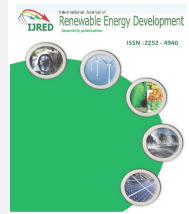




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Review Article

Evaluation of a PV-TEG Hybrid System Configuration for an Improved Energy Output: A Review

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ABSTRACT. The development of renewable energy, especially solar, is essential for meeting future energy demands. The use of a wide range of the solar spectrum through the solar cells will increase electricity generation and thereby improve energy supply. However, solar photovoltaics (PV) can only convert a portion of the spectrum into electricity. Excess solar radiation is wasted by heat, which decreases solar PV cells' efficiency and decreases their life span. Interestingly, thermoelectric generators (TEGs) are bidirectional devices that act as heat engines, converting the excess heat into electrical energy through thermoelectric effects through when integrated with a PV. These generators also enhance device efficiency and reduce the amount of heat that solar cells dissipate. Several experiments have been carried out to improve the hybrid PV-TEG system efficiency, and some are still underway. In the present study, the photovoltaic and thermoelectric theories are reviewed. Furthermore, different hybrid system integration methods and experimental and numerical investigations in improving the efficiency of PV-TEG hybrid systems are also discussed. This paper also assesses the effect of critical parameters of PV-TEG performance and highlights possible future research topics to enhancing the literature on photovoltaic-thermoelectric generator systems.

Keywords: Solar energy, photovoltaic, thermoelectric generator, hybrid photovoltaic-thermoelectric generator system, shingle

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1. Introduction

Renewable energy, such as wind, geothermal, hydroelectricity, solar, and bioenergy, is produced from natural processes that can be replenished. Such energy sources are directly or indirectly derived from the heat of the sun or from within the Earth.

Kusch-Brandt (2019) reported that renewable energy supplied an estimated power of about 181 gigawatts (GW) in 2018, representing over 26% of global electricity production that year. Considering the world's high energy needs and the environmental consequences of fossil fuel energy generation, renewable energy is seen as a means to curtail the climate change, global warming, and other ecological emissions (Hoang *et al.*, 2018). Furthermore, solar energy is advantageous because it is efficient, sustainable, and environment friendly (Fisac *et al.*, 2014).

Solar energy consists of visible light and heat used as photovoltaic or solar thermal energy. It is clean, inexhaustible, limitless, and eco-friendly. These unique characteristics have motivated researchers in the energy sector to widely embrace solar energy as an alternative

energy source. It is the most potent option for sustainably maintaining energy protection and meeting the global energy demand while substantially reducing greenhouse gas (GHG) emissions (Kabir *et al.*, 2018).

Photovoltaic (PV) systems directly convert solar energy into electricity without contributing to air pollution. While considerable progress has been made in the PV system area, much work remains unaccomplished in enhancing the overall efficiency and reducing the costs and associated risks (Sahin *et al.*, 2020). One of the critical concerns of PV technologies is the efficiency drop caused by the PV panel's relatively high operating temperatures when exposed to high solar irradiation during the day (Jatoi *et al.*, 2018). Therefore, the factors essential for attaining excellent performance and efficiency enhancement of the PV system depend primarily on the PV cells' cooling, through which the excess heat gets converted into additional power output and thermal energy, increasing the cells' life spans (Gu *et al.*, 2019). The efficiency is decreased by 0.25–0.5% per Celsius degree (Grubišić-Čabo *et al.*, 2016). In increasing solar

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irradiation's conversion efficiency into electricity, different power generation technologies can be implemented (Mohammadnia *et al.*, 2020a). Among the most exciting areas of study in the renewable energy sector are the advancements in energy harvesting technologies to generate more energy from solar irradiance, such as PV-TEG hybrid system, which has been gaining interest (Fathabadi, 2020). In this context, the objective of the present paper is to provide a comprehensive review of different hybrid system integration methods, including experimental and numerical investigations into the improvement of PV-TEG hybrid system efficiency and the influence of critical performance parameters, such as concentration ration, thermal contact resistance, temperature coefficient, and thermoelectric figure of merit.

2. Solar Cell

Solar cells, which generate electricity from sunlight, constitute the critical part of a PV system. The cells form a particular semiconductor diode, such as silicon, gallium arsenide or cadmium that converts electromagnetic radiation into direct currents. (Nižetić *et al.*, 2020). The power of PV modules is influenced by cell materials, ambient temperature, solar radiation, cell temperature, shading, and tilt angle (Jatoi *et al.*, 2021). These factors influence the efficiency of photovoltaic modules, both alone and in conjunction with each other (Coskun *et al.*, 2017)

2.1 Solar Cell Modelling

Solar cells' characteristics are modelled as in the current source (Mohammad *et al.*, 2020; Premkumar *et al.*, 2020). The solar cell is the main component for converting the light from the sun energy into electricity via PV effect; it, therefore, serves as a DC source.

The schematic diagram of the ideal PV cell is illustrated in Figure 1. The intensity of the output current (I) is influenced by the irradiation strength and solar cell's temperature.

The solar cell's current output is given by Equation (1) to (9) (Mohammad *et al.*, 2020):

$$I_D = I_o \left[\exp\left(\frac{q(V+I R_s)}{\gamma K T_c}\right) - 1 \right] \tag{1}$$

where I_D is current through the diode, q is the electron charge, I_o is the reverse saturation current, V is the circuit voltage, and K is the Boltzmann constant (Mohammad *et al.*, 2020).

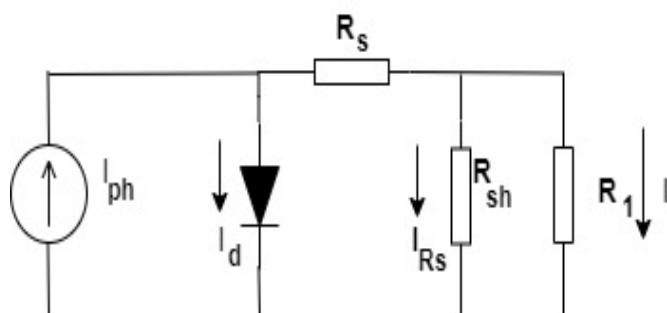


Fig. 1. Photovoltaic cell model

$$I_o = D T_{ab}^3 \exp\left(\frac{q \epsilon G}{A K T_{ab}}\right) \tag{2}$$

Where T_{ab} is the temperature coefficient, D is the diode diffused factor, ϵG is material bandgap, and A is the area of the solar cell. Solar cells are generally arranged in parallel and series depending on the system requirements. The voltage and current of a solar cell generator can be obtained using Equation (3) (Fisac *et al.*, 2014):

$$V_g = I_g R_s \frac{N_s}{N_p} I_n \left(1 + \frac{N_p I_{ph} - 1}{N_p I_o} \right) \tag{3}$$

where N_s and N_p are the numbers of series and parallel cells, respectively, R_s is the series resistance, and I_{ph} is the photocurrent of the solar cell proportional irradiance (Mohammad *et al.*, 2020).

$$I_g = I_{ph} - I_o \exp\left(\frac{q V_g}{K T} - 1\right) \tag{4}$$

where I_o is as in Equation 1, $I_{sc} = I_{ph}$ at $V_g = 0$, which varies with the open-circuit voltage (V_{oc}) obtained at $I_g = 0$ and irradiance of the solar cell (Mohammad *et al.*, 2020) thus,

$$V_o = \frac{K T}{q} I_n \left[\frac{I_{ph}}{I_o} \right] \tag{5}$$

The cell maximum power output is given as,

$$\frac{d(V_g \times I_g)}{dt} \tag{6}$$

$$V_{mp} = V_{oc} - \frac{K T}{q} \left[\frac{V_{mp}}{k T / q} + 1 \right] \tag{7}$$

Fill factor (FF) can be expressed as

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

The efficiency of the PV can be expressed as:

$$\eta_{PV} = \frac{FF \times V_{oc} \times I_{sc}}{P_{in}} \tag{9}$$

where the power of the incident radiation is represented as P_{in} .

