Review

Review on Performance Enhancement of Photovoltaic/Thermal–Thermoelectric Generator Systems with Nanofluid Cooling

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Abstract: Photovoltaics (PVs) are an effective technology to harvest the solar energy and satisfy the increasing global electricity demand. The effectiveness and life span of PVs could be enhanced by enabling effective thermal management. The conversion efficiency and surface temperature of PVs have an inverse relationship, and hence the cooling of PVs as an emerging body of work needs to have attention paid to it. The integration of a thermoelectric generator (TEG) to PVs is one of the widely applied thermal management techniques to improve the performance of PVs as well as combined systems. The TEG utilizes the waste heat of PVs and generate the additional electric power output. The nanofluid enables superior thermal properties compared to that of conventional cooling fluids, and therefore the performance of photovoltaic/thermal–thermoelectric generator (PV/T-TEG) systems with nanofluid cooling is further enhanced compared to that of conventional cooling. The TEG enables a symmetrical temperature difference with a hot side due to the heat from PVs, and a cold side due to the nanofluid cooling. Therefore, the symmetrical thermal management system, by integrating the PV/T, TEG, and nanofluid cooling, has been widely adopted in recent times. The present review comprehensively summarizes various experimental, numerical, and theoretical research works conducted on PV/T-TEG systems with nanofluid cooling. The research studies on PV/T-TEG systems with nanofluid cooling were reviewed, focusing on the time span of 2015–2021. This review elaborates the various approaches and advancement in techniques adopted to enhance the performance of PV/T-TEG systems with nanofluid cooling. The application of TEG with nanofluid cooling in the thermal management of PVs is an emerging research area; therefore, this comprehensive review can be considered as a reference for future development and innovations.

Keywords: nanofluid; performance; photovoltaic; thermal; thermoelectric generator

Citation: Garud, K.S.; Hwang, S.-G.; Han, J.-W.; Lee, M.-Y. Review on Performance Enhancement of Photovoltaic/Thermal–Thermoelectric Generator Systems with Nanofluid Cooling. *Symmetry* **2022**, *14*, 36. <https://doi.org/10.3390/sym14010036>

Academic Editor: Mikhail Sheremet

Received: 27 October 2021

Accepted: 5 December 2021

Published: 29 December 2021

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1. Introduction

Owing to the development in industries, populace, and innovations, the global energy demand continuously increases at the faster rate. The global energy demand is expected to have increased by 30% in 2040 [1]. Among all renewable energy sources, solar energy is a reliable energy source to compensate the increasing global energy demand [2]. Solar energy is non-polluting, free, clean, and an abundant source of energy for heat and power [3]. From the 7th century, magnifying glasses were applied to concentrate solar rays and use the thermal energy from them to generate the burning of ants and fire. Since then, thermal energy from the sun has been utilized to generate the electricity using the PV effect. The electricity harvested from the sun in one hour has the potential to satisfy global annual power consumption [4]. PVs can only convert 17–18% of available thermal energy from sun to electricity [5]. The high-surface temperature, low conversion efficiency, and dust accumulation are the limitations on PV technology that restrict the full utilization of available solar energy. PV surface temperature distribution is not symmetrical, as the falling solar radiation on its surface is uneven, fluctuating, and intermittent [6]. To improve

the conversion efficiency, the area of the PV cell needs to be increased, which increases its cost and degrades the market insights. Therefore, an effective strategy needs to be discovered to reduce the heat loss from PVs and enhance their effectiveness. The TEG is integrated with PVs to effectively harvest the solar spectrum and enhance the performance of standalone PVs as well as the combined system. Numerous research studies have been conducted on integrated systems of PV/T-TEGs. The researchers have summarized these research studies in various reviews. The most recent reviews conducted on PV/T-TEG systems are elaborated in Table 1 [7–13].

Table 1. Recent reviews conducted on PV/T-TEG system.

Reference	Year	Performance Index
Indira et al. [7]	2020	Summary of various experimental and numerical studies on different configurations of concentrated PV-TEG system
Shittu et al. [8]	2019	Review on concepts and applications of PVs, TEG, and PV-TEG systems and current research focus areas in PV-TEG systems
Huen and Daoud [9]	2017	Summary of research studies to understand the concept of PVs and thermoelectric and optimize the PV-TEG system
Li et al. [10]	2018	Review on feasibility, type, and performance of PV-TEG system for electricity generation
Irshad et al. [11]	2019	Review on energy efficient buildings using hybrid technology of PV-TEG system
Babu and Ponnambalam [12]	2017	Review on performance of PV/T, solar thermal-TEG and PV-TEG system
Nazri et al. [13]	2018	Review on energy and economic of air collector-based PV/T-TEG system

Despite a substantial number of reviews having been conducted on PV/T-TEG system, a concrete review focusing on the performance enhancement of PV/T-TEG systems has not been fully explored. Furthermore, nanofluid cooling has proven to be an effective cooling technique compared to conventional cooling techniques. Few research works have been implemented on PV/T-TEG systems with nanofluid cooling; however, there is no review to summarize these research works and elaborate the key findings. Therefore, the present review summarizes the various experimental, numerical, and theoretical research works on PV/T-TEG systems with nanofluid cooling. In addition, the recent research works conducted on performance enhancement of PV/T-TEG systems during the time period of 2015–2021 are also comprehensively summarized in the present review. The review is arranged as, Section 2 elaborates the background including PVs, TEG, hybrid PV-TEG, and nanofluid; Section 3 summarizes various research studies on PV-TEG; Section 4 summarizes various research studies on PV/T-TEG; Section 5 summarizes various research works on PV/T-TEG with nanofluid cooling; and finally, Section 6 discusses the key findings and future scope.

2. Background

2.1. Photovoltaics

PVs convert the thermal energy from solar insolation into electricity with no carbon footprint, and easy installation and maintenance [14,15]. The workings of a PV cell with p and n junctions are shown in Figure 1 [9]. Among all renewable energy technologies, the contribution of PV power generation has increased to 2.58% of the global power generation in the year 2018 [16]. PV systems are categorized into three generations: (a) first generation PV systems include mono- and polycrystalline silicon cells, which are fully commercialized and based on silicon technology; (b) second generation PV systems include cadmium telluride and indium copper selenide, amorphous silicon, indium, and gallium diselenide; and (c) third generation PV systems comprise of organic PV cells, which are in the developing stage [17].

Figure 1. Working of a PV cell with p and n junctions [9].

The conversion efficiency of PVs can be expressed as Equation (1) [8].

$$\eta_{pv} = \frac{FF \times V_{oc} \times I_{sc}}{P_{in}} \quad (1)$$

Here, V_{oc} is open circuit voltage, I_{sc} is short circuit current, P_{in} is PV incident power, and FF is a fill factor defined by Equation (2) [8].

$$FF = \frac{V_{mp} \times I_{mp}}{V_{oc} \times I_{sc}} \quad (2)$$

Here, V_{mp} and I_{mp} are voltage and current corresponding to the maximum PV power output.

The PV surface temperature is a critical parameter for its conversion efficiency. The influence of PV temperature on open circuit voltage, short circuit current, and conversion efficiency is depicted in Figure 2 [18]. The conversion efficiency of PVs is superior at low temperature and as the temperature increases, the conversion efficiency degrades. The larger portion of solar insolation falling on the surface of the PVs is absorbed as heat, which increases the PVs' operating temperature and thus reduces the conversion efficiency. Furthermore, the solar radiation falling on the PV surface is uneven, which results in a non-uniform temperature distribution [19]. Therefore, the PV surface needs to be cooled symmetrically. The accumulated heat on the surface of PVs needs to be removed using an effective cooling technique to enhance its conversion efficiency and life span. Therefore, PV/T and PV/T-TEG systems are proposed.

Figure 2. Influence of PV temperature on open circuit voltage, short circuit current, and conversion efficiency [18].

2.2. Thermoelectric Generator

A TEG utilizes the temperature difference between hot and cold sources to generate the electricity [20]. The Seebeck effect of thermoelectric materials enables the flow of current in the TEG owing to the temperature difference [21]. The TEG can depict an effective power output when the symmetrical temperature distribution is maintained. The TEG is named as the thermoelectric cooler when it generates the cooling effect by supplying the electricity. This phenomenon is called the Peltier effect. Hence, the TEG has an advantage of bi-directional operation. The operations of the TEG and the thermoelectric cooler are presented in Figure 3 [8]. The operation of the TEG is noise, vibration, and maintenance free and non-polluting [22].

Figure 3. Operations of (a) the TEG and (b) thermoelectric cooler [8].

The figure of merit (ZT) governs the conversion efficiency of the TEG as presented by Equation (3) [23].

$$ZT = \frac{S^2 \sigma T}{k} \quad (3)$$

Here, S is Seebeck coefficient, σ is electrical conductivity, k is thermal conductivity, and T is temperature.

