Effect of Thermoelectric Cooling System on the Performance of Photovoltaic-Thermal Collector: A Review

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Abstract- Renewable energy is critical for the mitigation of the dependency on fossil fuel-based energy. Solar energy has a vast potential compared to other renewable energy to replace fossil fuels. To harness solar energy, photovoltaic (PV) technology is utilised to convert light energy into electrical energy. The major drawback of PV is that its performance can deteriorate due to an increase in the temperature of PV panels. To address this limitation, solar thermal collectors have been developed to extract heat from PV surfaces purposely to cool them down. Numerous researchers in prior studies agreed that the combination of PV and the thermal collector as a whole system, also known as a photovoltaic-thermal (PVT) system, would be beneficial in increasing PV efficiency. There are multiple cooling systems that can notably reduce the temperature of PV panels. Water and air were used extensively before the emergence of advanced cooling systems such as nanofluid, phase change material, and thermoelectric (TE). The TE device can convert thermal energy into electricity using the Seebeck effect. Contrarily, it will act as a cooling system by supplying electricity due to the Peltier effect. The combination of PVT and TE modules is very beneficial in increasing energy production. This review paper mainly focuses on different designs of PVT-TE systems. The performance of PVT-TE is analysed using the first and second laws of thermodynamics. This paper found that the energy and exergy efficiency of PVT-TE is in the range of 23.21 – 81.47% and 6.39 – 16%, respectively.

Keywords Photovoltaic-thermal, thermoelectric, energy analysis, exergy analysis, Seebeck effect, Peltier effect.

1. Introduction

Energy is the most crucial component of all human actions. It is now an essential requirement for the world economy and development. The 20th century has seen a growth in energy demand and consumption, with fossil fuels supplying most of the energy. Most researchers anticipate and believe that the world's annual energy consumption will increase in the twenty-first century [1, 2]. Despite booming in popularity, renewable energy sources like solar and wind only supply around 18% of the world's energy demands, according to the International Energy Agency (IEA).

The usage of fossil fuels has a variety of environmental and human health consequences. The combustion of fossil fuels emits carbon dioxide (CO_2) and other pollutants into the atmosphere, contributing to climate change. Thus, the transition from fossil-based energy to clean energy is necessary to mitigate the climate change impact of fossil fuel burning [3, 4].

According to the National Oceanic and Atmospheric Administration (NOAA), solar energy has the potential to meet the energy needs of the entire world. Over 173,000 TW of solar energy, sufficient to power the entire world 10,000 times, are present in the world. Solar energy currently makes up approximately 2% of the world's total energy supply, but it has enormous growth potential. Also, according to the IEA, solar energy might supply up to 27% of the world's electrical requirements by 2050.

Photovoltaic (PV) cells can directly convert solar energy into power, with a practical efficiency ranging from 9 to 20% depending on solar cell technology [5, 6]. The remaining energy will accumulate as heat on the PV surface if it is not converted [7]. The accumulation of heat will increase the temperature, causing a deterioration in the performance of PV [8]. To solve this problem, a thermal collector system is essential as it will extract the excess heat energy via the heat transfer process [9, 10]. Photovoltaic-thermal (PVT) technology has been extensively used to harness solar energy. The PVT collectors can simultaneously convert solar irradiance into electricity and extract the heat effectively. Numerous designs have been proposed to improve the efficiency of the PV module. Water and air were utilized as the main heat collectors in the early stages of the mid-1970s [11, 12]. Currently, the PVT system had evolved with advanced thermal collectors including thermoelectric, organic, and metal hydride phase change material (PCM), splitting spectral and heat pipe [13]. Figure 1 shows the various cooling methods for the PVT system.