3. Thermoelectric Generator

Thermoelectric generators can use the Seebeck effect shown in Fig. 3a to produce electricity from the thermal energy. According to the Seebeck effect, once a delta T (ΔT) is established across the TEG consisting of p and n-type materials, a potential difference (ΔV) can be created (Li *et al.*, 2010) and expressed by Equation 10:

$$\alpha = \Delta V / \Delta T \tag{10}$$

where α , ΔV and ΔT are the Seebeck coefficient, generated voltage and the temperature difference across the TEG, respectively.

Conversely, applying a current through the two junctions of a thermoelectric couple creates a temperature difference, as discovered by a French physicist Jean Charles Peltier. called the Peltier effect; it is shown in Fig. 3b (Li *et al.*, 2010). This effect is essential for a TEG's performance as a coolant (Shittu *et al.*, 2019).

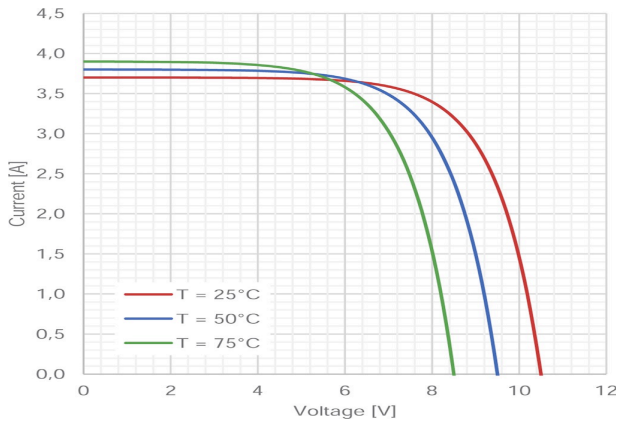


Fig. 2. Temperature Influence on a photovoltaic cell (Fisac et al., 2014).

A thermoelectric device (TE) is capable of converting heat into electricity. A thermoelectric cooler (TEC) can transfer heat out of the system (cooling) by applying an electrical current. A thermoelectric device is applicable in refrigeration and green energy generation, as shown in Fig. 3 (Elsheikh et al., 2014).

3.1 Thermoelectric Generator Modelling

The efficiency of the thermoelectric generator is given in Equation (11) (Shittu et al., 2019):

$$\eta = \frac{\text{Load Energy}}{\text{The energy of the hot junction}} \tag{11}$$

By maintaining appropriate properties of thermoelectric material with minimal contact resistance, the efficiency can be described as follows:

$$\eta_{\text{teg}} = \frac{I^2 R}{\alpha I T_H} = \frac{T^2 R}{K(T_H - T_C) - I/2I^2 R} \tag{12}$$

where I , R , T_H , T_C represent the thermoelectric generator current, series resistance, and hot and cold side temperatures, respectively.

The maximum TEG efficiency is expressed in Equation (13)

$$\eta_{\text{max}} = \eta_C = \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_C}{T_H}} \tag{13}$$

where η_C represents the Carnot efficiency expressed as (Shittu et al., 2019):

$$\eta_C = \frac{T_H - T_C}{T_H} \tag{14}$$

Thermoelectric cooler efficiency is expressed as its coefficient of performance (COP), which is given in Equation 15 (Shittu et al., 2019),

$$\text{COP} = \frac{\text{Heat absorbed}}{\text{Electrical power input}} = \frac{\alpha I T_C - K(T_H - T_C)}{\alpha I (T_H - T_C) + I^2 R} \tag{15}$$

where I , R , T_H , T_C are the same as in Equation (12) (Shittu et al., 2019),

The maximum cooling power current (I) is given in Equation (16):

$$I = \frac{\alpha T_C}{R} \tag{16}$$

The maximum coefficient of performance is:

$$\text{COP}_{\text{max}} = \frac{T_C [(1+ZT)^2] - \frac{T_C}{T_H}}{(T_H - T_C) [(1+ZT)^2] + 1} \tag{17}$$

The thermoelectric figure of merit (ZT) defines the optimum output coefficient of TEG.

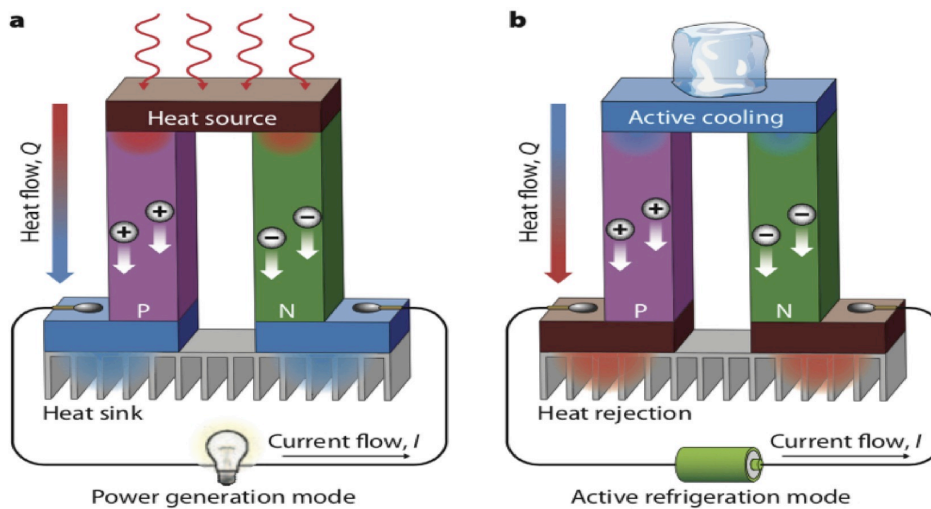


Fig. 3. A thermoelectric Device. (a) as an energy generator (b) a coolant (Li et al., 2010).

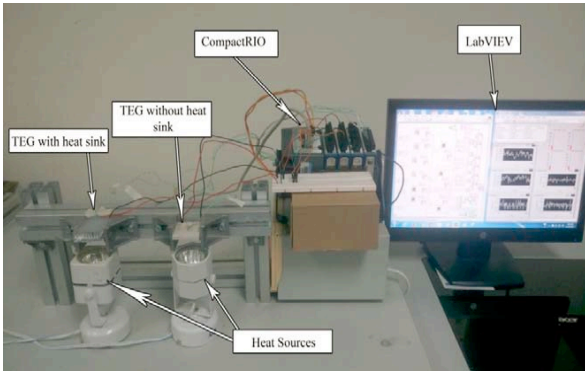


Fig. 4. Experimental setup of the TEG measurement. (Johar *et al.*, 2017)

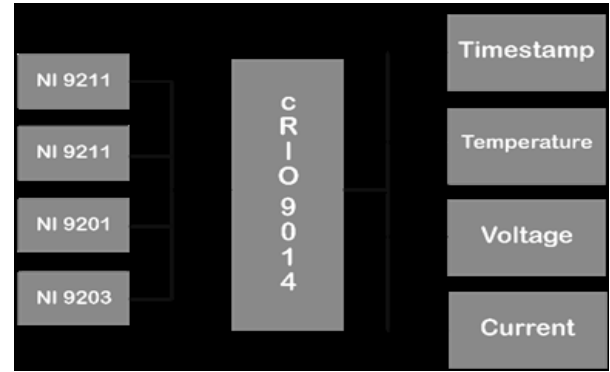


Fig. 5. Data Acquisition system for measuring voltage, current and temperature produced by TEGs (Wan Jamaludin *et al.*, 2020)

3.2 Application of Thermoelectric Generator

Thermoelectric generators are used in a broad range of applications, such as micropower generation (Aravind *et al.*, 2020), wearable sensors (Lund *et al.*, 2020), automotive waste heat recovery (Patel & Patel, 2020; Kumar *et al.*, 2020), wireless sensor network (Yuan *et al.*, 2020; Lineykin *et al.*, 2020), space power (Wang *et al.*, 2020) and buildings (AlMusleh *et al.*, 2020). TEGs are also used as coolers in different devices (Cai *et al.*, 2019), such as refrigerators and air conditioners (Rostamzadeh & Nourani, 2019; Khanmohammadi *et al.*, 2020), as well as for unique industrial application and usage in medicine, aerospace, and military and biological weapons (Mirzakhanyan, 2005; Aljaghtham & Celik, 2020).