The quality of thermoelectric materials is described through the Seebeck coefficient, thermal conductivity, and electrical conductivity. The optimum performance of the TEG can be achieved with a significant Seebeck coefficient, low thermal conductivity, and high electrical conductivity, which generate the temperature gradient across the TEG [24]. The TEG with a figure of merit above three is preferred because the efficiency of the TEG improves as the figure merit increases. However, the intrinsic properties of the Seebeck coefficient, thermal conductivity, and electrical conductivity affect the figure of merit, restricts its value to one. The thermoelectric materials are classified into three categories based on operating temperature range, i.e., low temperature range (<500 K), medium temperature range (500–900 K), and higher temperature range (>900 K) [6]. The thermal resistance and thermoelectric material thickness significantly affect the power output from the TEG. The conversion efficiency of the TEG is evaluated using Equation (4) [25]. The conversion efficiency of the TEG is low, which restricts its commercialization [26].

$$n_{max} = \frac{T_h - T_c}{T_h} \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + \frac{T_c}{T_h}} \quad (4)$$

Here, n_{max} is theoretical maximum efficiency, T_h and T_c are hot and cold sides temperatures of the TEG, respectively.

2.3. Hybrid Photovoltaic–Thermoelectric Generator

PVs generate electricity using a visible and ultra-violet solar spectrum, whereas the TEG utilizes infrared solar spectrum to generate electricity [27]. Hence, the combination of PV-TEG is proposed to widen the effective utilization of the solar spectrum and enable efficient energy harvesting. The TEG is integrated with PVs to improve the overall performance and thermal management of the PVs. The integrated TEG cools the PVs by extracting waste heat and generates the additional electrical power due to sufficient temperature difference across it. The thermoelectric cooler is also employed for thermal management of the PVs by removing the waste heat, and thus enhancing the overall performance [28].

The PVs and TEG are coupled using the spectrum splitting coupling method and direct coupling method [29]. The spectrum splitting method utilizes reflective components such as a spectrum splitter or prism, whereas the reflective component is missing when the direct coupling method is used. The direct coupling method shows superior conversion efficiency compared to spectrum splitting method. The spectrum splitting method has a lower value of hybrid system fill factor, which enables the advantage of a less active thermoelectric material per unit area compared to the direct coupling method. Furthermore, the cost of the spectrum splitting method is lower than the direct-coupling method [30]. However, the extra cost due to the splitting device makes the spectrum splitting method less favorable compared to the direct coupling method. Therefore, it is difficult to arrive at the selection for the best coupling method to integrate PVs and a TEG. The additional electrical output of 2–10%, due to integration of the TEG into PVs, depends on thermoelectric material, coupling method, and configuration [12].

2.4. Nanofluid

The metallic and non-metallic solid particles with a length scale of 1–100 nm are dispersed into base fluids such as water, oil, and ethylene glycol, etc., to improve the convective heat transfer coefficient and effective thermal conductivity [31,32]. Nanofluid comprises of a base fluid dispersed with nanoparticles that have superior thermophysical properties and heat transfer performance compared to conventional cooling fluids [33]. The thermal conductivities of different base fluids and nanoparticles are presented in Figure 4 [32]. The drawback of nanofluid is higher viscosity, which results in higher

pumping power compared to conventional cooling fluids [34]. The nanofluids are prepared using single-step and two-step methods [35]. The stability and homogeneity are also concerning issues while preparing the nanofluids because the nanoparticles interact with each other during motion. The interaction between the nanoparticles results in larger cluster and sedimentation. This causes degradation in heat transfer performance of the nanofluids. Therefore, various surfactants are employed to enable the symmetrical distribution of nanoparticles into the base fluid and improve the stability of nanofluids [36]. Furthermore, long-term stability tests of nanoparticles, such as Dynamic Light Scattering, Zeta potential, and UV–Visible Spectroscopy Analysis methods, are conducted [37].

Figure 4. Thermal conductivities of different base fluids and nanoparticles [32].

Owing to its superior thermal characteristics, nanofluid is applied to cool the PV system as a replacement for conventional cooling fluids in numerous research studies. The thermal collector is integrated with the PV system through which the nanofluid circulates and carries the waste heat from the PV surface [38]. This type of system is called the PV/T system. The PV/T system converts the solar insolation into electrical energy as well as thermal energy by heating the nanofluid. Since the thermal conductivity of the nanofluid is superior to conventional cooling fluid, the performance of the PV/T system with the nanofluid is better than that with conventional cooling fluid.

3. Research Studies on Photovoltaic–Thermoelectric Generator System without Thermal Collector

The influence of ceramic height, cross-section area, and height of the thermoelectric legs on the performance of the PV-TEG system were investigated by Shittu et al. [39]. Mahmoudinezhad et al. [40] experimentally and numerically investigated the open circuit voltage, short circuit current, temperature, and maximum power characteristics of solar cell-TEG systems under the influence of solar concentration ratio and thermoelement length. The triple-junction solar cell–TEG system shows stable power. Lamba and Kaushik [41] studied the influences of thermoelectric module geometry, thermal resistance, load resistance, electric current, fill factor, and thermoelectric properties on temperature, power output, and efficiency of a PV-TEG system. The proposed PV-TEG system is shown in Figure 5. The power output and efficiency of the proposed PV-TEG system were 5% higher than that of the PV system.

Rezania and Rosendahl [42] proved that the power output increased by integrating TEG into the PV system. The PV-TEG system comprising of thermoelectric materials with a figure of merit equal to one showed superior efficiency compared to standalone PV systems. The behavior of PV-TEG systems for thermoelectric load resistance under different working conditions was investigated by Li et al. [43]. Motiei et al. [44] proposed a transient, two-dimensional model to investigate the performance of PV-TEG systems integrated with phase change material. The compared PV, PV-TEG, and PV-TEG with phase change material systems are presented in Figure 6. The heat sink with phase change material absorbs the latent heat, reducing the PV surface temperature, and increasing the temperature difference across the TEG. The PV-TEG system with phase change material shows superior

electrical performance compared to PVs and PV-TEG systems. The optimum phase change material and thickness are suggested by investigating the effects of melting temperature and thickness of phase change material.

Figure 5. Proposed PV-TEG system [41].

Figure 6. Compared (a) PV, (b) PV-TEG, and (c) PV-TEG with phase change material systems [44].

Rodrigo et al. [45] developed a coupled electric/thermal/economic model to trade-off between the efficiency and cost of a concentrated PV-TEG system. The proposed model showed the maximum efficiency of 39.2% and maximum cost reduction of 46%. Furthermore, the sensitivity analysis showed that the effect of the TEG area and figure of merit is significant on performance results, as depicted in Figure 7. Yang et al. [46] developed a model to analyze the systemic efficiency of solar spectrum splitting based PV-TEG systems. The maximum efficiency of the solar spectrum splitting-based PV-TEG system improve by 39.5% and 40.2% for solar concentration of 30 and 100, respectively,

compared to the PV system. Further, the maximum efficiency improved as the area ratio of collector to PV cell was optimized. Li et al. [47] proposed a PV-TEG system with a micro-channel heat pipe array and experimentally investigated the PV temperature, PV power, and hot and cold sides temperatures of TEG. The PV-TEG system with a micro-channel heat pipe array showed high-cost performance compared to the PV-TEG system. The electrical efficiency of the proposed system was 14% superior compared to the PV system.

Figure 7. Effect of the TEG area and figure of merit is significant on performance results [45].

Yusuf et al. [48] developed a multi-objective non-dominated sorting genetic algorithm to optimize the number of thermoelements, area of p and n type thermoelements, length of thermoelements, solar concentration ratio, solar irradiance, and external load resistance to achieve the maximum power output and efficiency for a concentrated PV-TEG system. The maximized power output and efficiency of 461.12 W and 11.45%, respectively, were evaluated for the PV-TEG system. Marandi et al. [49] designed and fabricated a solar cavity-packed PV-TEG system to reduce the re-radiation loss solar insolation power. The developed system showed three times higher power generation compared to flat PV-TEG system. The efficiency and levelized cost of energy for solar cavity packed PV-TEG system were improved by 18.9% and 67%, respectively, compared to a flat PV-TEG system. The cost comparison for PVs, flat PV-TEG, and cavity-packed PV-TEG systems is presented in Table 2. Kohan et al. [50] developed a three-dimensional numerical model to study the performance characteristics of PV-TEG systems. The integration of TEG in PVs results in higher power output compared to a standalone PV system. However, the TEG creates undesirable effects on the cooling of the PV system. The results reveal that the maximum power generation was achieved at a particular value of concentration ratio.

Table 2. Cost comparison for PVs, flat PV-TEG, and cavity packed PV-TEG systems [49].

Parameters	PV	Flat PV-TEG	Cavity PV-TEG
Sum of lifetime cost (USD)	7.72	38.13	190.75
Sum of lifetime electrical energy (kWh)	8.37	6.74	20.22
Cost of energy (USD/kWh)	6.06	37.26	62.5
Levelized cost of energy (USD/kWh)	0.922	5.65	9.432

Liu et al. [51] showed improvement in the performance of the PV-TEG system by providing different glass cover coatings. The power generation of the PV-TEG improved by 0.8%, 1.3%, and 14% for self-assembled SiO₂ coating, antireflection coating, and selective coating, respectively. The self-assembled SiO₂ coating, antireflection coating, and selective coating depict payback periods less than three years, less than four years, and five years, respectively. Furthermore, the results revealed that the influence of concentration ratio, ambient temperature, and wind speed on power generation was critical compared to humidity. Zhang and Xuan [52] studied series and parallel electric connections of PV-TEG systems. The power of PV-TEG systems was lost due to different currents for PVs and the TEG. Series electric connection was used when the PV temperature varied with solar insolation, and parallel electric connection was used when PV temperature remained constant with solar insolation. Therefore, it was recommended that series electric connection for PV-TEG systems are used without phase change material, and parallel electric connection for PV-TEG system are used with phase change material. Zhang et al. [53] applied thermal interface material to reduce the thermal contact resistance and improve the heat transfer performance of PV-TEG systems. The thermal interface material improved the power output of PVs and the TEG by 14% and 60%, respectively.