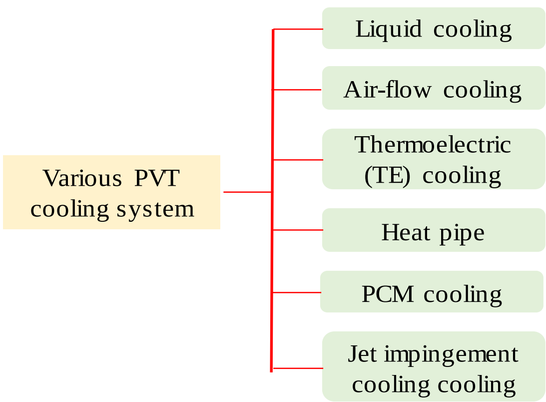

Fig. 1. Various cooling methods for PVT system [3].

Thermoelectric (TE) devices are gaining popularity in the energy industry for various applications, although conventional TE technologies are inefficient and expensive per unit of energy delivered [14]. In PV applications, TE devices will be useful as a secondary power generation system as well as a cooling system. By utilising the Seebeck effect, the TE device can directly convert the heat dissipated on the PV module to electricity [15]. Furthermore, TE devices can act as cooling systems using the Peltier effect due to the creation of different temperatures for both sides of the TE device [16]. Both effects have been proven by previous research to help in reducing the PV surface temperature and subsequently increasing PV efficiency.

The objective of this review article is mainly to evaluate the effects of TE systems on the performances of PVT systems in numerous designs, parameters, energy, and exergy performance. This study provides several potential novelties and contributions to the field of renewable energy and thermoelectric technology. This review study can create a holistic picture of the current state of knowledge regarding the interaction between TE systems and PVT systems. The study can examine various performance metrics, including energy and exergy performance, to determine how TE systems affect the overall efficiency and effectiveness of PVT systems. This can help quantify the impact of TE integration on energy generation and thermal output. The findings of this study will benefit researchers, engineers, manufacturers and industries in developing future innovations.

2. Working Principles of Thermoelectric

Thermoelectric was discovered by T.J. Seebeck in 1812 by proving that an electromotive force could be generated by heating the junction of two different electrical conductors. J. Peltier discovered the reversed process of the Seebeck effect, in which he discovered that by providing electricity through a thermocouple, a temperature gradient between two sides of the thermocouple can be generated depending on the direction of the current.

Thermoelectric devices consist of two dissimilar materials. The common material that was used to build complete TE devices consists of semiconductor n-type and p-type materials, connected electrically in a circuit and thermally in a series [17]. Figure 2 illustrates the complete structure of the TE device.

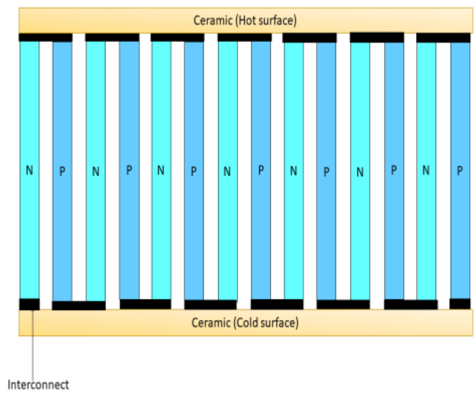

Fig. 2. Thermoelectric device structure [15].

Figure 3 illustrates the phenomena in the TE effect. Electrons can flow from one material to another, creating a potential difference, also known as voltage. When one end of the junction is heated, the temperature difference causes the electrons to flow from the hot end to the cold end, resulting in the generation of current. This phenomenon explains how Seebeck effect works. The Peltier effect works differently as the current will be provided through the TE device to create a temperature gradient between two TE junctions. The heat is either absorbed or released, depending on the direction of the current [18]. The reason for this is due to the transfer of energy between the electric current and thermal energy of the junction [19]. The temperature of the TE can be regulated by governing the current flow, which is determined based on the direction and magnitude of the current on the hot and cold sides of the TE [20].