3.3. Thermoelectric Generator as Renewable Energy Sources

Akashah *et al.* (2019) and Wan Jamaludin *et al.* (2020) conducted an experimental investigation to analyze the feasibility of using a thermoelectric generator as a renewable energy source. A 40 x 40 x 3.5 mm TEC1-12706 was used for the study. National Instrument (NI-CRIO 9014) was employed to acquire the temperature, current, and voltage measurements. Halogen lamps were used as the heat source for the TEG, and LabView software was used for data display, as shown in Fig. 4. The results showed that the two TEGs produced 416.82 μ W power when connected in series across 200 Ω , while they reached 100 Mw in parallel connections at ΔT of 7°C. This was in agreement with the work of Coskun *et al.* (2017).

In another study, the feasibility of sustainable heat energy from a shingle utilising a TEG was evaluated for residential usages (Wan Jamaludin *et al.*, 2020). For this evaluation, a test ring was used for TEG, and the shingle was connected to the National Instrument for DAQ, as shown in Fig. 5. The four modules of TEG in series were found to generate an average of 0.003 V at a load of 138 Ω , giving 65.22 μ W of power.

Johar *et al.* (2017) performed a temperature analysis in the preliminary studies of shingle-based TEG systems as a renewable energy source. The results showed that the shingle produced an input power of 10.8675 W at 1.5°C, while the TEG produced 0.21 W at 1.75°C.

4. PV-TEG Hybrid System

Various hybrid PV-TEG systems have been developed to effectively use the broad spectral region of solar energy. Radiation with energy in the bandgap region of a PV results in electricity generated by the PV-TEG hybrid system. TEG converts the energy absorbed as heat into electricity. Since TEG can act as a generator, it tends to increase the total electrical performance when incorporated into a PV-TEG system, resulting in 10% more energy produced than a single PV solar cell, depending on the geometry, connections and the material of the TEG (Zhao *et al.*, 2019).

The development of a hybrid PV-TEG system is, in principle, achieved in two ways. The first is the spectral splitting method for transmitting energy below the 2,500 nm cut-off wavelength to the PV and above 2,500 nm to the TEG. The second is the direct method, which connects the TEG directly to the back of the PV; the TEG uses the excess heat produced by the PV to generate additional electricity (Goldsmid *et al.*, 1980)

Several researchers have investigated the influence of various factors, such as the cooling system (Daghighi & Khaledian, 2018; Wu *et al.*, 2018), concentration ration (Soltani *et al.*, 2018; Yin *et al.*, 2018a), system structure (Babu & Ponnambalam, 2018; Yin *et al.*, 2019), and contact thermal resistance (Daghighi & Khaledian, 2018; Lamba & Kaushik, 2018), in an attempt to determine the optimum working condition of a hybrid PV-TEG system. The majority of these researchers concentrated on the influence of solar irradiance on the hybrid PV-TEG system's performance. Their findings showed that the concentration significantly affects the hybrid system efficiency if different PV cells are used. For instance, Zhang *et al.*, (2014) showed that a hybrid PV-TE system's performance increases when CIGS, polymer, c-Si, and p-Si PV cells with increased concentration rations are used. On the contrary, thermoelectric materials with $ZT \approx 1$ improve the overall system efficiency over concentration ration. Rezanian and Rosendahl (2017), and Kil *et al.* (2017) concluded that, using single-junction GaAs and three-junction PV cells, the system efficiency increases with an increase in the irradiance.

Shittu *et al.* (2019) conducted a thorough comparative evaluation of the influence of the solar concentration ratio and the flat plate heat pipe's effect as an air cooling system on minimising the temperature of the solar cell. Electrical performance analysis was conducted on PV-only, PV-TEG and PV-TEG-heat pipe systems.

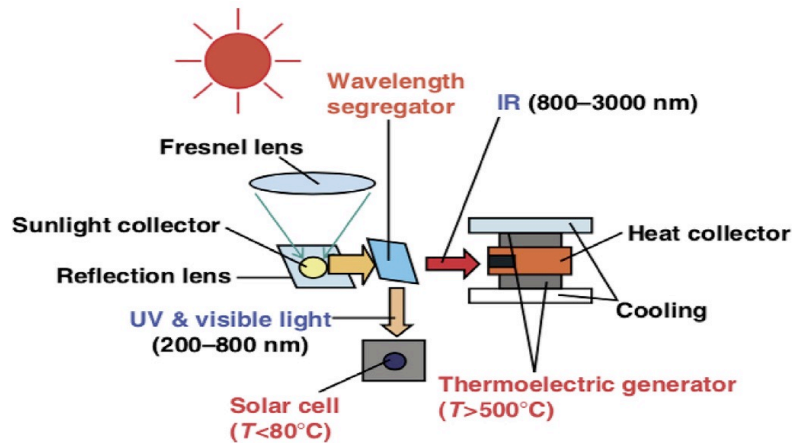


Fig. 6. PV-TEG spectrum splitting method schematics (Goldsmid *et al.*, 1980).

Furthermore, using COMSOL 5.4 Multiphysics tools, the effect of air temperature, TEG cold junction temperature, and wind speed on PV performance and hybrid PV-TEG systems were studied. In a three-dimensional finite element analysis, the authors considered temperature-dependent thermoelectric material properties to enhance optimisation accuracy. The findings indicated that the PV-TEG-heat pipe's efficiency was 61.01% and 1.47% higher than the PV-only and PV-TEG. The results further showed that a lack of sufficient cooling of the TEG could adversely harm the hybrid systems' performance.

Yin and Xuan (2019) presented an experimental optimisation for a CPV-TEG system's operating conditions, taking into account the system structure, connection modes, total input energy, and coupling characteristics of the devices. The authors stated that the hybrid CPV-TEG was evaluated at different concentration ratios with the concentrated photovoltaic (CPV) to demonstrate the effect of the optical concentration ratio on the system's efficiency. The TEG load resistance effect on power output was examined to assess the desired performance characteristics and the photovoltaic system's output voltage effect. The impacts of structural design and thermal resistance on the hybrid system's efficiency were analysed. Further, the parallel and series connections of the thermoelectric modules were investigated. The results showed a temperature difference of 28.9°C across the TEG when the optical concentration was increased from 74 W/m² to 217 W/m², demonstrating a substantial increase in the TEG efficiency.

Shittu (2020) presented a comprehensive three-dimensional numerical analysis of four contact resistances in CPV-TEG with COMSOL 5.4 Multiphysics software. The resistivity was seen between PV and TEG, TEG and heatsink, and TEG and thermal contact resistance. For all the cases, 12 contact resistances were selected to examine the most critical one. Shittu (2020) performed a parametric optimisation to explore the optimal load resistance, thermoelectric leg height, concentration ratio, and heat convection within the system. The results indicate that all the contact resistances play a significant role in determining the system's performance. The hybrid system efficiency increases with 7.4% and 7.6%. Furthermore, Shittu (2020) concluded that system thermal resistance must be minimised for effective energy harvesting.

4.1 Spectrum splitting technique

A PV-TE splitting system is a hybrid system consisting of the cooling system, spectrum splitting device, TE, and a PV module. The splitter reflects solar radiation at a defined wavelength in such a configuration, as shown in Fig. 6. The TEG also reflects radiation that is wider than the wavelength cut-off point. On the other hand, radiation smaller than the wavelength cut-off point is transmitted and absorbed by the PV through the spectrum splitter (Huen & Daoud, 2017a). It is worth noting that the TEG and PV operate separately when converting solar energy into electricity in this method; thus, the TEG does not use PV waste heat to convert energy or cool down the PV.

Yin *et al.* (2020) studied a concentrated tandem PV-TEG system using both experimental and theoretical models. During the experiment, the various solar concentration ratios, power outputs, and operating temperatures of both the systems were measured and recorded. Additionally, their influence on the coupling viability of various device parameters and device outputs, namely TE concentration ratio, the figure of merit, TE resistance, coolant temperature, efficiency, PV power, and temperature coefficient, were investigated. Finally, a few design considerations of the system were made. The findings indicated an improvement in the production from 1.38 W to 1.5 W, representing an 8.7% efficiency increase with a single-junction gallium arsenide PV cell.