Zhang and Xuan [54] showed the feasibility of a V-type structure for PV-TEG systems experimentally, and compared it with a conventional flat structure. The overall efficiency of the PV-TEG system was enhanced for the V-type structure due to its improvement in the optical absorption efficiency. Furthermore, the PV-TEG system without ceramic and copper plates was proposed, which showed improved TEG efficiency due to reduced total thermal resistance. Kossovakis et al. [55] experimentally tested the performance of a PV-TEG system with poly-Si and dye-sensitized solar cells. The improvements in the maximum PV temperature were evaluated as 22.5% and 30.2% for poly-Si and dye-sensitized solar cells, respectively. Furthermore, it was concluded that the TEG with shorter thermoelements showed enhanced power output. Lamba and Kaushik [56] developed a thermodynamic model with Thomson, Seebeck, Joule, and Fourier effects to investigate the performance of a concentrated PV-TEG system. The behavior of power generation and efficiency for PV, TEG, and PV-TEG systems were investigated under the influence of solar insolation, concentration ratio, number of thermoelectric modules, PVs, and thermoelectric currents.

Chen et al. [57] compared three geometries of PV-TEG systems using a three-dimensional finite element method. The power output of the TEG increased with a decrease in the cross-sectional area for the fixed element length of TEG. Deng et al. [58] developed a PV-TEG system with a heat collector to effectively absorb reflection and irradiation energies. The solar energy conversion and solar spectrum improved due to waste heat utilization by the TEG from the PVs and heat collector. Beeri et al. [59] proposed a concentrated PV-TEG system with electrical and total contributions of 20% and 40% by a thermoelectric generator at solar concentration ratios of 300 and 200 suns, respectively.

Li et al. [60,61] developed a concentrated solar TEG system integrated with micro-channel heat pipe. The proposed system showed higher heat transfer, power output, low thermal resistance, and superior economic value. Liao et al. [62] improved the power output of a low concentrating PV-TEG system by optimizing electrical load resistance and solar radiation. Da et al. [63] proposed a PV-TEG system integrated with enhanced transmission film and bio-inspired moth-eye anti-reflective surface. The influences of thermal concentration ratio, incident angle, geometrical parameters, and optical concentration ratio on performance of the proposed system were investigated. Zhou et al. [64] developed a concentrated PV-TEG system integrated with a moth-eyed nanostructure PV surface, which enabled the uniform distribution of absorbed solar radiation. The influence of a nanostructure PV surface and solar concentration were investigated using Monte Carlo-Finite Difference Time Domain approach. The nanostructure PV surface showed improvement in absorbed solar radiation by 1.6 times compared to plane PV surface. Zhu et al. [65] proposed an enclosed PV-TEG system to eliminate the convection heat losses. The larger temperature difference across the TEG was achieved using a copper plate thermal

absorber as thermal conductor and thermal concentrator. The proposed system achieved the maximum conversion efficiency of 23% and the TEG produced 648 J of electrical energy in absence of sunlight.

Li et al. [66] investigated energy and exergy performances of a concentrated PV-TEG system with various types of PV cells. The highest and lowest efficiencies were found for PV-TEG systems with polymer and crystalline silicon, respectively. The maximum energy and exergy outputs were evaluated for PV-TEG systems with copper indium gallium selenide cells. Teffah and Zhang [67] achieved higher power output and electrical efficiency by integrating the TEG and thermoelectric cooler in a PV system. Yin et al. [68] proposed a theoretical model integrated with thermal resistance theory to evaluate the effect of thermal contact resistance, TEG thermal resistance, and heat loss thermal resistance on the performance of a PV-TEG system. Furthermore, three cooling techniques and four types of PV cells were compared for the developed system. The performance of PV-TEG system was superior for higher thermal resistance of the TEG and water-cooling technique.

Zhang and Xuan [69] proposed a thermal resistance model for concentrated PV-TEG systems and showed that the thermal resistance between the ambient and the TEG has a greater impact compared to that between the PV cell and a TEG. The power output of the proposed system enhanced from 25.7 W to 26.6 W by employing copper plate between the PV cell and TEG, which reduced the thermal resistance and improved the thermal uniformity. Mahmoudinezhad et al. [70,71] investigated the efficiency of a concentrated PV-TEG system under variation of solar radiation. Furthermore, Mahmoudinezhad et al. concluded that as solar radiation increases, the efficiency of concentrated PVs decreases, and that of the TEG increases. Singh et al. [72] proposed a one-dimensional thermodynamic model to investigate the influences of solar radiation, TEG temperature difference and current irreversibilities, and the Thomson effect on exergy performance of concentrated PV-TEG systems.

Cotfas et al. [73] compared two structures of a PV-TEG system, one with four TEGs in series and another with one TEG. The performance of the structure with four TEGs in series was superior compared to structure with one TEG because of lower internal resistance. Acar and Ba [74] conducted an experimental study on concentrated TEG systems with a Fresnel lens. Water cooling was used to cool the PV and cold side of the TEG. The efficiency of proposed system improved by 15% and 60% at voltage and current, respectively, compared to system without a concentrator. Bamroongkhan et al. [75] developed a PV-TEG system integrated with a parabolic dish. For the focal distance of 57 cm, the proposed system showed a conversion efficiency of 19.65%. The output performance improved by 21.42% for the proposed system with air cooling, compared to that without air cooling.

Shittu et al. [76] simulated the performance of a concentrated PV-TEG system with flat plate heat pipe cooling. Compared to PV-TEG and PV systems, the PV-TEG system with flat plate heat pipe showed improved efficiency by 3.31% and 58.01%, respectively. Furthermore, the efficiency of PV-TEG systems with flat plate heat pipes enhanced by 1.47% and 61.01%, compared to PV-TEG and PV systems, respectively. Mahmoudinezhad et al. [77] showed enhancement in the temperature gradient of TEG and degradation in the figure of merit of thermoelectric material with an increase in the solar concentration ratio for a concentrated PV-TEG system. Yin et al. [78] investigated the performance characteristics of a concentrated PV-TEG system under the influence of the temperature coefficient of PVs and the figure of merit of thermoelectric materials. To achieve the superior performance of proposed system, the minimum figure of merit of thermoelectric material was optimized.

Yin et al. [79] optimized the solar concentration ratio, thermal, and load resistances and series-parallel connection of TEG to achieve the superior performance of a concentrated PV-TEG system. The higher thermal resistance and input power as well as the series connection of the TEG showed superior performance of the proposed system. Shittu et al. [80] developed a three-dimensional numerical model to study the performance of concentrated PV-TEG system under the influence of thermal and electrical contact resistances. The performance of concentrated the PV-TEG system was significantly affected

by thermal contact resistances between the PV-TEG and TEG-heat sink. The power output and efficiency of the concentrated PV-TEG system enhanced by 7.6% and 7.4%, respectively, by eliminating all contact resistances. The effect of concentration ratio on power output, efficiency, and temperature is depicted in Figure 8. Bjork and Nielsen [81] investigated the performance of PV-TEG systems considering four types of PV cells. The results reveal that owing to the low efficiency of TEG, the PV performance degraded rapidly compared to the increase in TEG power. Kwan and Wu [82] proposed a PV-TEG system with single-stage and two-stage TEG configurations. The power output and mass of TEG were optimized used a multi-objective NSGA-II genetic algorithm. The optimized PV-TEG system depicted better performance, and performance of single-stage TEG was optimal compared to the two-stage TEG. Zhang et al. [83] improved the performance of the PV-TEG system by employing a perovskite solar cell. Efficiency of 18.6% was achieved for the proposed PV-TEG system with a perovskite solar cell. Furthermore, the cost of the PV-TEG system could be decreased by altering the thermal concentration and reducing the volume of TEG material.

Figure 8. Effect of concentration ratio on (a) power output, efficiency and (b) temperature [80].

4. Research Studies on Photovoltaic Thermoelectric Generator Systems with Thermal Collector

Kidegho et al. [16] eliminated thermal coupling challenges using thermal interface materials, which improved the overall power output of the PV/T-TEG system. Zhang et al. [84] proposed a PV/T-TEG system comprising of a thermal collector with a hot water supply of 52.96 °C maximum temperature, photovoltaic cell with power output of 436.16 W, and a TEG with power output of 1.68 W. Kolahan et al. [85] proposed a PV/T-TEG system

with worse overall energy efficiency and superior overall exergy efficiency compared to PV systems. The comparison of thermal and electrical power outputs for PV/T and PV/T-TEG systems is presented in Figure 9. The PV/T-TEG system shows 2.5–4% improvement in overall electrical efficiency compared to the PV system. The thermal and electrical efficiency comparison for different PV/T-TEG systems is depicted in Table 3 [86].