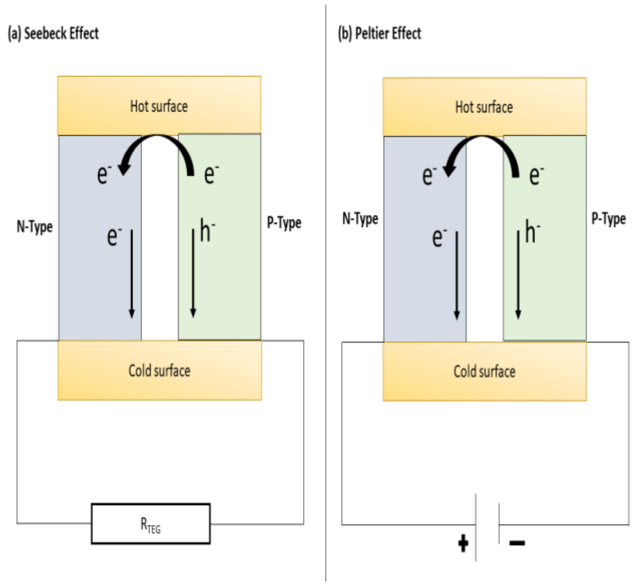

Fig. 3. The phenomena in the TE effect [21].

The Peltier effect also can be explained mathematically as

$$Q \propto I \quad (1)$$

where Q is the cooling or heating rate, and I is the current flow through the TE system. The proportionality constant for Eq. (1) is called the Peltier coefficient, π,

$$Q = \pi_{ab} I \quad (2)$$

where $\pi_{ab} = \pi_a - \pi_b$ is the coefficient for two different metals.

The Seebeck effect can be mathematically explained as follows:

$$V \propto \Delta T \quad (3)$$

where V denotes the generated voltage and ΔT denotes the temperature gradient between the two junctions of TE. The proportionality constant for Eq. (3) is called the Seebeck coefficient, α,

$$V = \alpha_{ab} \ \Delta T \quad (4)$$

where $\alpha_{ab} = \alpha_a - \alpha_b$ is the coefficient for two different metals.

Throughout the previous few decades, an extensive amount of research has been carried out regarding thermoelectricity. Moreover, numerous review papers have been disseminated, providing elucidation on various aspects of this field. Research conducted focused on the study of thermoelectricity can be classified into three mutually dependent domains: material science [22], TE device design [23] and system design [24].

Previous research [25] have discussed improving the efficiency of TE materials using charge transfer engineering. To achieve a notable increase in TE efficiency, the authors manipulated the chemical bonding in a lead-free germanium-telluride material. Additionally, they also increased microhardness and eliminated thermal expansion fluctuation. As a result, they obtained a conversion efficiency of 13.4% at a temperature difference of 463 K. The microstructure and stability of the material also were determined using various techniques. In a nutshell, this paper presents a promising approach to improving the efficiency of thermoelectric materials.

Zhao [26] investigated the performance of an exhaust TE generator by optimizing the structure of the exhaust heat exchanger. The study developed a mathematical model based on a fluid-thermal-electric multi-physical field. The addition of a perforated plate boosted the generator's output power, and there is an optimal installation position that increases the output power by 73.4%.

3. PVT-TE System

Several hybrid systems combining PVT collectors with TE devices have recently been studied [27]. In a conventional PVT-TE configuration, the TE module is attached at the backside of the PV module. This system is called a thermoelectric generator (TEG). For the power generation mode of the TE module, the hot side is attached to the backside of the PV module while the cold side of the TE module is attached to the cooling system, creating a temperature gradient between the two sides of the TE module, subsequently, produce some amount of electricity. In the reversed configuration, it is possible to use a TE module as a cooling system using a Peltier effect, which is known as thermoelectric cooling (TEC). The cold side of TE is attached to the backside of the PV module. The current flow is necessary in this configuration to create a temperature difference between two sides of the TE module. Figure 4 illustrates both configurations of PVT-TEG and PVT-TEC systems.

As depicted in Figure 5, PVT-TE can also be combined with other collectors such as water, air, heat pipe, phase change materials (PCM), etc. The combination of PVT-TE with other cooling systems contributes a better cooling efficiency for the PV module compared to the conventional PVT-TE. Besides, concentrated PVT (CPVT) and low concentrated PVT (LCPVT) were designed to concentrate the sunlight to a PV module. This ensures that a PV module absorbs more solar energy [28-29]. The drawback of CPVT is that it causes a rapid increase in temperature on the PV surface when compared to PVT, hence, decreasing the performance of the PV module [30].

