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A Comprehensive Review of Hybrid Photovoltaic-Thermoelectric Systems for Enhanced Solar Energy Utilization

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ABSTRACT

These systems show great promise by converting waste heat from photovoltaic modules into additional electrical power. The study analyzes the performance and efficiency of the hybrid PV-TEG systems under varying conditions, such as different solar concentration ratios, cooling methods, and materials. While these innovations promise to improve system efficiency, the review also identifies several challenges, including increased thermal resistance, higher system costs, and the minimal temperature difference across the TEG, which significantly limits its performance. This limitation, where the temperature differential is often too small to be effectively harnessed, reduces the TEG's overall efficiency and hinders the integrated system's potential gains. The review underscores the need for urgent and extensive research to develop optimized design configurations, durable mathematical models, and further experimental validation to ensure the practical viability of these systems under diverse environmental conditions. Despite these challenges, the potential of PV-TEG systems to revolutionize solar energy technologies is undeniable.PV-TEG performance is intricately linked to environmental conditions: higher solar radiation boosts efficiency, but increased ambient temperatures reduce it. TEGs often hinder PV cooling, yielding minimal efficiency gains. Non-uniform heat and low-temperature differences across TEGs further decrease performance. While hybrids can improve power conversion, high costs limit feasibility. However, with strategies such as enhancing solar concentration, using effective cooling methods like water or nanofluids, and advanced materials like phase change materials, the efficiency and reliability of these systems can be significantly improved.

1. Introduction

The utilization of renewable energy technologies, which come with minimal environmental impacts, will become even more significant as global concerns about climate change increase. Renewable energy sources such as solar power are essential to sustainable development through reduced dependency on fossil fuels and decreased greenhouse gas emissions. Among solar technologies, photovoltaic (PV) systems stand out for their effectiveness in harnessing sunlight, proving a promising approach to solar energy

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generation. This has led to a significant and rapid increase in their global energy market share in recent years[1].

Due to increasing concern and awareness about environmental sustainability, significant research efforts are being directed toward efficiently using and converting solar energy into electricity. A major issue with solar cells is the decline in conversion efficiency caused by the rise in cell temperature and the resulting waste heat, particularly in concentrated PV (CPV) systems[2]. Harnessing waste heat from solar PV cells using thermoelectric modules has driven research into integrated PV-TEG systems. However, this integration creates a complex system with additional energy transfer considerations. The increased temperature in the PV-TEG system has conflicting effects: while higher temperature gradients enhance TEG module efficiency, they reduce PV cell efficiency and lifespan. Recent research focuses on using phase change materials (PCMs) and nanotechnology to improve heat transfer and the overall efficiency of integrated PV-TEG systems[3],[4].

Integrated PV-TEG systems use both photovoltaic converters and thermoelectric generators to convert solar radiation into power efficiently [5]. As a result, there has been a surge in interest recently, with significant research efforts focused on enhancing the reliability and efficiency of PV-TEG systems[6],[7]

1.1 The literature related to numerical photovoltaic–thermoelectric hybrid systems (PVT-TEG)

Solid-state thermoelectric power generation technologies for waste heat recovery Solid-state materials, or TE (thermoelectric) elements, can convert thermal energy directly into electrical power based on the Seebeck effect. Thermoelectric Coolers (TECs) and Thermoelectric Generators (TEGs) utilize thermoelectric principles but serve different functions, working with heat and electricity differently. TECs are designed to cool things down when you pass electricity through them; one side gets cold while the other gets hot, making them perfect for cooling small devices. On the other hand, TEGs do the opposite: they take a difference in temperature and turn it into electricity. So, while TECs need power to cool things, TEGs can create power from heat, making them great for turning waste heat into useful energy. [8] compared to other traditional methods, which make billions of tons of CO2 emissions around the world every year, so this is an urgent solution strategy regarding increasing the efficiency in utilization of primary resources and reducing CO2 output due to global high demand for sufficient supply resources issues particularly environmental related problems such as greenhouse effects or even deterioration natural systems supporting our life causing by inappropriate processed of produced wasted industrial remainder because we manufacture it without carefully controlled conditions after initial production stages... etc. Its operational practice has benefits, including solid reactivity, yet pollution is deeply managed; furthermore, scaling up is feasible at the practical axis, with a minimal maintenance complex, and neither part is used only as a chemical mechanism towards its survival habitat. It can also be reversible - i.e. use electrical energy to create thermal for cooling/heating[9]. The thermoelectric generator is made of neuroses thermocouples (TCs) connected thermally in parallel and electrically in series, as shown in Figure 1. The thermocouple consists of different semiconductor materials connected at their ends with an opposite sign Seebeck coefficient. The two ends of the thermocouples being exposed to the temperature difference generate an electric voltage based on the Seebeck effect, given by $\Delta T = Thot - Tcold$. If two dissimilar metals are joined in two points and are maintained at different temperatures, then electromotive force (e.m.f.) will arise from the migration of electrons from the negatively charged semiconductor to the positively charged semiconductor [10]. Figure 2 shows the entire thermoelectric generator [11].