Figure 9. Comparison of thermal and electrical power outputs for PV/T and PV/T-TEG systems [85].

Table 3. Thermal and electrical efficiency comparison for PV/T-TEG systems [86].

Configuration	Thermal Efficiency (%)	Electrical Efficiency (%)
Water-without TEG	47.35	6.76
Water-with TEG	46.13	7.26
Water-without TEG	57.28	13.26
Water-with TEG	55.07	14.64
Al ₂ O ₃ nanofluid-without TEG	60.5	12.6
Al ₂ O ₃ nanofluid-without TEG	59.2	13.1

Salari et al. [87] proposed a three-dimensional numerical model to compare the thermal and electrical performances of PV/T and PV/T-TEG systems. The influences of solar radiation, ambient temperature, fluid inlet temperature, and mass flow rate are investigated on thermal and electrical efficiency. The PV/T system showed superior thermal efficiency, whereas the electrical efficiency was maximum for the PV/T-TEG system. The thermal and electrical efficiencies of PV/T and PV/T-TEG systems are depicted in Table 4. Wen et al. [88] compared thermal and electrical performances of PV/T-TEG systems with, and without, a gravity-driven heat pipe. The PV/T-TEG system with the gravity-driven heat pipe showed thermal and comprehensive efficiencies superior by 10.23% and 2.55%, respectively, compared to that without gravity-driven heat pipe. The electrical and exergy efficiencies of the PV/T-TEG system with gravity-driven heat pipe were lower by 2.91% and 1.56%, respectively, compared to that without gravity-driven heat pipe.

Table 4. Thermal and electrical efficiencies of PV/T and PV/T-TEG systems [87].

Systems	Thermal Efficiency (%)	PV Efficiency (%)	TEG Efficiency (%)
PV/T	55.28	13.58	-
PV/T-TEG	53.26	13.60	1.11

Nazri et al. [89] studied the exergetic performance of an air based PV/T-TEG system for mass flow rate variation of 0.001 kg/s to 0.15 kg/s. The effect of mass flow rate variation on exergy rate and exergy efficiency of the proposed system is shown in Table 5. In addition, a theoretical model was proposed to conduct steady state thermal analysis and predict PV and air-outlet temperatures of the PV/T-TEG system. Babu and Ponnambalam [90] developed an economic theoretical model, which evaluated the levelized cost of

energy for a PV/T-TEG system as 8.71% higher than that for PV systems. Miljkovic and Wang [91] tested the performance of a parabolic concentrated solar-TEG system integrated with thermosyphon cooling for three types of thermoelectric materials. The conversion efficiency of the proposed system depended on solar concentration ratio and temperature of bottoming cycle.

Table 5. Effect of mass flow rate variation on exergy rate and exergy efficiency of proposed system [89].

Mass Flow Rate (kg/s)	Thermal Exergy Rate (W)	PV Exergy Rate (W)	TEG Exergy Rate (W)	Overall Exergy Efficiency (%)
0.001	1.4283	33.0565	72.9198	0.3695
0.004	1.1717	33.3498	76.3994	0.3816
0.01	0.9431	33.6283	77.2690	0.3848
0.02	0.7502	33.8777	77.4840	0.3857
0.04	0.6512	34.2677	77.1934	0.3857
0.07	0.6499	34.8021	76.4662	0.3851
0.09	0.6301	35.0636	76.0966	0.3846
0.12	0.5945	35.3737	75.6492	0.3840
0.15	0.5591	35.6188	75.2896	0.3835

Willars-Rodriguez et al. [92] developed a PV-TEG system with solar cells placed over the Fresnel lens, and the TEG comprised of water cooling was placed beneath the Fresnel lens. The performance and effectiveness of the proposed system was evaluated through an experimental and COMSOL Multiphysics simulation. Li et al. [93] concluded that with an increase in ambient temperature and wind speed, the efficiency of parabolic trough concentration-TEG system decreases. Mohsenzadeh et al. [94] developed a triangular cooling channel comprising of PV cells at the outer surface and a TEG at the inner surface. Kil et al. [95] developed a single-junction concentrated PV-TEG system whose conversion efficiency was 3% superior to standalone concentrated PV system.

Soltani et al. [96] proposed a mathematical model to study the heat transfer and electrical performance of a parabolic trough concentrator-based PV-TEG system. Haiping et al. [97] conducted an experimental study on concentrated PV-TEG systems with a microchannel heat pipe and water cooling. The maximum power of 88.5 W was achieved by the proposed system at flow rate of 60 L/h and the efficiency of the proposed system improved as the flow rate increases. Yin et al. [98] proposed a PV-TEG with two water cooling loops, one for cooling of PV cell and other one maintaining the low temperature at cold side of TEG. The exergy output of the proposed system from the high-grade thermal output was superior compared to conventional system.

Sharaf and Orhan [99] compared the exergy, economic, and environmental performances of a concentrated PV/T-TEG system. The proposed system was compared for two configurations, one with receiver components that were connected thermally in series, and other one with a parallel connection. The proposed system with the series connection showed best electrical output and that with the parallel connection depicted the best thermal output in terms of thermodynamic and economic value. Shadmehri et al. [100] proposed a hybrid three-dimensional model of finite volume method, and the Monte Carlo method was used to investigate the thermal and electrical performances of a concentrated PV/T-TEG system. The thermal and electrical performances of the proposed system were superior for aperture width and apex angle ranges of 1.6~2.2 m and 80~120°, respectively.

Lashin et al. [101] concluded that the electrical power of a PV/T-TEG system decreases by 32% compared to PV cells with a heat sink. Furthermore, the total electrical power for a multi-junction PV cell with TEG was superior compared to multi-junction PV cell with heat sink. Abdo et al. [102] proposed a concentrated PV-TEG system with a Fresnel lens, reflectors, and a microchannel heat sink. The PV cell and TEG were cooled using water flowing through microchannel heat sink. The proposed system generated thermal and electrical power outputs of 30 kW/m² and 3.2 kW/m², respectively at 20 suns. Riahi

et al. [103] developed a concentrated PV/T-TEG system integrated with a rectangular receiver. Despite the higher PV temperature in the concentrated PV/T-TEG system, the electrical power output was 7.46% higher compared to the concentrated PV/T system. The electrical power output of various parts in proposed system is shown in Figure 10.

Figure 10. Electrical power output of various parts in proposed system [103].

5. Research Studies on Photovoltaic/Thermal–Thermoelectric Generator with Nanofluid Cooling

Rejeb et al. [104] studied the influence of TEGs in a concentrated solar PV/T collector with water and 0.5% graphene nanofluid. The energy and exergy characteristics of the concentrated solar PV/T collector without, and with, the TEG were investigated under cloudy, and sunny, ambient conditions in London. The 0.5% graphene nanofluid showed superior energy and exergy performance than water. The concentrated solar PV/T collector without TEG presented higher thermal output compared to that with the TEG. However, the total electrical power and exergy outputs were superior for the concentrated solar PV/T collector with TEG.

Lekbir et al. [105] concluded that the PV/T-TEG system with nanofluid shows electrical energy higher by 49.5%, 47.7%, and 10% compared to PV-TEG, PV, and PV/T systems, respectively. The conventional PV system, PV/T-TEG system with heat sink cooling, PV/T system with nanofluid cooling, and PV/T-TEG system with nanofluid cooling are depicted in Figure 11. The comparison of thermal and electrical performances of proposed systems for various solar concentrations is presented in Figure 12. Soltani et al. [106] presented a PV-TEG system with SiO₂ nanofluid cooling showing improvement of 54.29% and 3.35%, and that with Fe₃O₄ nanofluid cooling showing improvement of 52.40% and 3.13% in power output and efficiency, respectively. The PV-TEG system with air and liquid cooling is shown in Figure 13. The comparison of PV temperature for different cooling methods is presented in Figure 14.

Akbar et al. [107] optimized the performance of PV/T-TEG systems using a multi-objective genetic algorithm. The lowest PV surface temperature and highest efficiency were found for Ag nanofluid compared to air, water, and SiO₂ nanofluid. The overall electrical,

thermal, and exergy efficiencies of PV/T-TEG systems were compared for water, Co_3O_4 nanofluid, and paraffin wax/ Al_2O_3 powder by Rajaei et al. [108]. The overall electrical and exergy efficiencies were higher by 12.28% and 11.6%, respectively for 1% nanofluid with enhanced phase change material. The exergy efficiency comparison for various cooling techniques is presented in Figure 15.

Figure 11. Conventional (a) PV system, (b) PV-TEG system with heat sink cooling, (c) PV/T system with nanofluid cooling, and (d) PV/T-TEG system with nanofluid cooling [105].

Figure 12. Comparison of (a) PV power, (b) TEG power, (c) overall electrical power, and (d) thermal power of proposed systems for various solar concentrations [105].

Figure 13. PV-TEG system with (a) air and (b) liquid cooling [106].

Figure 14. Comparison of PV temperature for different cooling methods [106].

Figure 15. Exergy efficiency comparison for various cooling techniques [108].