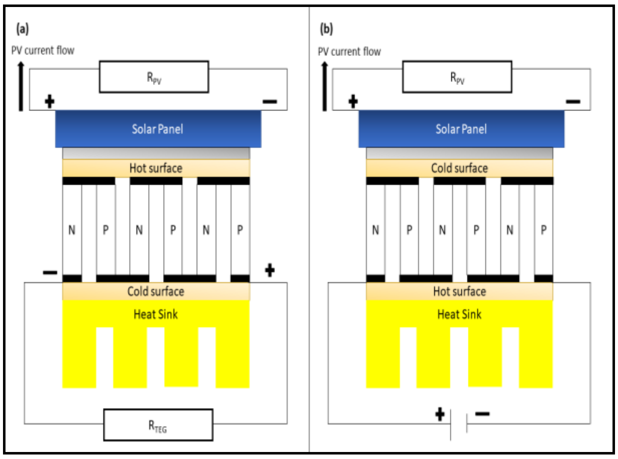

Fig. 4. The schematic diagram of (a) PVT-TEG and (b) PVT-TEC

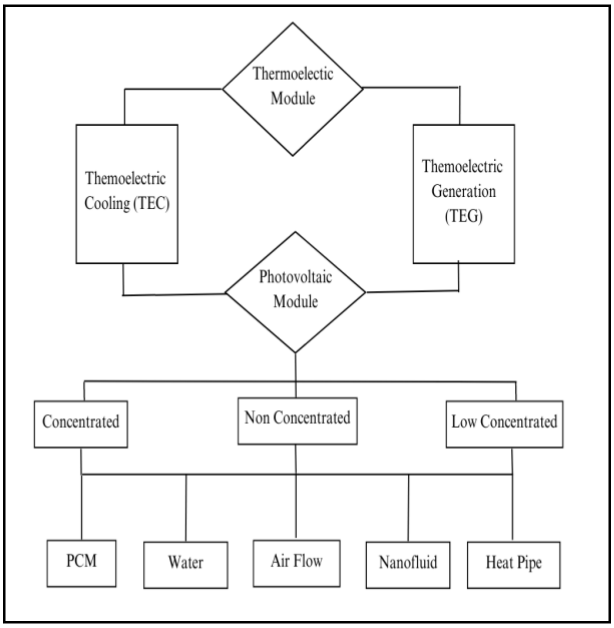

Fig. 5. The combination of PVT-TE designs

Choi et al. [31] proposed a cooling system using TE elements to enhance the output of building-integrated photovoltaic (BIPV). The thermoelectric cooling (TEC) system was compared to the ventilation cooling system, which is the conventional cooling system for BIPV. Both cooling systems were tested using the nominal operating cell temperature (NOCT) and the standard test condition (STC), and the output was analysed. The STC results indicated that the mean temperature of the BIPV system with TE component was 24.5 ˚C, while the temperature of the BIPV system with ventilator was 33.3 ˚C. The NOCT test discovered that the temperature of the BIPV module with thermoelectric element and ventilator was 38.5 ˚C and 41.02 ˚C, respectively. This concludes that TEC provides better cooling for the PV module compared to the ventilation system.

He et al. [32] conducted theoretical and experimental research in PVT, which is a heat pipe combined with the TE module as a cooling system of the building during winter and summer seasons. Both the cold and hot sides of TE were utilised in this experiment. The hot side of TE will be warming inside the building while the cold side will be used to cool PVT during winter, and the method will be reversed during summer. The results were compared between the two seasons, and they showed an increase in electrical and thermal efficiency during the winter compared to summer. The electrical efficiency reported was 16.7%, which was higher than that in summer (15.4%).

Hybrid PVT-TE with sky radiative cooling (RC) systems also have been investigated by Lv et al. [33]. The climate chosen for the simulation was in Hefei, China, and this experiment runs annually. The result showed that electricity production initially increases every month due to solar radiation, peaking at 17.83 kWh in August, and then gradually diminishing. This paper concludes that the combination of PV-TE and RC is a feasible method for generating electricity and achieving day-long cooling.