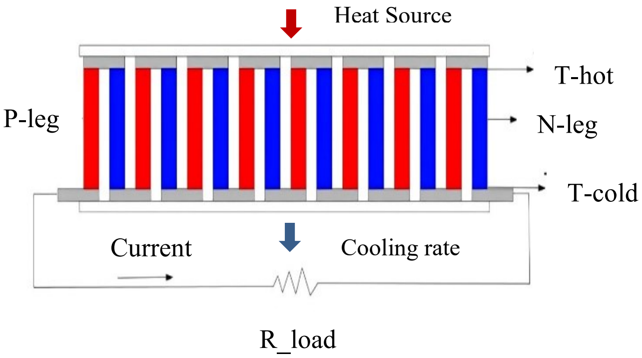

Figure 1. Typical thermoelectric generator.

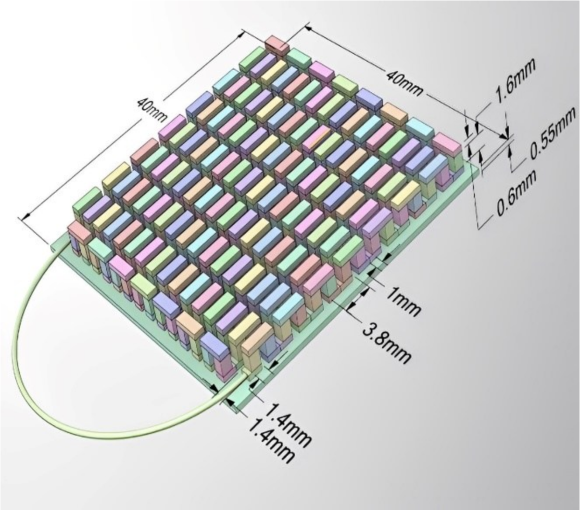

Figure 2. The entire thermoelectric generator consists of 127 thermocouple pairs [11].

1.2 The PV-TEG hybrid system concept.

Despite solar panels converting solar radiation into electrical energy with a certain efficiency, a portion of the radiation is stored as heat in the photovoltaic panel. Several combined photovoltaic and heat recovery systems have been suggested recently to address this. The simplest systems use thermoelectric generators (TEGs) to transform heat into electrical energy. (TEGs) rely on the Seebeck effect, which generates electricity by moving charge carriers across a temperature difference within the generator[12]. Therefore, the external power of the hybrid system is the sum of the solar panel output and the thermoelectric generator [13]. Figure 3 shows the simple hybrid system (PV-TEG).

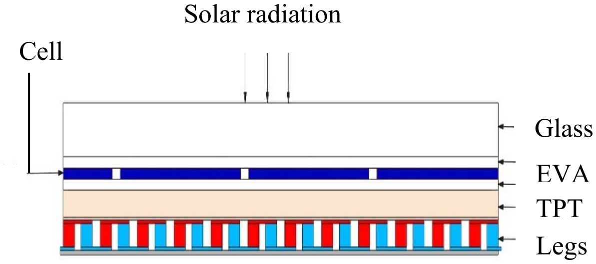

Figure 3. Simple hybrid system (PV-TEG).

Despite the advancements presented in this study on optimizing hybrid photovoltaic-thermoelectric (PV-TEG) systems, several limitations must be acknowledged. The effectiveness of the proposed optimizations, such as higher solar concentration ratios and advanced cooling techniques, is highly dependent on specific environmental conditions, including solar intensity and ambient temperature, which can vary significantly across different geographic regions. This variability may limit the applicability of the findings in diverse climates. Moreover, integrating advanced materials and complex cooling systems, while beneficial for enhancing efficiency, may increase the overall cost and complexity of PV-TEG systems, potentially hindering their widespread adoption in cost-sensitive markets. Additionally, the presence of the thermoelectric generator (TEG) itself can introduce additional thermal resistance between the photovoltaic (PV) module and the environment, potentially affecting the cooling efficiency of the PV module. This added thermal resistance may reduce the overall effectiveness of the cooling methods, thereby impacting the system's performance. Furthermore, the mathematical models developed in this study, though robust, may not fully capture the intricacies of real-world systems, as they are based on certain assumptions and ideal conditions. Consequently, further experimental validation is required to confirm the accuracy of these models and ensure their reliability in practical applications. Therefore, the objectives of this work can be summarized as follows:

- To show the performance and efficiency of hybrid photovoltaic-thermoelectric (PV-TEG) systems under varying conditions, such as different solar concentration ratios, cooling methods, and materials.
- To highlight the adverse effects of thermoelectric generators on solar panels and explore the limitations that hybrid systems face.
- To highlight the impact of integrating phase change materials (PCM), cooling techniques, and advanced thermoelectric materials on the performance and reliability of PV-TEG systems in real-world applications.

2. Literature Survey

2.1 The literature related to numerical research photovoltaic-thermoelectric hybrid systems (PV-TEG)

R. Bjørk and K.K. Nielsen [14] analyzed the performance of a combined solar photovoltaic (PV) and thermoelectric generator (TEG) system, finding that for crystalline Si (c-Si), copper indium gallium selenide (CIGS), and cadmium telluride (CdTe) PV cells, the system produced lower power and efficiency than the PV alone due to the low efficiency of the TEG. Only the amorphous Si (a-Si) cell showed a slight improvement, with a total system performance increase of about 30%. The results demonstrated that the degradation in PV performance with temperature outweighed the power gains from the TEG, suggesting that combined PV and TEG systems were generally not viable for power production except in specific configurations.

R Avita Lamba and S.C. Kaushik [15] developed a model for a concentrated photovoltaic–thermoelectric (CPV–TEG) hybrid system, demonstrating that it generated more power and had higher efficiency than a standalone photovoltaic (PV) system. At a concentration ratio of 3, where sunlight is focused to three times its natural intensity (from 1,000 W/m^2 to 3,000 W/m^2) using lenses or mirrors, the hybrid system, with 127 thermocouples, produced a maximum power output of 111 W. In comparison, the standalone thermoelectric (TE) and PV systems generated 12.99 W and 97.97 W, respectively, with efficiencies of 5.8% for the hybrid system, 4.3% for the TE system, and 5.2% for the PV system. The study also observed that the Thomson effect reduced power output by 0.7% and 4.78% under concentration ratios of 1 and 5, respectively, highlighting the importance of effective cooling in such systems.

H. Hashim et al. [16] The optimization model for the geometry of thermoelectric devices in PV/TE is developed for hybrid photovoltaic-thermoelectric systems to maximize power output and efficiency. Simulations show that embedding the TEG in the system to harvest the waste heat of a PV cell enhances the total power output and conversion efficiency. The power output in optimal geometry is much higher but still maintains minimal use of the thermoelectric materials. For example, output power from a small TEG module increased from 5.2 mW to 7.0 mW (35%) when it was operated in a vacuum compared to an ambient environment.

To boost solar energy efficiency, Tengfei Cui et al. [17] designed and evaluated a novel PV–Te system with PCM. Using a Fresnel lens, GaAs PV cells, and bismuth telluride TE modules stabilized by paraffin PCM, the system maintained a constant temperature and operated efficiently. The PV–PCM–TE system achieved a daily total efficiency of 26.57%, surpassing the 25.55% of the single PV system. This demonstrates significant improvements in energy conversion and stable performance over traditional PV/TE systems (Figure 4).

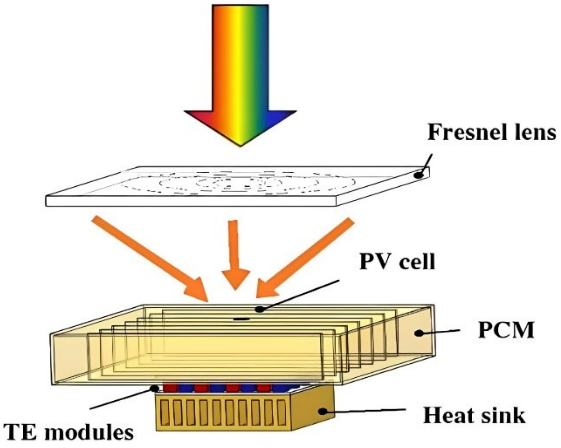

Figure 4.The proposed PV–PCM–TE hybrid system diagram[17].