Soltani et al. [109] investigated the power output, carbon mitigation, and credit characteristics of PV/T-TEG systems with air, water, SiO₂, and Fe₃O₄ nanofluids. The comparison of generated power by PV/T-TEG systems for various cooling methods is presented in Figure 16. The proposed system with nanofluids present superior energy, exergy, and environmental characteristics compared to that with air and water. Wu et al. [110] proposed a

theoretical model to investigate the performance of a PV-TEG system with, and without, the integration of glass cover. Furthermore, the comparison of water and nanofluid cooling and effect of wind speed were studied using the proposed model. The PV-TEG system with glass cover depicted better performance compared to that without glass cover. The PV-TEG system with nanofluid cooling had superior performance compared to that with water cooling.

Figure 16. Comparison of generated power by PV/T-TEG systems for various cooling methods [109].

6. Discussion

The performance of PV systems integrated with a TEG is superior compared to a standalone PV system has been proven in many research works. The structure and material optimization of the TEG could further improve the feasibility and performance of hybrid systems. The efficiency of TEG could be significantly improved by enhancing the figure of merit of thermoelectric materials. Therefore, research work is encouraged to emphasize more on improving thermoelectric material properties to achieve the desired performance of hybrid PV-TEG systems. Furthermore, increasing the absorptivity of the PV surface could enhance the efficiency of the PV-TEG system. The structure optimization of the TEG including the TEG and thermoelectric leg geometries, as well as optimization of load resistance are also simultaneous research works going on to improve the overall performance of PV-TEG systems. The PV surface temperature should be reduced to increase the power output, whereas the TEG needs a higher surface temperature to generate more power. Therefore, effective coupling of PVs and a TEG considering thermal contact resistance is needed to be focused. The performance of PVs and a TEG depend on the cooling technique employed because lower PV surface temperature and higher temperature difference across the TEG depict higher power output and efficiency for both. Nanofluid cooling has superior cooling performance compared to water cooling due to improved thermophysical properties. Despite its superior heat transfer characteristics, attention needs to be paid to the high viscosity and low stability of the nanofluid. In addition, the additional cost due to integration of nanofluid cooling must be taken into consideration by making a trade-off comparison between performance and cost of a PV/T-TEG system with nanofluid cooling. Therefore, PV/T-TEG systems with nanofluid cooling are an emerging research area and significant amount of research work is needed to propose an efficient hybrid system.

7. Conclusions

The present review summarizes the recent advancements in PV/T-TEG system. Numerous research studies, including experimental, numerical, and theoretical approaches in the field of PV/T-TEG systems with nanofluid cooling are elaborated comprehensively. The thermal and electrical performance characteristics for different configurations of PV/T-TEG system, are reviewed. The influence of structure, material, thermal resistance, and operating conditions is also summarized. The key findings from the present review and future scope are highlighted as follows.

- (a) The PV-TEG system generates superior electrical power output compared to standalone PV system. In addition, the PV/T-TEG system generates electrical as well as thermal power outputs, which further enhances the overall performance of system.
- (b) The nanofluid cooling of PV/T-TEG systems depict improved thermal and electrical performances compared to PV/T-TEG systems with conventional cooling fluids.
- (c) The thermoelectric leg length has a significant effect on the performance of PV/T-TEG systems. Higher thermoelectric leg length enhances the TEG power output but also increases PV temperature because of an increase in thermal resistance. Therefore, thermoelectric leg length needs to be optimized to maximize the performance of hybrid system.
- (d) The performance of hybrid systems degrades due to thermal contact resistance between PVs and the TEG. The thermal contact resistance could be reduced by applying thermal interface materials, enhancing the contact area, and reducing the thermoelectric legs.
- (e) The research studies on PV/T-TEG systems with nanofluid cooling are very limited. This area needs to be focused on more for future development and innovation on PV/T-TEG systems. The phase change materials could also be integrated with PV/T-TEG systems without, and with, nanofluid cooling to evaluate and compare the overall performance improvement.
- (f) Most of the reviewed research studies focused on numerical and theoretical approaches. The number of experimental works are limited. In addition, three-dimensional numerical models based on thermo–fluid–thermoelectric coupling for PV/T-TEG system have been explored by very few in the literature.
- (g) Further research on PV/T-TEG systems focusing on energy and exergy performances, economic, environmental sustainability, and life cycle analysis based on long-term operation needs to be conducted to assure the commercialization of hybrid PV/T-TEG systems.

Author Contributions: Conceptualization, K.S.G. and M.-Y.L.; methodology, K.S.G. and M.-Y.L.; investigation, K.S.G., S.-G.H., J.-W.H., and M.-Y.L.; resources, K.S.G., S.-G.H., J.-W.H., and M.-Y.L.; writing—original draft preparation, K.S.G. and M.-Y.L.; writing—review and editing, K.S.G. and M.-Y.L.; supervision, M.-Y.L.; project administration, M.-Y.L.; funding acquisition, M.-Y.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Dong-A University research fund.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study will be available on request to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. International Energy Agency. WEO 2017. IEA World Energy Outlook. 2017. Available online: <https://www.iea.org/reports/world-energy-outlook-2017#section-1-1> (accessed on 19 October 2021).
2. Raj, A.K.; Kunal, G.; Srinivas, M.; Jayaraj, S. Performance analysis of a double-pass solar air heater system with asymmetric channel flow passages. *J. Therm. Anal. Calorim.* **2019**, *136*, 21–38. [CrossRef]