Shatar *et al.* (2019) conducted a Global Climate Performance study of an unconcentrated PV-TEG system using a panel of 100 W, 5.99 A as a short-circuit current and 22.45 Voc. A 5 m LED light was used as a load for the indoor farm. The LED was set to be switched on and off during the day at given times: between 08:00 and 22:00 in December, every 18 hours in February, and every 24 hours in March. Under the shaded area of 2.5 m², the hybrid system was found to obtain a power output of 100 W without shading conditions. Shatar *et al.* (2019) stated that the PV was under partial shading conditions at 13:30. In December, the maximum power was observed between 15 W and 20 W. Furthermore, Shatar *et al.* (2019) concluded that there was a significantly low power output of about 15 W in February and below the same in March. Factors such as a rise in solar cell temperature, dust accumulation, and losses from wiring could also affect the output of the solar panels. The effects of weather, annual performance,

optimal working, and the seasonal conditions on the unsteady-state tandem hybrid PV-TEG system's superior performance to traditional PV systems were investigated (Yin & Li, 2020). The findings suggested that the tandem PV-TE performed more than the PV alone in both seasons. The efficiencies of the tandem hybrid system were 27.43%, compared to 26.46% of the traditional PV. However, the authors emphasised that the system's performance increase was detrimental to the system's protection and reliability. Yin & Li concluded that the hybrid tandem system has a better operating temperature due to the PV cell's presence. As solar irradiance increases, the system's temperature also increases, thereby affecting the system's performance.

Li *et al.* (2016) conducted a simulation for generic optimisation technique on the PV-TEG hybrid system, using a spectrum splitting approach. For the simulation, Cadmium telluride, Gallium arsenide and Dye-sensitized solar cell were used. The result shows that a better hybrid system with 13.26% efficiency was produced by the amorphous silicon cell. Li *et al.* (2016) reported that solar TEG and solar cell spectral efficiency depended on the hybrid system's overall performance. Ju *et al.* (2012) performed a comprehensive investigation of a concentrated PV-TEG spectrum splitting system. Furthermore, they suggested two fundamental ways of enhancing hybrid systems' performance: improving the cooling system's enhancement and increasing the concentration ratio. The results show an optimised efficiency of 27.49%, with the TEG contributing 10%.

Looi *et al.* (2020) investigated the PV-TEG air-conditioning system for residential use in a warm environment. According to Looi *et al.* (2020), the hybrid system was integrated with nine TEG modules to provide cooling for a 3.6 m³ volume chamber. Besides, they investigated the effect of the moisture removal rate and inputted current through a controlled experiment. The results revealed 5 A as the optimal current level and 0.14 L/hour as the moisture removal rate at air temperature. During the investigation, the indoor chamber's temperature was 4°C less than the unconditioned chamber's temperature in contrast to the air temperature. The indoor environment's humidity level was observed to be 58–83 %.

Additionally, the system energy consumption was 1.45 kWh at 5 A for a 12-hour operation. Furthermore, the authors also studied the viability of PT A/C for residential cooling under the same study circumstances of temperature reduction, humidity level, and temperature of the enclosed chamber. The research findings suggested 1.67 COP at 5 A with an optimum removal rate value of 0.14 L/h and 150 to 205 W cooling capacity.

Yin *et al.* (2018b) suggested an optimised configuration for the concentrated spectrum-splitting PV-TEG system in order to maximise the solar energy in CPV-TEG spectrum splitting without sacrificing the individual's optimal configuration systems. The findings indicate that the thermoelectric ZT and the optimum cut-off wavelength of the splitter were inversely related. Yan *et al.* (2018) analysed the efficiency through computational simulation of the PV-TEG spectrum-splitting system. The thermoelectric generator dimensionless current and the solar cell voltage were also studied. The findings show improved system performance by 2.67% and 2.19%, respectively, at 30 and above concentration.

Bjørk and Nielsen (2018) analysed the optimal mathematical efficiency of a concentration-free PV-TEG system. They adopted an empirical approach during the research, and the results showed that a peak efficiency gain of 1.8% could be achieved using spectrum splitting in the hybrid system.

Simulating a hybrid PV-TEG using 127 TEG numbers (Yin *et al.*, 2019) revealed that the system's average output power was 12.99 W and 13.37% higher at 600 W/m² than the PV alone with a concentration ratio of 3 W/m². Yin *et al.*, (2019) noted that PV, TE, and hybrid PV-TEG systems' output power reduces when the concentration is one and five. The system's output power decreases from 0.7% to 4.78% at 700 W/m², respectively, taking into account the Thomson effect. This experiment was in line with the results of Lamba and Kaushik (2016), who showed that the PV-TEG hybrid system's power output decreases at 720 W/m².

Rezania and Rosendahl (2017) conducted additional research on the P-TEG hybrid-concentrated system with the latest TEG of ZT ≈ 1. The study showed that the CPV-TEG system has improved efficiency compared to the CPV system, as shown in Fig. 7. Applying the energy equation to the first law of thermodynamics, Cai *et al.* (2020) analysed the effect of the number of TEGs, air temperatures, and solar irradiance on the hybrid CPV-TEG output power. To improve the TEV system's cooling and heating efficiency, the TEC number and input current were carefully varied. An incorporated numerical and mathematical technique was eventually developed to align the TEV power input with the CPV-TEG power output. The modelled findings showed that when the thermoelectric cooler input currents for cooling and heating modes are not more than 2.5 A and 2.8 A, respectively, the CPV-TEG output power could meet the energy demand of the TEV system. The system's minimum energy performance was 0.24% for the CPV-TEG and 1.67% for the TEV with CPV-TEG in the winter heating mode, which was much better than those of the summer cooling mode.

The results also show that the CPV-TEG system's performance depends heavily on the physical parameters, like the air temperature in the environment, and the number of TEGs. The power output for C = 5 rises to 967 W/m², decreasing with an increase in solar irradiance. The results further show that the system achieves a maximum power output at 154.29 W.

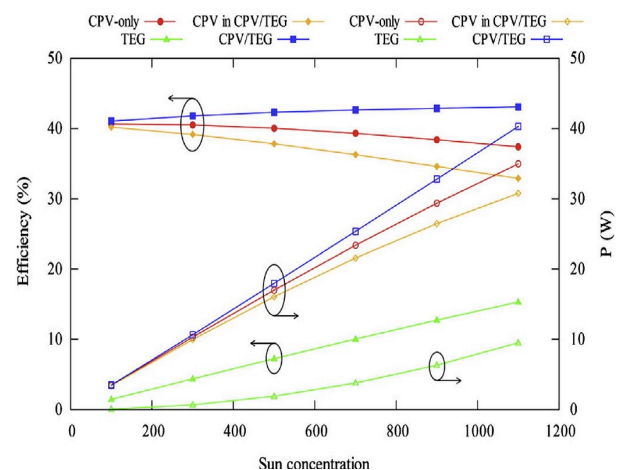


Fig. 7 Variation of sun concentration in system efficiency (Rezania & Rosendahl, 2017).

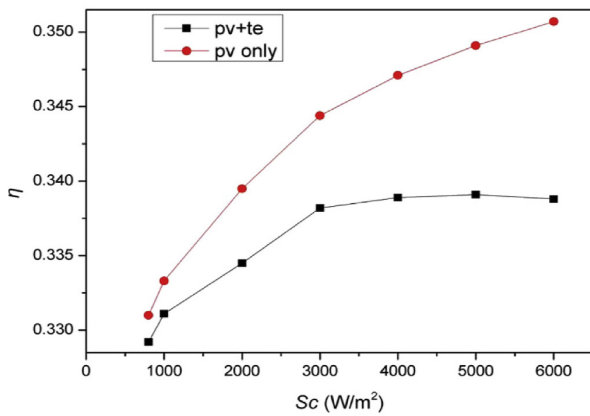


Fig. 8 Variation of the Hybrid and PV system (Lin *et al.*, 2014).