An experimental analysis using TEC in hot climate change was performed by Benghanem et al. in 2016 [34]. The result showed that with the usage of TE, the PV temperature dropped from 83 ˚C to 65 ˚C. In terms of electrical efficiency, the presented results showed that the maximum increase of efficiency was 1.3%, the minimum increase was 0.19% and the average increase in 0.55% with the aid of thermoelectric.

A theoretical model of concentrated PVT-TEG was developed by Lamba et al. 2018 [35]. The first and second laws of thermodynamics were used in this paper to predict the best performance of the concentrated PVT-TEG. The Thomson effect has been symmetrically distributed between the cold and hot sides of TEG. The result showed that the concentrated PVT-TEG has better performance of electrical efficiency which is 13.37% compared with concentrated PVT which is 13.26%.

A novel design of PVT-TE system to mitigate the fluctuation from solar temperature was proposed by Zhang and Xuan 2017 [36]. The design involved four adjustable cooling blocks and water flow used as a heat transfer. The following design was compared with the same design with aid of PCM. From the result, the new design of PVT-TE achieved higher overall efficiency compared to conventional PVT-TEG. Moreover, the addition of PCM in the design has improved the overall efficiency when compared to the design without PCM.

A comparative study of PVT-TE systems with different types of fluid was conducted by Soltani et al. 2017 [37]. There were five different cooling methods used experimentally, namely natural cooling, water cooling, Fe_3O_4/water nanofluid cooling, SiO_2/water nanofluid cooling and forced air cooling. The copper pipe was attached to the cold side of TE as a fluid path whereas the hot side was attached at the back of the PV module to create the temperature gradient. The finding from the study indicated that the liquid cooling system gave better energy production compared to the air cooling system which was 47.7% more power production. Besides, from the three different types of liquid used, SiO_2/water nanofluid cooling recorded the highest efficiency improvement relative to natural cooling (air cooling) which was a 3.4% improvement, followed by Fe_3O_4/water nanofluid cooling showing 3.1% improvement and water record 3.0% improvement.

4. Energy Analysis

Energy analysis will determine the performance of the hybrid PVT collector based on the first law of thermodynamics. The term total energy will be used to understand the performance of the PVT collector, which is the sum of the electrical energy, η_{pv} and thermal energy, η_{th} [38]. The total energy, η_{pvt} produced can be written as:

$$\eta_{pvt} = \eta_{pv} + \eta_{th} \quad (5)$$

The η_{pv} of the PV/T collector can be determined with Eq. (6) [39]:

$$\eta_{pv} = P/AG \quad (6)$$

where P is the power generated by the PV module, A is the surface area of the PVT collector, and G is the intensity of solar radiation. Eq. (7) is an extended formula for P,

$$P = IV \quad (7)$$

where I is current flow and V is voltage. Additionally, η_{pv} can be calculated in terms of module temperature and written as follows:

$$\eta_{pv} = \eta_{ref}\,[1 - \beta_{ref}\,(T_{PV} - T_{ref})] \quad (8)$$

where η_{ref} is the reference efficiency of the PV module, βref is the temperature of the coefficient (0.0041 K^{-1}), T_{Pv} temperature of the PV module and Tref is the reference temperature of 25 °C.

The TEG electrical efficiency can be estimated using Eq. (9) [40].

$$\eta_{TEG} = [T_h - T_c\,(1+ZT_M)^{0.5} - 1] \,/\, [T_c\,(1+ZT_M)^{0.5} + (T_h/T_c)] \quad (9)$$

T_h, T_c, T_M, and Z represent the hot side temperature, cold side temperature, average temperature, and the figure of merit of the TE material, respectively. In addition, Z is also calculated according to Eq. (10) [41]:

$$Z = \alpha^2\sigma/K \quad (10)$$

where α is the Seebeck coefficient, K is the thermal conductivity and σ is the electrical conductivity.