3. Liu, Y.W.; Feng, H.; Li, H.Y.; Li, L.L. An Improved Whale Algorithm for Support Vector Machine Prediction of Photovoltaic Power Generation. *Symmetry* **2021**, *13*, 212. [\[CrossRef\]](#)
4. Wang, L.; Liu, Y.; Li, T.; Xie, X.; Chang, C. The Short-Term Forecasting of Asymmetry Photovoltaic Power Based on the Feature Extraction of PV Power and SVM Algorithm. *Symmetry* **2020**, *12*, 1777. [\[CrossRef\]](#)
5. Ogbomo, O.O.; Amalu, E.H.; Ekere, N.N.; Olagbegi, P.O. A review of photovoltaic module technologies for increased performance in tropical climate. *Renew. Sustain. Energy Rev.* **2017**, *75*, 1225–1238. [\[CrossRef\]](#)
6. Hasan, A.; Sarwar, J.; Shah, A.H. Concentrated photovoltaic: A review of thermal aspects, challenges and opportunities. *Renew. Sustain. Energy Rev.* **2018**, *94*, 835–852. [\[CrossRef\]](#)
7. Indira, S.S.; Vaithilingam, C.A.; Chong, K.K.; Saidur, R.; Faizal, M.; Abubakar, S.; Paiman, S. A review on various configurations of hybrid concentrator photovoltaic and thermoelectric generator system. *Sol. Energy* **2020**, *201*, 122–148. [\[CrossRef\]](#)
8. Shittu, S.; Li, G.; Akhlaghi, Y.G.; Ma, X.; Zhao, X.; Ayodele, E. Advancements in thermoelectric generators for enhanced hybrid photovoltaic system performance. *Renew. Sustain. Energy Rev.* **2019**, *109*, 24–54. [\[CrossRef\]](#)
9. Huen, P.; Daoud, W.A. Advances in hybrid solar photovoltaic and thermoelectric generators. *Renew. Sustain. Energy Rev.* **2017**, *72*, 1295–1302. [\[CrossRef\]](#)
10. Li, G.; Shittu, S.; Diallo, T.M.; Yu, M.; Zhao, X.; Ji, J. A review of solar photovoltaic-thermoelectric hybrid system for electricity generation. *Energy* **2018**, *158*, 41–58. [\[CrossRef\]](#)
11. Irshad, K.; Habib, K.; Saidur, R.; Kareem, M.W.; Saha, B.B. Study of thermoelectric and photovoltaic facade system for energy efficient building development: A review. *J. Clean. Prod.* **2019**, *209*, 1376–1395. [\[CrossRef\]](#)
12. Babu, C.; Ponnambalam, P. The role of thermoelectric generators in the hybrid PV/T systems: A review. *Energy Convers. Manag.* **2017**, *151*, 368–385. [\[CrossRef\]](#)
13. Nazri, N.S.; Fudholi, A.; Bakhtyar, B.; Yen, C.H.; Ibrahim, A.; Ruslan, M.H.; Sopian, K. Energy economic analysis of photovoltaic-thermal-thermoelectric (PVT-TE) air collectors. *Renew. Sustain. Energy Rev.* **2018**, *92*, 187–197. [\[CrossRef\]](#)
14. Chapin, D.M.; Fuller, C.S.; Pearson, G.L. A new silicon p-n junction photocell for converting solar radiation into electrical power. *J. Appl. Phys.* **1954**, *25*, 676–677. [\[CrossRef\]](#)
15. Garud, K.S.; Jayaraj, S.; Lee, M.Y. A review on modeling of solar photovoltaic systems using artificial neural networks, fuzzy logic, genetic algorithm and hybrid models. *Int. J. Energy Res.* **2021**, *45*, 6–35. [\[CrossRef\]](#)
16. Kidegho, G.; Njoka, F.; Muriithi, C.; Kinyua, R. Evaluation of thermal interface materials in mediating PV cell temperature mismatch in PV-TEG power generation. *Energy Rep.* **2021**, *7*, 1636–1650. [\[CrossRef\]](#)
17. Sampaio, P.G.V.; González, M.O.A.; de Vasconcelos, R.M.; dos Santos, M.A.T.; de Toledo, J.C.; Pereira, J.P.P. Photovoltaic technologies: Mapping from patent analysis. *Renew. Sustain. Energy Rev.* **2018**, *93*, 215–224. [\[CrossRef\]](#)
18. Singh, P.; Singh, S.N.; Lal, M.; Husain, M. Temperature dependence of I-V characteristics and performance parameters of silicon solar cell. *Sol. Energy Mater. Sol. Cells* **2008**, *92*, 1611–1616. [\[CrossRef\]](#)
19. Li, Y.; Sun, Y.; Li, K.; Zhuang, J.; Liang, Y.; Pang, Y. Analysis and Suppression of Voltage Violation and Fluctuation with Distributed Photovoltaic Integration. *Symmetry* **2021**, *13*, 1894. [\[CrossRef\]](#)
20. Garud, K.S.; Seo, J.-H.; Cho, C.-P.; Lee, M.-Y. Artificial neural network and adaptive neuro-fuzzy interface system modelling to predict thermal performances of thermoelectric generator for waste heat recovery. *Symmetry* **2020**, *12*, 259. [\[CrossRef\]](#)
21. Garud, K.S.; Patil, M.S.; Seo, J.-H.; Bang, Y.-M.; Cho, C.-P.; Lee, M.-Y. Electrical Performance Comparison between Conventional Pi Shaped and Linear Shaped Thermoelectric Generators. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *894*, 012001. [\[CrossRef\]](#)
22. Seo, J.-H.; Garud, K.S.; Lee, M.-Y. Grey relational based Taguchi analysis on thermal and electrical performances of thermoelectric generator system with inclined fins hot heat exchanger. *Appl. Therm. Eng.* **2021**, *184*, 116279. [\[CrossRef\]](#)
23. Garud, K.S.; Seo, J.-H.; Patil, M.S.; Bang, Y.-M.; Pyo, Y.-D.; Cho, C.-P.; Lee, M.-Y. Thermal-electrical-structural performances of hot heat exchanger with different internal fins of thermoelectric generator for low power generation application. *J. Therm. Anal. Calorim.* **2021**, *143*, 387–419. [\[CrossRef\]](#)
24. Elsheikh, M.H.; Shnawah, D.A.; Sabri, M.F.M.; Said, S.B.M.; Hassan, M.H.; Bashir, M.B.A.; Mohamad, M. A review on thermoelectric renewable energy: Principle parameters that affect their performance. *Renew. Sustain. Energy Rev.* **2014**, *30*, 337–355. [\[CrossRef\]](#)
25. Lee, M.-Y.; Seo, J.-H.; Lee, H.-S.; Garud, K.S. Power generation, efficiency and thermal stress of thermoelectric module with leg geometry, material, segmentation and two-stage arrangement. *Symmetry* **2020**, *12*, 786. [\[CrossRef\]](#)
26. Garud, K.S.; Seo, J.-H.; Lee, M.-Y. Effect of guide fin structures and boundary parameters on thermal performances of heat exchanger for waste heat recovery thermoelectric generator. *J. Korea Acad. Ind. Coop. Soc.* **2021**, *22*, 30–35.
27. Goldsmid, H.J.; Giutronich, J.E.; Kaila, M.M. Solar thermoelectric generation using bismuth telluride alloys. *Sol. Energy* **1980**, *24*, 435–440. [\[CrossRef\]](#)
28. Moore, G.; Peterson, W. Solar PV-thermoelectric generator hybrid system: Case studies. In Proceedings of the 10th International Telecommunications Energy Conference, San Diego, CA, USA, 30 October–2 November 1988; pp. 308–311.
29. Contento, G.; Lorenzi, B.; Rizzo, A.; Narducci, D. Efficiency enhancement of a-Si and CZTS solar cells using different thermoelectric hybridization strategies. *Energy* **2017**, *131*, 230–238. [\[CrossRef\]](#)
30. Lorenzi, B.; Contento, G.; Sabatelli, V.; Rizzo, A.; Narducci, D. Theoretical Analysis of Two Novel Hybrid Thermoelectric-Photovoltaic Systems Based on Cu₂ZnSnS₄ Solar Cells. *J. Nanosci. Nanotechnol.* **2017**, *17*, 1608–1615. [\[CrossRef\]](#)

31. Pandya, N.S.; Shah, H.; Molana, M.; Tiwari, A.K. Heat transfer enhancement with nanofluids in plate heat exchangers: A comprehensive review. *Eur. J. Mech. B/Fluids* **2020**, *81*, 173–190. [\[CrossRef\]](#)
32. Pordanjani, A.H.; Aghakhani, S.; Afrand, M.; Mahmoudi, B.; Mahian, O.; Wongwises, S. An updated review on application of nanofluids in heat exchangers for saving energy. *Energy Convers. Manag.* **2019**, *198*, 111886. [\[CrossRef\]](#)
33. Garud, K.S.; Hwang, S.-G.; Lim, T.-K.; Kim, N.; Lee, M.-Y. First and Second Law Thermodynamic Analyses of Hybrid Nanofluid with Different Particle Shapes in a Microplate Heat Exchanger. *Symmetry* **2021**, *13*, 1466. [\[CrossRef\]](#)
34. Garud, K.S.; Lee, M.-Y. Numerical Investigations on Heat Transfer Characteristics of Single Particle and Hybrid Nanofluids in Uniformly Heated Tube. *Symmetry* **2021**, *13*, 876. [\[CrossRef\]](#)
35. Ghalambaz, M.; Hashem Zadeh, S.M.; Veismoradi, A.; Sheremet, M.A.; Pop, I. Free Convection Heat Transfer and Entropy Generation in an Odd-Shaped Cavity Filled with a Cu-Al₂O₃ Hybrid Nanofluid. *Symmetry* **2021**, *13*, 122. [\[CrossRef\]](#)
36. Sanches, M.; Marsegia, G.; Ribeiro, A.P.; Moreira, A.L.; Moita, A.S. Nanofluids Characterization for Spray Cooling Applications. *Symmetry* **2021**, *13*, 788. [\[CrossRef\]](#)
37. Abbas, N.; Awan, M.B.; Amer, M.; Ammar, S.M.; Sajjad, U.; Ali, H.M.; Jafry, A.T. Applications of nanofluids in photovoltaic thermal systems: A review of recent advances. *Phys. A Stat. Mech. Its Appl.* **2019**, *536*, 122513. [\[CrossRef\]](#)
38. Arun, K.R.; Kunal, G.; Srinivas, M.; Kumar, C.S.; Mohanraj, M.; Jayaraj, S. Drying of untreated Musa nendra and Momordica charantia in a forced convection solar cabinet dryer with thermal storage. *Energy* **2020**, *192*, 116697. [\[CrossRef\]](#)
39. Shittu, S.; Li, G.; Tang, X.; Zhao, X.; Ma, X.; Badiei, A. Analysis of thermoelectric geometry in a concentrated photovoltaic-thermoelectric under varying weather conditions. *Energy* **2020**, *202*, 117742. [\[CrossRef\]](#)
40. Mahmoudinezhad, S.; Atouei, S.A.; Cotfas, P.A.; Cotfas, D.T.; Rosendahl, L.A.; Rezaia, A. Experimental and numerical study on the transient behavior of multi-junction solar cell-thermoelectric generator hybrid system. *Energy Convers. Manag.* **2019**, *184*, 448–455. [\[CrossRef\]](#)
41. Lamba, R.; Kaushik, S.C. Solar driven concentrated photovoltaic-thermoelectric hybrid system: Numerical analysis and optimization. *Energy Convers. Manag.* **2018**, *170*, 34–49. [\[CrossRef\]](#)
42. Rezaia, A.; Rosendahl, L.A. Feasibility and parametric evaluation of hybrid concentrated photovoltaic-thermoelectric system. *Appl. Energy* **2017**, *187*, 380–389. [\[CrossRef\]](#)
43. Li, G.; Zhou, K.; Song, Z.; Zhao, X.; Ji, J. Inconsistent phenomenon of thermoelectric load resistance for photovoltaic-thermoelectric module. *Energy Convers. Manag.* **2018**, *161*, 155–161. [\[CrossRef\]](#)
44. Motiei, P.; Yaghoubi, M.; GoshtasbiRad, E. Transient simulation of a hybrid photovoltaic-thermoelectric system using a phase change material. *Sustain. Energy Technol. Assess.* **2019**, *34*, 200–213. [\[CrossRef\]](#)
45. Rodrigo, P.M.; Valera, A.; Fernández, E.F.; Almonacid, F.M. Performance and economic limits of passively cooled hybrid thermoelectric generator-concentrator photovoltaic modules. *Appl. Energy* **2019**, *238*, 1150–1162. [\[CrossRef\]](#)
46. Yang, Z.; Li, W.; Chen, X.; Su, S.; Lin, G.; Chen, J. Maximum efficiency and parametric optimum selection of a concentrated solar spectrum splitting photovoltaic cell-thermoelectric generator system. *Energy Convers. Manag.* **2018**, *174*, 65–71. [\[CrossRef\]](#)
47. Li, G.; Shittu, S.; Zhou, K.; Zhao, X.; Ma, X. Preliminary experiment on a novel photovoltaic-thermoelectric system in summer. *Energy* **2019**, *188*, 116041. [\[CrossRef\]](#)
48. Yusuf, A.; Bayhan, N.; Tiryaki, H.; Hamawandi, B.; Toprak, M.S.; Ballikaya, S. Multi-objective optimization of concentrated Photovoltaic-Thermoelectric hybrid system via non-dominated sorting genetic algorithm (NSGA II). *Energy Convers. Manag.* **2021**, *236*, 114065. [\[CrossRef\]](#)
49. Marandi, O.F.; Ameri, M.; Adelshahian, B. The experimental investigation of a hybrid photovoltaic-thermoelectric power generator solar cavity-receiver. *Sol. Energy* **2018**, *161*, 38–46. [\[CrossRef\]](#)
50. Kohan, H.F.; Lotfipour, F.; Eslami, M. Numerical simulation of a photovoltaic thermoelectric hybrid power generation system. *Sol. Energy* **2018**, *174*, 537–548. [\[CrossRef\]](#)
51. Liu, J.; Tang, H.; Zhang, D.; Jiao, S.; Zhou, Z.; Zhang, Z.; Zuo, J. Performance evaluation of the hybrid photovoltaic-thermoelectric system with light and heat management. *Energy* **2020**, *211*, 118618. [\[CrossRef\]](#)
52. Zhang, J.; Xuan, Y. The electric feature synergy in the photovoltaic-Thermoelectric hybrid system. *Energy* **2019**, *181*, 387–394. [\[CrossRef\]](#)
53. Zhang, J.; Zhai, H.; Wu, Z.; Wang, Y.; Xie, H.; Zhang, M. Enhanced performance of photovoltaic-thermoelectric coupling devices with thermal interface materials. *Energy Rep.* **2020**, *6*, 116–122. [\[CrossRef\]](#)
54. Zhang, J.; Xuan, Y. An integrated design of the photovoltaic-thermoelectric hybrid system. *Sol. Energy* **2019**, *177*, 293–298. [\[CrossRef\]](#)
55. Kossyvakis, D.N.; Voutsinas, G.D.; Hristoforou, E.V. Experimental analysis and performance evaluation of a tandem photovoltaic-thermoelectric hybrid system. *Energy Convers. Manag.* **2016**, *117*, 490–500. [\[CrossRef\]](#)
56. Lamba, R.; Kaushik, S.C. Modeling and performance analysis of a concentrated photovoltaic-thermoelectric hybrid power generation system. *Energy Convers. Manag.* **2016**, *115*, 288–298. [\[CrossRef\]](#)
57. Chen, W.H.; Wang, C.C.; Hung, C.I.; Yang, C.C.; Juang, R.C. Modeling and simulation for the design of thermal-concentrated solar thermoelectric generator. *Energy* **2014**, *64*, 287–297. [\[CrossRef\]](#)
58. Deng, Y.; Zhu, W.; Wang, Y.; Shi, Y. Enhanced performance of solar-driven photovoltaic-thermoelectric hybrid system in an integrated design. *Sol. Energy* **2013**, *88*, 182–191. [\[CrossRef\]](#)