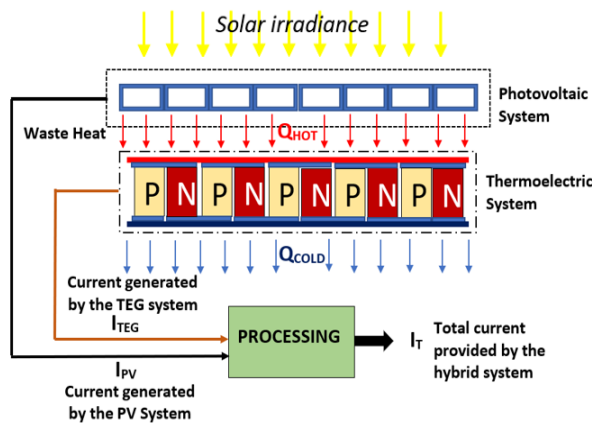


Fig. 9 Direct coupling integration of PV-TEG (Fisac *et al.*, 2014).

Cai *et al.* (2020) concluded that, at 1.3 A, 1.68 A, and 2.62, the maximum exergy efficiency was 5.33%, 3.17% and 0.75%, respectively, in summer mode. Mahmoudinezhad *et al.* (2018) performed a theoretical investigation of a low solar simulator CPV-TEG hybrid system. The findings suggested that the simulation's outcome agreed with the laboratory results, which showed that the CPV-TEG's optimum efficiency was 35.33%. The variation of the PV-TEG system with PV only is shown in Fig. 8.

Singh *et al.* (2018) presented the thermodynamic evaluation of a hybrid CPV-TEG cogenerated device's irreversibility and the optimum efficiency of a large solar spectrum in cool and warm weather conditions for a large solar spectrum. To understand its viability and assess the system's irreversibility and degradation, which is caused by the irreversible conversion of solar energy to electricity, Singh *et al.* (2018) modelled and simulated the hybrid system. Furthermore, they analysed the exergy and the irreversibility destruction of the system using the second law of thermodynamics. Exergy analysis was used to measure the different losses in the exergy of the system. The authors examined the influence of solar radiation's exergy up to 1000 W/m², irreversibility and energy loss, concentration ratio, Thomson coefficient, TEG temperature ratio, and current. The results indicate that as the concentration increases, the Thomson effect negatively affects the hybrid system's performance and increases its irreversibility. The hybrid system's power output also increases to 86% when the concentration rises between 1sum and 3sum, with system exergy efficiency being 8%

higher than energy efficiency. The highest number of irreversibility makes the system less efficient, as the temperature rise can lead to a substantial increase in hot sports. Singh *et al.* (2018) concluded that the study findings could be useful in developing a functional CPV-TEG hybrid system.

4.2. Direct coupling technique

This technique ensures that TEG is connected to the PV's backside with a heat sink positioned at the bottom of the TEG, as shown in Fig. 9. The photovoltaic cell absorbs the shorter wavelength in this method, while the thermoelectric generator absorbs the longer wavelength (Huen & Daoud, 2017b). Acut *et al.* (2019) designed and investigated PV-TEG-WiFi Energy system for WSN usage. The system developed a power combiner circuit that utilises a cross-coupled charge pump to combine it with wind energy. The system was simulated by using 65 nm CMOS. The findings indicated that when a load of 500 Ω was applied, 1.69 mW was produced, achieving 69% efficiency. A highly efficient CPV-TEG was analysed and presented by Kil *et al.* (2017); they demonstrated a hybrid CPV-TEG using a conventional TEG module and a single-junction GaAs-solar cell to form a concentrated hybrid system based on the direct coupling method. The experiment was under 50 suns concentration. The heat flow was controlled using TEG in the system. The results showed a 3% improvement in the overall efficiency of the hybrid system. Kil *et al.* (2017) concluded that the Peltier effect was crucial in achieving better efficiency.

The preliminary experiment on a novel PV-TEG system was presented in the sunny season (Shittu *et al.*, 2019). Shittu *et al.* (2019) attached the PV modules to the top surface of an MCHP, and, as shown in Figure 10, the TE modules were mounted to the bottom condenser layer. The solar energy falls to the surface of the PV in this model. In contrast, the PV's thermal energy is transported to the MCHP through the heat exchanger in the MCHP. Also, by condensation of the heat exchanger through evaporation, heat is released and passed to the TEG, creating a delta T that converts thermal energy through the Seebeck effect to electrical power. Furthermore, air cooling cools the TEG and the cooling structure. The findings suggest that the proposed design has a 14.0% efficiency gain, producing a better electrical output than the PV.

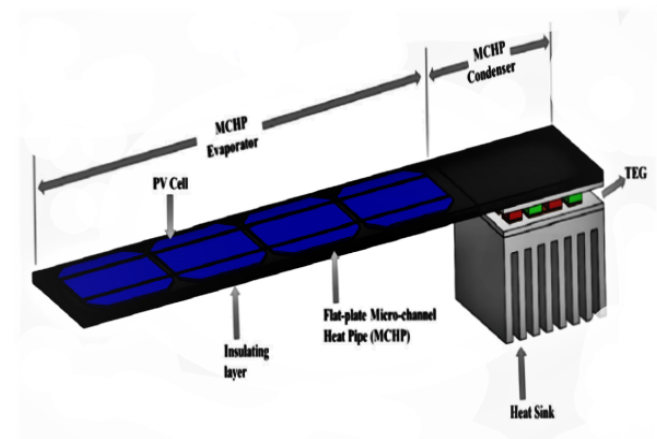


Fig. 10. Pictorial representation of PV-TE-MCHP (Shittu *et al.*, 2019)

A new CPV-TEG system incorporated into PCM to form PV-PCM-TEG has been developed by Cui *et al.* (2016). PCM has been used to minimise the fluctuation in temperature between the modules of PV and TEG. Four PV cells—CIGS, c-Si, GaInP/InGaAs/Ge, and single-junction—were used for the investigation. The authors obtained the optimal operating temperature in the system. They stated that the hybrid system with PCM as a buffer is preferred to the single PV or PV-TEG system in terms of efficiency.

Using a phase change material as an absorber plate connected with a PV-TEG to develop a PV-TEG-PCM unit, a transient simulation of a PV-TEG system was carried out (Motiei *et al.*, 2019). The PCM saved a considerable amount of heat energy during the phase change operation and provided increased storing space. Ultimately, this configuration manages the system's temperature, decreases PV temperature, increases the delta T through TEG, and enhances its efficiency. For the days in the warm and cold season, two-dimensional modelling was accomplished. In the simulation, ambient air temperature, wind speed, heat loss, and concentration are included. The results were better than the PV alone and PV-TEG system for hybrid performance. Motiei *et al.* (2019) further investigated the thickness and the melting point of the PCM and concluded that the optimum thickness and material depend on the environmental situation. Hajji *et al.* (2017) presented an analysis based on advanced PV-TEG hybrid system with a high-performance output, utilising avant-garde heat exchanger tracking. Hajji *et al.* (2017) placed a concentrator between TEG and the PV by avoiding any direct contact of the three elements. The results show a temperature of an irradiance flux of 53°C at an irradiance of around 1000 W/m² of the PV.

Sark (2011) proposed an active thermal management technique to develop a PV-TEG hybrid system for improved electrical efficiency, using a direct coupling approach. Two scenarios have been introduced for Utrecht in the Netherlands and Malaga in Spain. The total electricity output was also calculated by utilising weather data from both locations. The author also provided efficiency improvement forecasts based on potential thermoelectric materials to be produced. The result is shown in Fig. 10.

Liu *et al.* (2020) performed a hybrid PV-TEG system efficiency assessment with light and heat control. The

hybrid system was developed with various glass cover coating to investigate the performance improvement, as shown in Figure 12. The results in Figure 13 illustrate that the selective coating increased the system's power output by around 0.8%, 1.3%, and 14%, respectively. The impact factor analysis also shows that the effect of moisture content on system performance is less significant. In contrast, the concentration ratio, wind speed, and ambient temperature have a vital role in power generation. The SiO₂ coating has at least three years' payback period. The values of selective coatings and anti-reflective coatings are roughly five years and not up to four years, respectively. Liu *et al.* (2020) concluded that their work would give new ways of improving the system's efficiency.