The thermal efficiency (η_{th}) of the PV/T collector is calculated as in Eq. (11)[42]:

$$\eta_{th} = Q_u/AG \quad (11)$$

where Q_u is the heat collected, which can extend as in Eq. (12):

$$Q_u = mC(T_{out} - T_{in}) \quad (12)$$

where m is the mass flow rate of fluid, C is the specific heat of fluid, Tin is fluid inlet fluid temperature and Tout is the outlet fluid temperature.

The Eq. (10) is the heat collector specifically for fluid. For other cooling systems such as PCM, the equation from Eq. (12) can be modified in Eq. (13) [43]:

$$Q_c = mC(T_{out} - T_{in}) + \dot{E}_{PCM} \quad (13)$$

where E˙PCM is the thermal power absorbed by PCM.

5. Exergy Analysis

Exergy analysis provides a more comprehensive and accurate assessment of system efficiency compared to traditional energy analysis. While energy analysis focuses solely on the quantity of energy input and output, exergy analysis considers the quality of energy and how effectively it can be converted into useful work. This allows for a better understanding of system performance. Exergy analysis can pinpoint the sources of irreversibility and losses in a system. By identifying where exergy is destroyed or lost, engineers and researchers can target specific components or processes for optimization, leading to improved overall system efficiency [44]. The exergy can be defined as the maximum amount of work produced by a system, mass flow, or energy flow as it reaches equilibrium with a reference environment [45].

Exergy analysis also can be named as the quality of the energy [46] and related to the second law of thermodynamics in terms of total exergy inflow ($E_{\chi in}$), exergy outflow ($E_{\chi out}$) and exergy destructed ($E_{\chi dest}$). The application of exergy-based analysis has considerable significance in the identification of various irreversibilities that contribute to the reduction in overall efficiency of a given system in terms of their underlying causes, locations, and magnitudes [47]. The equation of exergy analysis can be written as [48]:

$$E\chi_{in} - E\chi_{out} = E\chi_{dest} \quad (14)$$

where

$$E\chi_{in} = ANG\,[1 - (4/3(T_a/T_s)) + (1/3(T_a/T_s)^4)] \quad (15)$$

$$E\chi_{out} = E\chi_{PV} + E\chi_{th} \quad (16)$$

where N is the number of collectors, T_a is the ambient temperature and T_s is the temperature of Sun in Kelvin.

The electrical exergy, $E_{\chi PV}$, and thermal exergy, $E_{\chi th}$, can be expressed as:

$$E\chi_{PV} = \eta_{PV}AG \quad (17)$$

$$E\chi_{th} = mC_p\,(T_{out} - T_{in})\,[1 - ((T_a - 273) / (T_{out} - 273))] \quad (18)$$

The exergy efficiency of the whole system of PVT is the ratio between the total exergy output to the total exergy input and can expressed as:

$$\eta_{E\chi Pvt} = E\chi_{in} / E\chi_{out} \quad (19)$$

The exergy efficiency typically demonstrates a lower magnitude than its energy equivalent in the broad scope of energy analysis, and this can be attributed to the presence of several irreversibilities arising from intrinsic thermodynamic imperfections encountered during the process [44, 45]. Exergy analysis is especially valuable in energy and resource management. It helps in optimizing the use of finite resources by minimizing waste and maximizing useful work output. This is crucial for sustainable energy systems and resource conservation.

6. Results and Discussions

Table 1 presents the results of the previous studies based on the different configurations of PVT-TE system. The result mainly focuses on energy and exergy analysis as the main concern of this review paper. In addition, TE efficiency is included in the system that applies Seebeck effect in the TE module. The NaN indicates that the system does not use a Seebeck effect but rather than Peltier effect. Based on previous research, the combination of PV and TEC effect helps to reduce PV module temperature while increasing the PV efficiency. Research from Yin and Zhi-Zhu He [54] found that TEC has cooling power with increasing input current. However, the major drawback of the TEC is it requires a continuous current supply to operate, making it ineffective for contributing to electricity generation when combined with PV [61]. Another research from Najafi et al. [62], supported those statements as they found that the overall efficiency of PV-TEC system remains unchanged despite the decrease in PV surface temperature due to electrical consumption from TEC.

