Figure 14. The model was performed during 24 hours of Klein days, which are the 6th of July and the 5th of January in Shiraz. The model is designed to reduce the PV module temperature, increase the temperature gradient across TEG plates, and improve the overall power and efficiency. It was found the PV-TEG-PCM showed more temperature reduction and higher efficiency in comparison with PV alone and the PV-TEG system. Moreover, using an appropriate PCM results in the mitigation of fluctuations in the system's temperature. PCM thickness plays an important role in efficiency improvement, and it needs to be optimized.

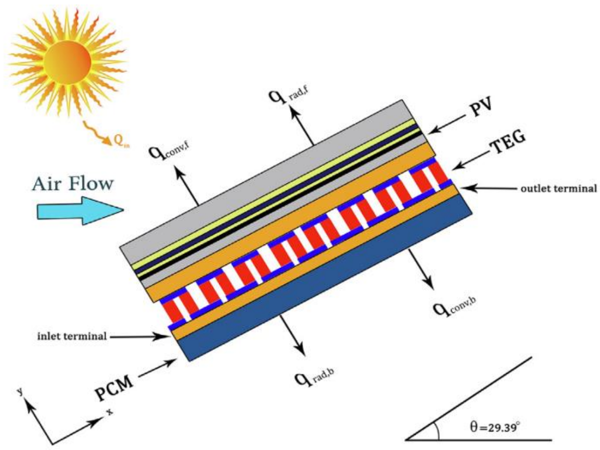

Figure14. Schematic of a PV-TEG-PCM hybrid system [48]

An in-depth three-dimensional transient numerical model of non-uniform solar radiation conditions was developed by Gao et al. [50] to analyze the potential impact of PCM on the performance of the hybrid PV-TEG system. They specifically examined the effect of the height and position of the PCM. It was concluded that PV-TEG-PCM systems are more efficient when the PCM height is higher. In comparison to the PV-TEG-PCM system, the PV-PCM-TEG system demonstrated more reduction in PV temperature. Moreover, according to a simulation study conducted by Darkwa et al. [49], PV-TEG-PCM could operate optimally at a PCM thickness of 50 mm and a thermal conductivity of 5 W/mK with phase change temperature of 40-45°C. An integrated PV system with TEG and PCM was proposed by Kang et al. [51], where the performance of the system was analyzed through simulation and experiments (Figure 15). They used microencapsulated phase change material (mPCM) to prevent PCM leakage from the PCM container. As a result of this unique design, the TEGs also generate electricity at night since the reverse temperature gradient at night enables the TEG to operate and generate electricity. Simulation analysis has concluded that by employing a PCM material with a suitable melting temperature and proper heat fin spacing, PV temperatures will be reduced, and PV efficiency will be increased. Based on their experimental results, the PV-TEG-PCM system reduced PV temperature by 20C and increased panel efficiency by 13% compared to the PV panel alone.

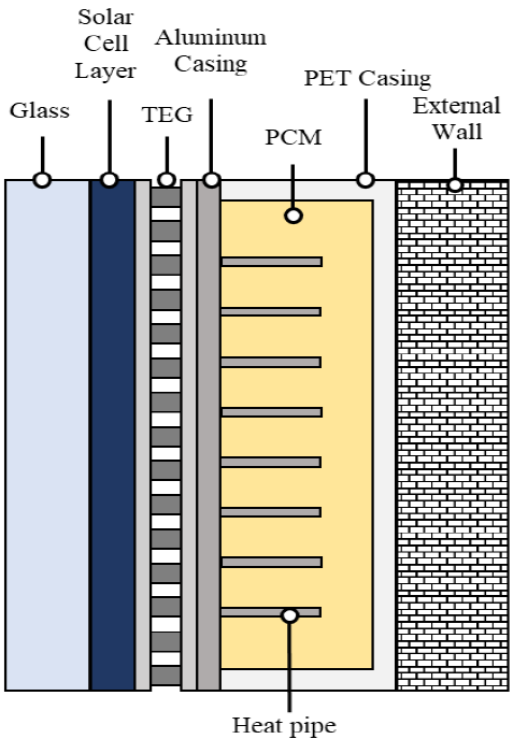

Figure 15. Building-Integrated PV-TEG-PCM developed by Kang et al. [51]