59. Beeri, O.; Rotem, O.; Hazan, E.; Katz, E.A.; Braun, A.; Gelbstein, Y. Hybrid photovoltaic-thermoelectric system for concentrated solar energy conversion: Experimental realization and modeling. *J. Appl. Phys.* **2015**, *118*, 115104. [\[CrossRef\]](#)
60. Li, G.; Zhang, G.; He, W.; Ji, J.; Lv, S.; Chen, X.; Chen, H. Performance analysis on a solar concentrating thermoelectric generator using the micro-channel heat pipe array. *Energy Convers. Manag.* **2016**, *112*, 191–198. [\[CrossRef\]](#)
61. Li, G.; Zhao, X.; Ji, J. Conceptual development of a novel photovoltaic-thermoelectric system and preliminary economic analysis. *Energy Convers. Manag.* **2016**, *126*, 935–943. [\[CrossRef\]](#)
62. Liao, T.; Lin, B.; Yang, Z. Performance characteristics of a low concentrated photovoltaic–thermoelectric hybrid power generation device. *Int. J. Therm. Sci.* **2014**, *77*, 158–164. [\[CrossRef\]](#)
63. Da, Y.; Xuan, Y.; Li, Q. From light trapping to solar energy utilization: A novel photovoltaic–thermoelectric hybrid system to fully utilize solar spectrum. *Energy* **2016**, *95*, 200–210. [\[CrossRef\]](#)
64. Zhou, Y.-P.; He, Y.-L.; Qiu, Y.; Ren, Q.; Xie, T. Multi-scale investigation on the absorbed irradiance distribution of the nano-structured front surface of the concentrated PV-TE device by a MC-FDTD coupled method. *Appl. Energy* **2017**, *207*, 18–26. [\[CrossRef\]](#)
65. Zhu, W.; Deng, Y.; Wang, Y.; Shen, S.; Gulfam, R. High-performance photovoltaic-thermoelectric hybrid power generation system with optimized thermal management. *Energy* **2016**, *100*, 91–101. [\[CrossRef\]](#)
66. Li, D.; Xuan, Y.; Li, Q.; Hong, H. Exergy and energy analysis of photovoltaic-thermoelectric hybrid systems. *Energy* **2017**, *126*, 343–351. [\[CrossRef\]](#)
67. Teffah, K.; Zhang, Y. Modeling and experimental research of hybrid PV-thermoelectric system for high concentrated solar energy conversion. *Sol. Energy* **2017**, *157*, 10–19. [\[CrossRef\]](#)
68. Yin, E.; Li, Q.; Xuan, Y. Thermal resistance analysis and optimization of photovoltaic-thermoelectric hybrid system. *Energy Convers. Manag.* **2017**, *143*, 188–202. [\[CrossRef\]](#)
69. Zhang, J.; Xuan, Y. Investigation on the effect of thermal resistances on a highly concentrated photovoltaic-thermoelectric hybrid system. *Energy Convers. Manag.* **2016**, *129*, 1–10. [\[CrossRef\]](#)
70. Mahmoudinezhad, S.; Qing, S.; Rezaniakolaei, A.; Rosendahl, L.A. Transient model of hybrid concentrated photovoltaic with thermoelectric generator. *Energy Procedia* **2017**, *142*, 564–569. [\[CrossRef\]](#)
71. Mahmoudinezhad, S.; Rezaia, A.; Rosendahl, L.A. Behavior of hybrid concentrated photovoltaic-thermoelectric generator under variable solar radiation. *Energy Convers. Manag.* **2018**, *164*, 443–452. [\[CrossRef\]](#)
72. Singh, S.; Ibeagwu, O.I.; Lamba, R. Thermodynamic evaluation of irreversibility and optimum performance of a concentrated PV-TEG cogenerated hybrid system. *Sol. Energy* **2018**, *170*, 896–905. [\[CrossRef\]](#)
73. Cotfas, D.T.; Cotfas, P.A.; Floroian, L.; Floroian, D.I. Study of combined photovoltaic cell/thermoelectric element/solar collector in medium concentrated light. In Proceedings of the 2017 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM) & 2017 Intl Aegean Conference on Electrical Machines and Power Electronics (ACEMP), Brasov, Romania, 25–27 May 2017; pp. 747–752.
74. Acar, B.; Baş, Ş. Investigation of Energy Generation at Test System Designed by use of Concentrated Photo-Voltaic Panel and Thermoelectric Modules. *Int. J. Renew. Energy Res.* **2018**, *8*, 1859–1867.
75. Bamroongkhan, P.; Lertsatitthanakorn, C.; Soponronnarit, S. Experimental performance study of a solar parabolic dish photovoltaic-thermoelectric generator. *Energy Procedia* **2019**, *158*, 528–533. [\[CrossRef\]](#)
76. Shittu, S.; Li, G.; Zhao, X.; Akhlaghi, Y.G.; Ma, X.; Yu, M. Comparative study of a concentrated photovoltaic-thermoelectric system with and without flat plate heat pipe. *Energy Convers. Manag.* **2019**, *193*, 1–14. [\[CrossRef\]](#)
77. Mahmoudinezhad, S.; Rezaia, A.; Cotfas, D.T.; Cotfas, P.A.; Rosendahl, L.A. Experimental and numerical investigation of hybrid concentrated photovoltaic–thermoelectric module under low solar concentration. *Energy* **2018**, *159*, 1123–1131. [\[CrossRef\]](#)
78. Yin, E.; Li, Q.; Xuan, Y. Optimal design method for concentrating photovoltaic-thermoelectric hybrid system. *Appl. Energy* **2018**, *226*, 320–329. [\[CrossRef\]](#)
79. Yin, E.; Li, Q.; Xuan, Y. Experimental optimization of operating conditions for concentrating photovoltaic-thermoelectric hybrid system. *J. Power Sources* **2019**, *422*, 25–32. [\[CrossRef\]](#)
80. Shittu, S.; Li, G.; Zhao, X.; Ma, X.; Akhlaghi, Y.G.; Fan, Y. Comprehensive study and optimization of concentrated photovoltaic-thermoelectric considering all contact resistances. *Energy Convers. Manag.* **2020**, *205*, 112422. [\[CrossRef\]](#)
81. Bjørk, R.; Nielsen, K.K. The performance of a combined solar photovoltaic (PV) and thermoelectric generator (TEG) system. *Sol. Energy* **2015**, *120*, 187–194. [\[CrossRef\]](#)
82. Kwan, T.H.; Wu, X. Power and mass optimization of the hybrid solar panel and thermoelectric generators. *Appl. Energy* **2016**, *165*, 297–307. [\[CrossRef\]](#)
83. Zhang, J.; Xuan, Y.; Yang, L. A novel choice for the photovoltaic–thermoelectric hybrid system: The perovskite solar cell. *Int. J. Energy Res.* **2016**, *40*, 1400–1409. [\[CrossRef\]](#)
84. Zhang, H.; Yue, H.; Huang, J.; Liang, K.; Chen, H. Experimental studies on a low concentrating photovoltaic/thermal (LCPV/T) collector with a thermoelectric generator (TEG) module. *Renew. Energy* **2021**, *171*, 1026–1040. [\[CrossRef\]](#)
85. Kolahan, A.; Maadi, S.R.; Kazemian, A.; Schenone, C.; Ma, T. Semi-3D transient simulation of a nanofluid-base photovoltaic thermal system integrated with a thermoelectric generator. *Energy Convers. Manag.* **2020**, *220*, 113073. [\[CrossRef\]](#)
86. Maadi, S.R.; Navegi, A.; Solomin, E.; Ahn, H.S.; Wongwises, S.; Mahian, O. Performance Improvement of a Photovoltaic-Thermal System using a Wavy-strip Insert with and without nanofluids. *Energy* **2021**, *234*, 121190. [\[CrossRef\]](#)