Research from Kane et. al [51] optimised the use of the supply current to TEC while reducing the temperature PV surface by using the MPPT controller. In this study, the current flow was controlled according to solar irradiance. As the solar irradiance and temperature gradient of TEC declined, the temperature gradient of TEC dropped, correspondingly declining in the current supply. Next, research from Wang et al. [57] combined the TEG and TEC to harvest thermal energy and cool the PV module according to the set temperature value of 35˚C. When the temperature of the PV surface exceeds 35˚C, the TEC will activate to cool it down. Conversely, if the temperature is below 35˚C, the TEG will activate to harvest thermal energy. In this experiment, water was used as a heat collector and aided the TEG to increase its temperature gradient. The combination of these two systems will alleviate the major drawback of TEC.

Liao et. al [58] proposed a new system of PVT-TEC by using different quantity TEC and the structure parameters. The difference between this research with Kane et. al [51] was they investigated the optimal quantity of TECs and structure parameters whereas Kane et al. investigated the best current supply for different solar irradiance. According to Table 1, the system proposed by Kane et. al [46] provided better electrical performance than Liao et. al [58], but in terms of TEC's current input, Liao et al. used lower current input than Kane et. al, which was 1.55 A and 2.30 A, respectively. The research by Wang et. al [57] obtained the overall electrical efficiency for the TE system combined with both TEG and TEC. As a result, it attained higher electrical efficiency than other systems in Table 1, making it the most efficient system.

The TEG is mainly dependent on its temperature gradient. According to Maleki et al. [56], the combination of PVT-TEG with PCM provides better thermal and electrical efficiency compared to the PVT-TEG alone. This system utilised a dual PCM, which consisted of two PCMs with different phase transitions, with the front part of the first PCM placed behind the PV and the back part attached to the hot side of the TEG. The second PCM will be attached to the TEG's cold side to increase the temperature gradient. The incorporation of two different PCMs allowed a broader temperature control range and enhanced the temperature gradient across the TEG modules, resulting in higher power generation and efficiency.

In another research from Rajaee et al. [54], the PCM and nanofluid were employed to enhance the performance of PVT-TEG. The nanofluid and PCM were attached to the cool side of TEG, while the hot side of TEG was attached to the back of the PV. This research also compared the performance of nanofluid versus water, and nanofluid outperforms water in terms of electrical and thermal efficiency of the PVT-TEG system. This achievement was attributed to the nanofluid having thermal conductivity compared to the water.

By comparing the adoption of water as a working fluid and air, Dimri, Tiwari, and Tiwari [52] demonstrate the significance of considering a higher thermal conductivity of fluid as a heat transfer. As shown in Table 1, the performance of PVT-TEG with water surpassed air as a working fluid in electrical and thermal efficiency.

As indicated in Table 1, there are only four research papers that disclosed their exergy efficiency. The highest exergy was obtained by Dimri et al. [52] whereas the lowest was from Shittu et al.[30]. These outcomes were unexpected considering Shittu et al.'s energy efficiency was the highest compared to other systems. The justification stipulated by the author is that the radiation of the Sun cannot entirely illuminate the area of the PV cell surface. On top of that, the exergy efficiency of the water tank employed as the heat collector in this system is significantly reliant on both the thermal effectiveness and the prevailing environmental circumstances. Hence, the ambient temperature contributes to the reduction in exergy efficiency when compared to energy efficiency.