Rejeb *et al.* (2020) conducted an optimisation study on a solar hybrid CPV-TE system, using COMSOL Multiphysics software centred on the finite element approach. The programme was used to perform three-dimensional numerical analysis. The results showed that the system produced an efficiency of 7.8%. Using ANOVA, a response surface statistical method, the numerical model results were analysed with a quadratic regression tool. The results showed that the coefficient of determination (R²) is 0.9945 for electrical efficiency. Furthermore, a simple polynomial numerical algorithm was developed to project and optimise the system's electrical performance, focusing on the four input variables investigated. The proposed method's maximum electrical efficiency was 17.448% at 2 KΩ electrical load resistance, 229.698 W/m² irradiances, 3.083 mm TE module height value, and 303 to 353 K ambient temperature values for optimum operating parameters.

A double cooling system with a solar PV-TE collector in three modes was experimentally and theoretically investigated (Daghigh & Khaledian, 2018) in Sanandaj, Iran. A single and double evaporator cooling system without a PV collector, a network-connected in a series arrangement with a PV-TE-air system and a compression was investigated in three modes in July 2016. Twenty-two (22) TEG modules were tested in the PV-TE mode, according to Daghigh and Khaledian (2018). Eleven TEG were grouped in parallel out of the 22, while the other 11 were in series.

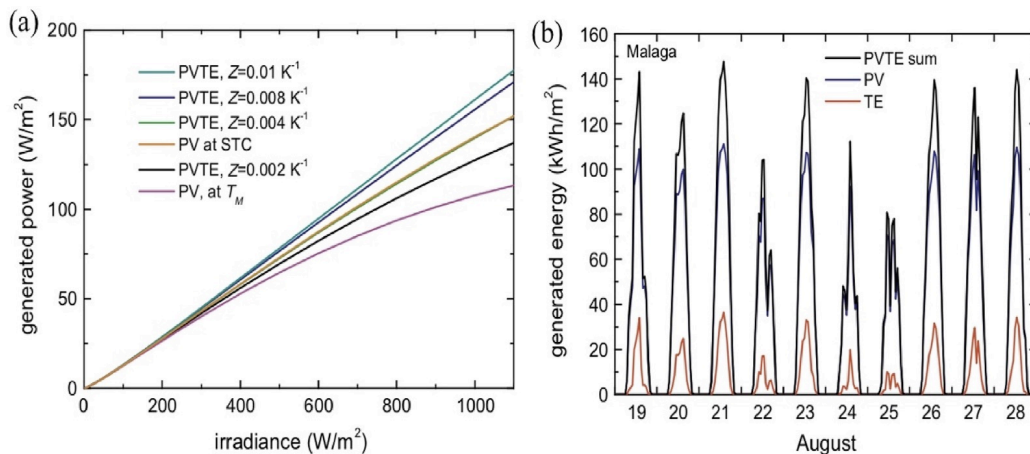


Fig. 11 Power Output of the hybrid system (a) power generated using four (ZT) values and (b) total power of Malaga, Spain (Sark, 2011).

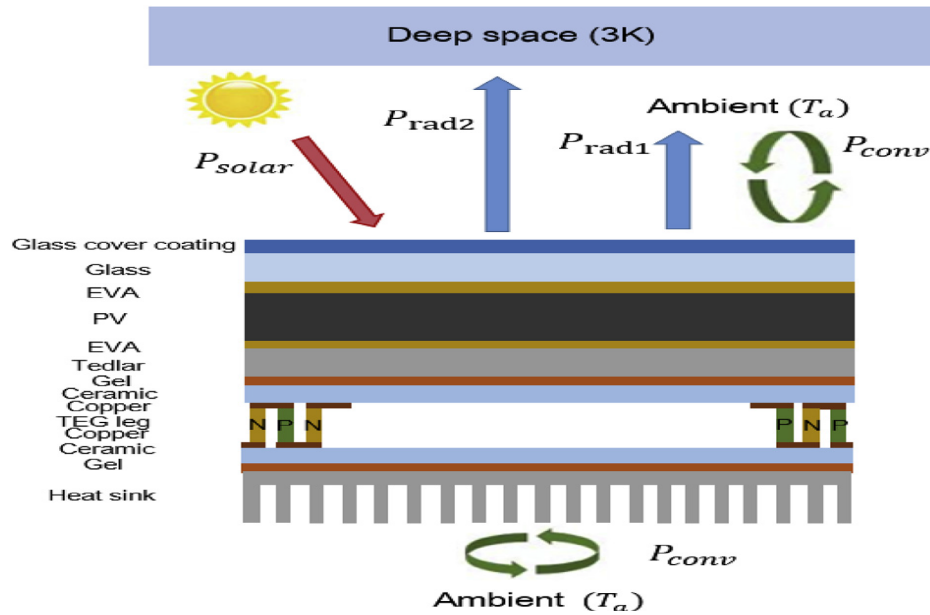


Fig. 12. Developed hybrids PV-TEG system with glass cover coatings (Liu *et al.*, 2020)

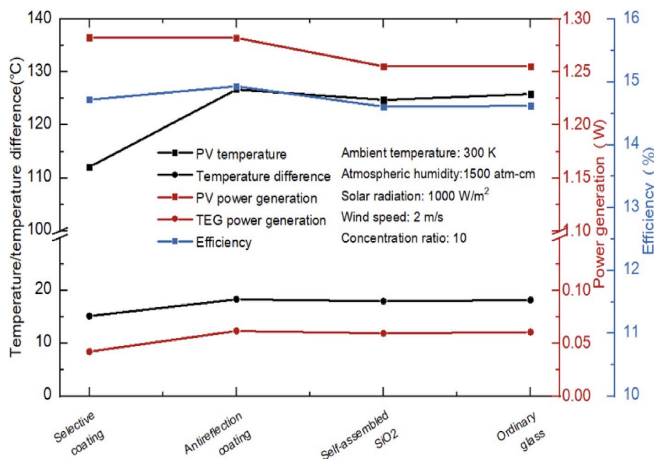


Fig. 13. Performance of Power generation by hybrid PV-TEG system using various glass cover coatings (Liu *et al.*, 2020)

The findings showed that, in the single-evaporator cooling and the hybrid double-evaporator cooling systems with the PV-TE collector, the compressor's power consumption and performance coefficients were 3,754 kW, 1,353 kW, 1,332 kW, and 3.69, respectively. They signified a positive impact of the PV-TE system on the compressor's energy consumption and COP. Their results also showed that the overall electrical performance and power output for a TEG device is 0.038 W, 0.063 W, 0.063 W, 1.12 W, and 1004 W/m² solar irradiance for the evaporator and the PV-TE-air system, respectively. The PV collector's electrical power generation rates were 0.11 W and 0.119 W for the two modes. These values reflect the positive refrigeration effect of the TEG device with an improved collector electrical efficiency.

An innovative technique of the different geometric placement of TEG within the concentrated systems with a delta of 50 °C and 200 °C was suggested by Chávez-Urbiola *et al.* (2012). The optimised PV-TEG system has a higher thermal power ratio to electrical power output than the

hybrid PV-T. The TEG's efficiency is dependent on solar irradiance. However, PV performance mostly relies on a linear solar irradiance function. For a T of 150 °C, the efficiency of the TEG is 4%.

Further research of the hybrid PV-TEG system's design optimisation was carried out using a direct coupling technique (Lin *et al.*, 2014; Makki *et al.*, 2016). The hybrid PV-TEG's overall performance was measured in the design for over twenty-four hours to observe any effects on the hybrid system's performance by solar radiation variance overtime. The findings showed a 16.7% efficiency improvement, which is much bigger than the PV alone. The results correspond with Li *et al.* (2019) and Babu and Ponnambalam (2017).

Gu *et al.* (2019) proposed a numerical model to evaluate a PV-TEG hybrid system's performance. The system design focused on the thermal resistance theory of PV panel, and the TEG. According to the authors, the system's electrical and thermal output was achieved through an iterative analysis of temperature measurement, connecting power generation with heat coupling. Additionally, during the numerical simulation, different heat losses and environmental factors were considered, and the PV alone was determined to be a comparative benchmark. The impact of the temperature coefficient and concentration ratio on system performance was also studied. The results suggest that a lower temperature coefficient and a higher PV cell concentration ratio are desirable for the hybrid system.