87. Salari, A.; Parcheforosh, A.; Hakkaki-Fard, A.; Amadeh, A. A numerical study on a photovoltaic thermal system integrated with a thermoelectric generator module. *Renew. Energy* **2020**, *153*, 1261–1271. [\[CrossRef\]](#)
88. Wen, X.; Ji, J.; Song, Z.; Li, Z.; Xie, H.; Wang, J. Comparison analysis of two different concentrated photovoltaic/thermal-TEG hybrid systems. *Energy Convers. Manag.* **2021**, *234*, 113940. [\[CrossRef\]](#)
89. Nazri, N.S.; Fudholi, A.; Mustafa, W.; Yen, C.H.; Mohammad, M.; Ruslan, M.H.; Sopian, K. Exergy and improvement potential of hybrid photovoltaic thermal/thermoelectric (PVT/TE) air collector. *Renew. Sustain. Energy Rev.* **2019**, *111*, 132–144. [\[CrossRef\]](#)
90. Babu, C.; Ponnambalam, P. Economic analysis of hybrid Photovoltaic Thermal Configurations: A comparative study. *Sustain. Energy Technol. Assess.* **2021**, *43*, 100932. [\[CrossRef\]](#)
91. Miljkovic, N.; Wang, E.N. Modeling and optimization of hybrid solar thermoelectric systems with thermosyphons. *Sol. Energy* **2011**, *85*, 2843–2855. [\[CrossRef\]](#)
92. Willars-Rodríguez, F.J.; Chávez-Urbiola, E.A.; Vorobiev, P.; Vorobiev, Y.V. Investigation of solar hybrid system with concentrating Fresnel lens, photovoltaic and thermoelectric generators. *Int. J. Energy Res.* **2017**, *41*, 377–388. [\[CrossRef\]](#)
93. Li, C.; Zhang, M.; Miao, L.; Zhou, J.; Kang, Y.P.; Fisher, C.A.J.; Ohno, K.; Shen, Y.; Lin, H. Effects of environmental factors on the conversion efficiency of solar thermoelectric co-generators comprising parabola trough collectors and thermoelectric modules without evacuated tubular collector. *Energy Convers. Manag.* **2014**, *86*, 944–951. [\[CrossRef\]](#)
94. Mohsenzadeh, M.; Shafii, M.B.; Mosleh, H.J. A novel concentrating photovoltaic/thermal solar system combined with thermoelectric module in an integrated design. *Renew. Energy* **2017**, *113*, 822–834. [\[CrossRef\]](#)
95. Kil, T.-H.; Kim, S.; Jeong, D.-H.; Geum, D.-M.; Lee, S.; Jung, S.-J.; Kim, S.; Park, C.; Kim, J.-S.; Baik, J.M.; et al. A highly-efficient, concentrating-photovoltaic/thermoelectric hybrid generator. *Nano Energy* **2017**, *37*, 242–247. [\[CrossRef\]](#)
96. Soltani, S.; Kasaeian, A.; Sokhansefat, T.; Shafii, M.B. Performance investigation of a hybrid photovoltaic/thermoelectric system integrated with parabolic trough collector. *Energy Convers. Manag.* **2018**, *159*, 371–380. [\[CrossRef\]](#)
97. Haiping, C.; Jiguang, H.; Heng, Z.; Kai, L.; Haowen, L.; Shuangyin, L. Experimental investigation of a novel low concentrating photovoltaic/thermal-thermoelectric generator hybrid system. *Energy* **2019**, *166*, 83–95. [\[CrossRef\]](#)
98. Yin, E.; Li, Q.; Xuan, Y. Feasibility analysis of a concentrating photovoltaic-thermoelectric-thermal cogeneration. *Appl. Energy* **2019**, *236*, 560–573. [\[CrossRef\]](#)
99. Sharaf, O.Z.; Orhan, M.F. Comparative thermodynamic analysis of densely-packed concentrated photovoltaic thermal (CPVT) solar collectors in thermally in-series and in-parallel receiver configurations. *Renew. Energy* **2018**, *126*, 296–321. [\[CrossRef\]](#)
100. Shadmehri, M.; Narei, H.; Ghasempour, R.; Shafii, M.B. Numerical simulation of a concentrating photovoltaic-thermal solar system combined with thermoelectric modules by coupling Finite Volume and Monte Carlo Ray-Tracing methods. *Energy Convers. Manag.* **2018**, *172*, 343–356. [\[CrossRef\]](#)
101. Lashin, A.; Turkestani, M.A.; Sabry, M. Concentrated photovoltaic/thermal hybrid system coupled with a thermoelectric generator. *Energies* **2019**, *12*, 2623. [\[CrossRef\]](#)
102. Abdo, A.; Ookawara, S.; Ahmed, M. Performance evaluation of a new design of concentrator photovoltaic and solar thermoelectric generator hybrid system. *Energy Convers. Manag.* **2019**, *195*, 1382–1401. [\[CrossRef\]](#)
103. Riahi, A.; Ali, A.B.H.; Fadhel, A.; Guizani, A.; Balghouthi, M. Performance investigation of a concentrating photovoltaic thermal hybrid solar system combined with thermoelectric generators. *Energy Convers. Manag.* **2020**, *205*, 112377. [\[CrossRef\]](#)
104. Rejeb, O.; Shittu, S.; Li, G.; Ghenai, C.; Zhao, X.; Ménéz, C.; Bettayeb, M. Comparative investigation of concentrated photovoltaic thermal-thermoelectric with nanofluid cooling. *Energy Convers. Manag.* **2021**, *235*, 113968. [\[CrossRef\]](#)
105. Lekbir, A.; Hassani, S.; Ab Ghani, M.R.; Gan, C.K.; Mekhilef, S.; Saidur, R. Improved energy conversion performance of a novel design of concentrated photovoltaic system combined with thermoelectric generator with advance cooling system. *Energy Convers. Manag.* **2018**, *177*, 19–29. [\[CrossRef\]](#)
106. Soltani, S.; Kasaeian, A.; Sarrafha, H.; Wen, D. An experimental investigation of a hybrid photovoltaic/thermoelectric system with nanofluid application. *Sol. Energy* **2017**, *155*, 1033–1043. [\[CrossRef\]](#)
107. Akbar, A.; Najafi, G.; Gorjian, S.; Kasaeian, A.; Mazlan, M. Performance enhancement of a hybrid photovoltaic-thermal-thermoelectric (PVT-TE) module using nanofluid-based cooling: Indoor experimental tests and multi-objective optimization. *Sustain. Energy Technol. Assess.* **2021**, *46*, 101276. [\[CrossRef\]](#)
108. Rajaei, F.; Rad, M.A.V.; Kasaeian, A.; Mahian, O.; Yan, W.M. Experimental analysis of a photovoltaic/thermoelectric generator using cobalt oxide nanofluid and phase change material heat sink. *Energy Convers. Manag.* **2020**, *212*, 112780. [\[CrossRef\]](#)
109. Soltani, S.; Kasaeian, A.; Lavajoo, A.; Loni, R.; Najafi, G.; Mahian, O. Exergetic and environmental assessment of a photovoltaic thermal-thermoelectric system using nanofluids: Indoor experimental tests. *Energy Convers. Manag.* **2020**, *218*, 112907. [\[CrossRef\]](#)
110. Wu, Y.-Y.; Wu, S.-Y.; Xiao, L. Performance analysis of photovoltaic-thermoelectric hybrid system with and without glass cover. *Energy Convers. Manag.* **2015**, *93*, 151–159. [\[CrossRef\]](#)