Table 1. The energy and exergy performances of the PVT-TE system

Authors	Configurations of PVT-TE systems	TE Efficiency (%)	Energy Efficiency (%)			Exergy Efficiency (%)	Highlights
			Electrical	Thermal	Overall		
Kane et al. [51]	The cold side of the TE cooler is attached to the back of a PV module, which is mounted on an aluminum substrate. The hot side of the TEC is connected to a heat sink that is exposed to the surrounding ambient environment.	-	18.00	-	-	-	6–26% reduction in PV temperature (25–45 °C)
Dimri et al. [52]	Three different types of PV modules (opaque, semitransparent, aluminium) is placed on top of a TEC module. Air and water were used as a working fluid in this study.	14.20 (air) 16.20 (water)		9.01 (air) 30.80 (water)	23.21 (air) 47.00 (water)	16.80 (water)	The highest electrical, thermal and exergy gain is aluminium base PVT-TEC
Dimri et al. [53]	TEC integrated with base opaque PV (without air duct (case A and with air duct (case B)	Case B is higher than Case A by 4.46–6.23%		-	-	-	The opaque PV-TEC collector without air duct generates only electrical energy, whereas the opaque PV-TEC collector with air duct produces both thermal and electrical energy
Rajaee et al. [54]	PVT-TEG using cobalt nanofluid and PCM (paraffin wax/alumina powder) heat sink	1.83	14.99	35.30	50.29	10.67	1% nanofluid with PCM improve the overall electrical efficiency by 12.28% compared to water
Shittu et al. [30]	PVT-TE with flat plate micro-channel heat pipe	0.18	12.19	69.53	81.47	6.39	The lack of insulation behind the micro-channel heat pipe improves the electrical performance of the hybrid system. Additionally, the results indicate that the hybrid system is feasible for simultaneously generating electricity and providing a source of small-scale hot water.

Haiping et al. [55]	A novel low concentrating PVT/TEG (consists of a compound parabolic concentrator, a double-glazing PV panel, a micro-channel heat pipe array and TEG)	0.23	11.80	45.00	57.03	-	The efficiencies of both PV and TEG systems rise as the mass flow rate increases.
Maleki et al. [56]	PV/T-TEG with two PCM	2.63	9.30	40.90	50.20	10.80	The system successfully reduced the average temperature of the Photovoltaic (PV) module while simultaneously increasing the temperature gradient of the Thermoelectric Generator (TEG) by approximately 89.4% and 1.2%, respectively.
Wang et al. [57]	PVT-TE with combination Seebeck and Peltier effect	27.78		-	-	-	In the PV-TEC mode, the effective output power of the Photovoltaic (PV) system has been enhanced from 6 watts to 8.1 watts.
Liao et al. [58]	A new energy system combining PV with thermoelectric refrigerators (TER)	-	13.90	-	-	-	Maximum efficiency = 20% (due to the effects of the solar irradiance)
Wen et al. [59]	PV/T system employing micro-channel heat pipes and TEG	0.97	10.04	33.19	-	-	The incorporation of a glass cover amplifies heat gain but diminishes the overall electrical output due to the compromised performance of the Photovoltaic (PV) system. On the other hand, the presence of a large-volume water tank diminishes the final temperature but proves advantageous for electricity generation.

7. Conclusion

This paper analysed the energy and exergy efficiency of PVT-TE with the combination of the various cooling system. The combination of PVT-TE with various cooling systems significantly improves the overall efficiency of the whole system. In addition, the electrical generated by TEG also improves when combined with other cooling systems due to the increase of temperature gradient as compared to TEG standalone.

Based on the result, the electrical and thermal efficiency of PVT-TE is in the range of 9.3 – 18.0% and 9.01 – 69.53%, respectively. Moreover, the energy and exergy efficiency are in the range of 23.21 – 81.47% and 6.39 – 16%, respectively. Future endeavours to be contemplated should encompass the inclusion of exergy efficiency in the analysis. It has been observed that most papers have solely concentrated on energy analysis, and have disregarded exergy analysis, as evidenced by the papers presented in this review. The significance of exergy efficiency lies in its ability to scrutinize the usable energy generated by the PVT-TE. Furthermore, an exergy efficiency analysis can also assist researchers in identifying energy losses.

As a future study, upcoming research should focus on assessing the techno-economic implications of cooling techniques to advance the feasibility of sustainable PVT systems. In addition, it is imperative to conduct a more comprehensive investigation into the PVT-TE collector incorporating concentrated PV and nanofluid phase change materials.

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