Furthermore, a sensitivity analysis of each component's thermal resistance within the hybrid system was performed and the relevant design parameters analysed. Gu *et al.* argued that the heat sink was found to influence the hybrid system's thermal resistance to the cooling system, proposing that limiting the cooling system's thermal resistance would be the most effective strategy for improving its performance. Finally, it was concluded that the hybrid system generated 1.24 to 2.85% efficiency, which was higher than that of the PV alone

Table 1

Summary of PV-TEG system related work

Author	Application	Results	Remark
Zhang <i>et al.</i> (2020)	Commercial monocrystalline PV cell and Bi ₂ Te ₃ were used in a controlled experiment based on the direct coupling using the Alumina layer between the PV and TEG.	The PV in the integrated system achieved 14.9% output power, which was higher than the PV alone under 350 mW cm ⁻² and 15 °C using a 16.1 μm alumina, and the system achieved 7.56%, which was more than the approach using 18.8 μm alumina layer.	Controlled experiment
Wang <i>et al.</i> (2020)	A numerical simulation was used to compare the CPV-TEC with CPV-TEG using thermodynamic and exert economic comparison	An increase in TEG operating current of about 0.27 A could convert the TEG to TEC with a minimal system exergy price of 0.263 \$/kWh, 0.148 \$/kWh, 0.113 \$/kWh, 0.266 \$/kWh, 0.152 \$/kWh, and 0.118 \$/kWh for the system, respectively.	Difference between CPV-TEC and CPV-TEG using numerical analysis
Rodrigo <i>et al.</i> (2019)	A triple-junction GaInP/GaInAs/Ge 3 mm × 3 mm solar cell was thermally coupled with a TEG through simulation.	A maximum predicted efficiency of 39.2% at 800x with a cost reduction of 46.0% at 1900x was achieved.	Simulation
Lakeh <i>et al.</i> (2019)	The coupling was done through simulation using the direct coupling of the PV with Bi ₂ Te ₃ TE module non-concentration.	The results show that an increase in solar irradiance can increase the PV-TEG utilisation.	Solar irradiance and analysis
Xu <i>et al.</i> (2018)	The TEG module and the PV were arranged using a direct coupling method with the TEG placed at the PSC's carbon side.	The hybrid system achieved a V _{oc} of 1.29 V and 20.3% power output using the irradiation of 100 mW cm ⁻² .	Controlled experiment
Keser <i>et al.</i> (2019)	Numerical analysis and optimisation were performed based on direct coupling approach.	This approach could improve the solar cell efficiency by 21.9% and the total hybrid efficiency by 2.95% via the substrate material with thermal conductivity of k = 0,01 W/mK	Numerical simulation
Johar <i>et al.</i> (2017)	TEC1-12706 with the size of 40 x 40 x 3.5 mm was used for this study. National Instrument (NI-CRIO 9014) was employed for DAQ for the temperature, current, and voltage measurements. Halogen lamps were used as a heat source for the TEG. LabView software was used for data display.	Two TEGs generated 416.82μW of power output in series at 200 Ω and 100 MW when in parallel at ΔT of 7°C.	Halogen as the source of heat for the TEG
Wan Jamaludin <i>et al.</i> (2020)	Test ring was used for the TEG and the Shingle, and it was connected to the National Instrument for DAQ	Four modules of TEG in series generated an average of 0.003 V at a load of 138Ω this gives 65.22 uW of power.	TEG attached to shingle thereby giving TEG + Shingle energy
Akashah <i>et al.</i> (2019)	The TEG was attached to the backside of shingle, and heatsink was placed at the TEG cold side. The system was connected to the NI for data recording.	The analysis results indicate that at 1.5°C, the shingle produced an input power of 10.8675 W while the TEG produced an output power of 0.21 W at the temperature difference of 1.75°C.	TEG + shingle

Dallan <i>et al.</i> (2015)	A direct moth was used for the PV-TE coupling. Using a monocrystalline Solar PV module with specifications of 60 x 60 x 2.8 mm and a graphite-coated Bi ₂ Te ₃ TEG1-1263 with a dimension of 30 x 30 x 3.75 mm in a controlled experiment using ten bulbs, eight of which were Eurolite 9005XB 65 W Xenon crystal bulbs, while the other two were solar simulators 400 W FloraSun bulbs and a load of 21 Ω .	The output of PV was 60.5 W/m ² and the production of TEEG was 0.01 W/m ² . The hybrid PV-TE system achieved an efficiency of 13.2%.	TEG in a controlled environment using the direct method of coupling
Zhou <i>et al.</i> (2016)	Controlled lab. experiment using a direct method.	Hybrid PV-TEG obtained 9.08% conversion efficiency, which is substantially improved by 20.6% and 725.5%, compared to just PV and TEG alone, respectively	Controlled experiment
Sark (2011)	Direct method using the simulation. A mathematical model was developed for this analysis.	The efficiency of the hybrid PV-TEG was 13.98% at 83°C PV temperature and 1000W/m ² irradiance. The PV alone has 10.78%, and the TEG has 3.02%.	PV + TEG and simulation
Mohammadnia <i>et al.</i> (2020b)	Control experiment. 65 W halogen bulb was used as the solar simulator and as the source of irradiance.	The simulation results show an overall system total electric power output of 45.4 kW at 455 suns.	Control experiment
Wang <i>et al.</i> (2011)	A direct coupling using simulation and an SSA between the TEG and PV.	There was an increase in the efficiency of up to 13% and the temperature difference of 6.2°C at the TEG. DSSC contributed 9.26%, TEG contributed 4.41%, and SSA/TEG contributed 4.6%.	Control experiment and simulation
Chávez-Urbiola <i>et al.</i> (2012)	Controlled laboratory experiment using a direct coupling method.	The TEG produced an output of 3 W, which contributed 4% efficiency at a temperature difference of 150°C.	Control experiment
Lin <i>et al.</i> (2014)	Direct coupling. The TEG was attached to the PV's rear.	Using the c-si, the PV-TEG efficiency is 11.7%, PV only is 9.5% at 0.7 ohms load, while using GaAs, the efficiency is 22.94% at 1.6 ohms load for PV-TEG and 21.9% for the PV only.	The TEG contributed to adding heat to the solar cell
Mustofa <i>et al.</i> (2018)	Spectrum splitting method was used with a shorter wavelength for the PV, while the longer wavelength for the TEG used a mirror as a medium for the irradiance transmission. A spectrometer software was used for the wavelength measurements.	A long wavelength of approximately 800 nm was released by halogen light for TEG use. The incandescent lamp produces the maximum heat radiation of 54.76 W.nm, and the lowest heat radiation is 25.65 W.nm.	Controlled environment
Yang <i>et al.</i> (2018)	Spectrum splitting was used for this experiment. The TEG was placed perpendicular to the PV. The TEG used the irradiance above the spectrum wavelength.	The overall hybrid system efficiency was estimated at 18.6%, while it was 17.8% for the PV alone, using perovskite solar cell.	Simulation
Elsarrag <i>et al.</i> (2015)	The experiment was done in a controlled environment using spectrum splitting.	At a temperature difference of 18 K under the solar radiation of 1.1 suns, the power output of the TEG was 32 mW. Between 200 and 800 W/m ² , the split spectrum PV performed better at low irradiance level, up to 700W/m ² which is the average PV.	The TEG is independent of the PV
Bjork and Nielsen (2018)	The work was done using the analytical model by adopting the spectrum splitting method.	The PV-TEG efficiency was 4.5%	Analytical method