5. Summary of recent experimental advancement in PV-TEG systems

A brief overview of recent developments regarding PV-TEG systems with different types of cooling is presented in Table 1. The hybrid PV-TEG system has been proven to reduce the temperature of PV panels and improve the efficiency of power generation. Nevertheless, it is essential to design an effective cooling system to reduce the PV temperature to an acceptable level and extend its life span. Various cooling systems have been added to PV-TEG, and the most recent developments are summarized in Table 1. It is evident that the addition of a heat sink to the TEGs will increase the temperature gradient through the TEG plates, cool down the PV panel, and increase the overall efficiency of the system. There are, however, other methods, such as PCM and wicks, that have proven to be more effective, as shown in Table 1.

Table 1. Recent research studies on hybrid PV-TEG systems

Reference	System configuration	Cooling method	Results compared to PV standalone
Li et al. [52]	PV-TEG-MCHP	MCHP + heat sink	Output power increase of ~ 14%
Motiei et al. [48]	PV-TEG-PCM	PCM	• Improved PV efficiency • PCM mitigates fluctuations in system's temperature • Optimum PCM thickness is necessary
Darkwa et al. [49]	PV-TEG-PCM	PCM	• Improved PV efficiency • Optimum PCM thickness of 50 mm • Optimum phase change temperature of 40-45 °C
Zhang et al. [42]	PV-TEG with thin alumina layer between the PV and TEG	water cooling heat sink	• Output power increase of 14.9% • Optimum thickness of alumina is necessary
Khan et al. [34]	PV-TEG	air	• Temperature drop of 5.5% • Output Power increase of 19%
Gao et al. [53]	PV-TEG-PCM & PV-PCM-TEG	PCM	• PV-PCM-TEG more effective
Chandan et al. [21]	PV-TEG	air, wick, water	• Best results with wick cooling • Temperature drop of 22% • Efficiency increase of ~16%
Kang et al. [51]	PV-TEG	mPCM	• Temperature drop (at the peak) of 26% • Efficiency increase of ~13%
Khang et al. [53]	PV-TEG	heat sink	• Output power increase of ~ 8%
Gopinath et al. [44]	PV-TEG	Heat sink & graphite sheet	• Best Results with heat sink • Power increase of up to 1.78 times • Temperature gradient increase of 52% across TEG

As a passive cooling approach, wicks immersed in water have been reported to reduce panel temperature by 22% and to increase overall output power by 16% compared to PV alone [21]. The integration of PCMs into hybrid systems has also been suggested as a potential means to increase the efficiency of the system even further [48,49,51]. The majority of studies, however, are conducted through simulation modeling or indoor experiments. It is therefore recommended that further research be conducted concerning the use of the PCM in conjunction with a hybrid system in the future. In order to improve the technology of PV solar panels in the future, it is imperative that further studies be conducted in this area.

6. Conclusion

Studies have shown that when TEGs are utilized in integration with solar PV panels, PV panels generate more power. The TEGs convert the thermal energy of solar radiation into electricity either when the thermal part of the solar spectrum is directed into its plates or attached directly at the back of the PV panels. TEGs not only reduce the temperature of PV panels but generate a small amount of electric power. In combining two systems, new complexities arise that have been the subject of extensive research and efforts to design the system as efficiently as possible. It is noted that employing the best cooling method for the whole system is challenging. Two cooling methods have been found to be more effective: wicks and PCMs. Studies show that with wicks, the output power will be increased by approximately 16%, and the PV temperature will be reduced by approximately 22%. Moreover, according to numerical analysis and experimental validation, the PV-TEG-PCM system is capable of achieving about 13% more efficiency compared to PV alone. While the studies that have been done until now demonstrated successful improvement in power generation, they also recognized some limitations. The hybrid PV-TEG systems require further experimental evaluation and optimization before they can be commercially available.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The datasets analyzed during the current study are available and can be given upon reasonable request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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