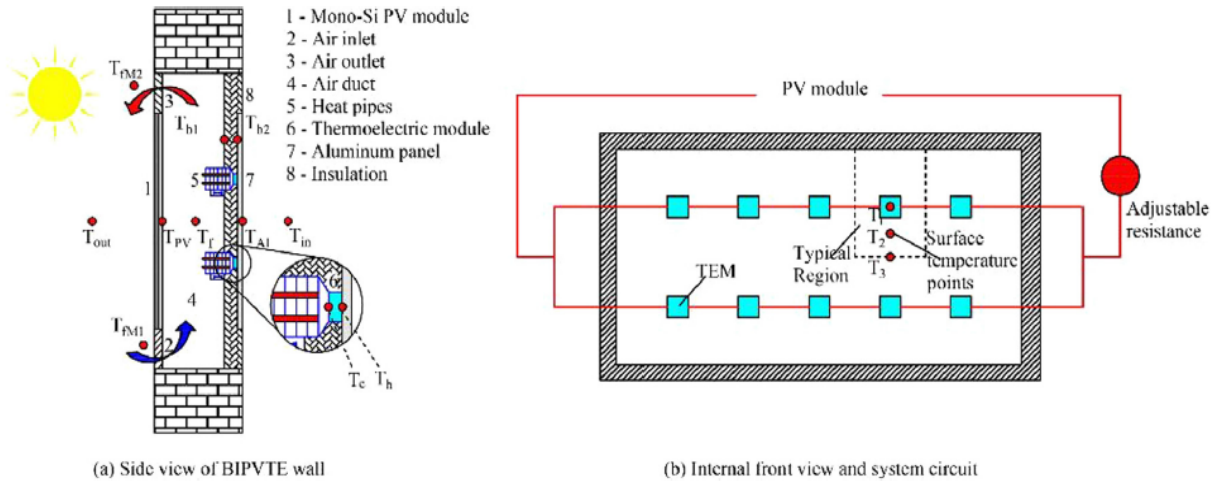


Fig. 14. System structure of BIPVTE (Luo et al., 2020)

A three-generation network containing a PV cell and TEG, combined with a solar collector using MATLAB software, was implemented in a non-dimensional model (Soltani *et al.*, 2018). The influence of solar irradiance and air temperature on the hybrid system output was examined. In solving eight nonlinear algebraic equations, the authors used iterative Newton–Raphson methods to evaluate the electrical characteristics of the TEG and PV as well as the electrical and thermal efficiencies and thermal and electrical strengths of the system. The effect of solar irradiance and air temperature on the hybrid system’s output was examined. The findings indicate improvements in electrical efficiency by positioning the TEG unit and PV cell on the absorber tube’s lateral region. 22,714 W was also attained at a 998 W/m² concentration.

A new concept of double zeroes for building envelopes was developed (Luo *et al.*, 2020). The first zero represents zero heat loss or heat gain via the structure envelopes, while the second zero represents the net-zero energy utilisation to attain the first zero. The system was achieved through the coupling of PV, TEG, and the battery. The formed envelope structure in Figure 14 shows that external PV modules were mounted perpendicular to the wall, and the envelope structure had many TE devices coupled to its back and it was mounted such that it faced the tank’s internal environment.

The heat flux of the TE module achieved the first zero using power from the PV control; the second zero was attained in a model that predicted control of power flow. Analytical and numerical methods were used for this study and were further validated by the experimental measurements for both winter and summer conditions. The findings of the research showed that this system is highly adaptable to various geographical areas. The system achieved 72–92% energy savings for winter areas, 88–100% for mixed-season areas, and 100% for summer areas. Luo *et al.* (2020) concluded their study with the creation of net energy utilisation maps. The zero-energy line can be defined as a significant specification for developing "double zero" in the structures’ envelopes for various service years.

Zhang *et al.* (2014) designed a concentrated PV-TEG system that combined a high-performing CIGS with various photovoltaic cells (polymer, polysilicon thin-film,

crystalline, silicon and CIGS). Of these combinations, the polysilicon thin-film photovoltaic cell design provided the maximum performance. The combined hybrid system achieved about 8% performance. Incorporating a selective absorber layer between TEG and PV, Wang *et al.* (2011) simulated PV-TEG efficiency. This innovative method of integrating a DSSC to form a PV-TEG system improved the system’s performance by 13% with a TEG temperature gradient of 6.2°C. As the two energy sources are distinct from nature, the PV-TEG hybrid’s maximum power point is harder to track than that of the stand-alone PV. Another model was developed by Hashim *et al.* (2016) to track the MPPT of PV and TEG. The addition of TEG to the PV resulted in a 2 mW power output reduction due to its thermal resistance, and the 5 mW TEG power balanced the losses. The MPP of the TEG in this study was based on the optimum length of the TEG unit.

The MPPT controller was attached to the system to maximise the energy output from TEG and PV systems separately. For the PV, the MPPT was employed based on power versus voltage characteristics (Javed *et al.*, 2018). While power versus current characteristics for the TEG. For TE, the MPPT was used based on power versus current TEG characteristics (Amaral *et al.*, 2014). Luo *et al.* (2020) presented the proposed system’s layout. The experimental and simulation analysis of the different PV-TEG system configurations discussed in this review are summarised in Table 1.

5. Conclusion and Suggestion for Future Works

One of the technological advancements that can simultaneously harness electrical and thermal energy and increase the overall performance is the hybrid PV-TEG system presented in this work. Simulation and experimental analyses of different hybrid PV-TEG configurations and PV cells, thermoelectric machinery, thermal performance, and electrical efficiency were also presented and discussed. The PV-TEG systems provide a mechanism for broad-spectrum solar radiation harvesting based on the potential of both the PV generators and TEGs for power generation. TEG’s combination with a multi-junction solar cell tends to produce electricity more

effectively. Multi-junction solar cells with a maximum energy conversion efficiency of more than 40% are considered the most efficient, unlike amorphous silicon, polymer solar cells, and crystalline silicon. With concentrated solar radiation, they show suitable performance. The thermal contact resistance between PV and TEG and between TEG and the heat sink reduces the PV-TEG system's efficiency by producing excess PV temperatures. This can be avoided by adding a shingle between the PV and the TEG.

The maximum possible wavelength of PV cells determines the optimum wavelength in a CPV-TEG system with a spectrum splitter. In general, the cold side of the TEG is cooled using various techniques to maintain a large temperature difference in the TEG. By increasing the hot junction temperature, the TEG temperature difference can also be increased. However, only a few PV-TEG system configurations use this technique to maintain the temperature gradient. Therefore, PV-TEG hybrid systems seem to have room for future enhancement. These systems have gained recognition in recent times, and noticeable scientific works have aimed at making PV-TEG systems more dependable and feasible. Both experimental and analytical studies on the hybrid system's performance improvement have been technically reviewed in this paper. Despite the abundance of reported research in this domain, little effort has been committed to maintaining the temperature gradient, which is germane. Therefore, further research effort in this area is necessary and recommended. Most of the literature contains studies performed in a controlled atmosphere, and little to no attention has been given to a transient condition. Therefore, experimental work that considers changes in weather conditions should be conducted to compare each of the techniques' strengths and weaknesses. The combination of TEG and PV tends to generate more power, which is essential in dealing with the present power supply challenges.

Further, the concentration ratio, the figure of merit, temperature coefficient, and heat transfer coefficient are factors that affect the PV-TEG coupling system's efficiency. To address these technical challenges, the various methods used to investigate these parameters were introduced and examined in this paper. Different approaches from recent studies were also reviewed to enhance the performance of the coupled system. Based on the analysis, the current review presents the following conclusions:

- Increasing the concentration ratio enhances the TEG's efficiency and, thus, increases its contributions to the hybrid system. This, however, is only possible with an effective heat sink.
- A hybrid system comprising a multi-junction PV and Bi₂Te₃ TEG and with a high concentration ratio results in a high conversion efficiency.
- Effective temperature variations from the PV to the TEG can significantly improve the overall efficiency.

Abbreviations

AM	Air mass
Bi ₂ Te ₃	Bismuth telluride
CdTe	Cadmium telluride
CIGS	Copper indium gallium selenide
CoSb ₃	Copper antimony

CPV-TEG	Concentrated photovoltaic-thermoelectric generator
DSSC	Dye-sensitized solar cell
GaAs	Gallium arsenide
GaSb	Gallium antimonide
GeTe	Germanium telluride
I-V	Current-voltage
PCM	Phase change material
PV	Photovoltaic
PV-TEG	Photovoltaic/thermoelectric generator
TEG	Thermoelectric generator
SSA	Solar selective absorber

Greek symbols

η	Efficiency, %
σ	Electrical conductivity, S/m
α	Seebeck coefficient, V/K
κ	Thermal conductivity, W/m/K

Subscripts

H	Hot side
C	Cold side

Nomenclature

A	Area, m
C	Concentration ratio
FF	Fill factor
G	Solar irradiance, W/m ²
I _{sc}	Short circuit current, A
P _{in}	Input power, W
T	Temperature, K
V _{oc}	Open circuit voltage, V
ZT	Figure of merit

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