Dianhong Li et al. [18] used a one-dimensional thermodynamic model to analyze hybrid PV-TE systems, showing that these systems generally produced more electric power than standalone PV cells. The results indicated that the CIGS-TE hybrid system achieved a maximum efficiency of 21.6%, with a 4.1% increase at a concentration ratio 200. The polymer-TE hybrid system experienced a 6.6% efficiency boost at a concentration ratio 180. In this study, "concentration" referred to the use of lenses or mirrors to focus solar energy, intensifying sunlight on the photovoltaic (PV) cells and thermoelectric (TE) components. The "concentration ratio" quantified this intensification, with higher ratios indicating stronger solar radiation; for instance, 200 meant sunlight was 200 times more intense, enhancing energy conversion and overall system efficiency. The research concluded that higher concentration ratios and appropriate PV cell technologies significantly improved system efficiency. However, it also highlighted that major exergy losses occurred during the conversion of solar radiation into electric power and thermal energy.

Ershuai Yin et al. [19] analyzed and optimized a photovoltaic-thermoelectric (PV-TE) hybrid system, finding that water cooling was the most effective. Amorphous silicon (a-Si) and polymer PV cells were identified as most suitable due to their lower temperature coefficients. Increased total efficiency of the a-Si PV-TE system by approximately 78% (from 5.1% to 9.1%) and the polymer PV-TE system by 283% (from 2.3% to 8.8%) when adjusting the thermal resistance of the TE module. Improved efficiency by 15% (from 7.8% to 6.6%) by reducing thermal contact resistance.

Jin Zhang and Yimin Xuan [20] Improved photovoltaic-thermoelectric (PV-TE) hybrid systems and adjustable cooling blocks were introduced to manage temperature fluctuations from varying solar radiation, leading to a higher output power. Using a GaAs PV cell and Bi2Te3 TE generators, the experimental setup demonstrated that the system achieved an output power of 1.262 W under a concentrated radiation of 31.4 W. This focused radiation represents the solar power incident on the PV cell after sunlight is focused, calculated by multiplying solar intensity by the PV area. The new system significantly outperformed the traditional PV setup, with numerical models confirming its efficiency surpassed the traditional and PV-PCM-TE systems, particularly under fluctuating solar conditions.

Koushik S et al. [21] A PV–TEG combined hybrid power generation system for efficiency enhancement is presented. Both light and heat from solar radiation were used to increase the efficiency by 10.74% for monocrystalline cells and by 20.79% for multifunction cells compared to conventional solar technologies. MATLAB/Simulink simulations showed that the system yielded a maximum of 48.88 W from the PV and 28.82 W from the TEG using monocrystalline cells, with an increase in power density of 58.09%. With multifunction cells, the system gave 78.76 W from the PV and 26.12 W from the TEG, with an Increased power output of 36.68%.

H.R. Fallah Kohan et al. [22] The newly introduced hybrid power generation systems based on PV-TEG performance characteristics were investigated using developed numerical three-dimensional models for the PV module and a thermoelectric generator device. In this arrangement, TEGs were attached to the backside of a PV module. The numerical model accounted for the whole system and considered it a homogeneous medium. It did not account for any internal structural complexities. A sink for internal energy was modeled and solved using the finite volume approach for the energy governing equations. The electrical response of both PV and TEG devices was modeled through custom user-defined functions. The results show that this combined system has a higher power output at particular environmental conditions than the standalone PV module. Such a gain in power is minuscule; a significant temperature difference could not be created for the TEG device. However, the presence of the TEG does not allow the PV module to cool correctly.

Birol Kılkış [23] Developed and tested a multi-layered composite photovoltaic thermal (PVT) module, which integrated stand-alone mini PVT cartridges. These cartridges included photovoltaic cells, thermoelectric generator (TEG) units, a packed-bed phase change material (PCM) layer for thermal storage, and dynamically controlled heat pipes. When installed, the cartridges were designed for easy removal and maintenance, forming a complete module with a flat-plate collector layer. An array of pulse-controlled heat pipes adjusted heat flux to maximize total exergy output, removing the need for external thermal storage and coolant pumping. Pilot-scale tests showed that the Rational Exergy Management Model efficiency improved by about 25% compared to conventional PVT systems. Additionally, the total net electrical power output per unit of solar insolation area exceeded that of conventional systems by more than 30%, and the total exergy output (power and heat) was twice as much as a conventional PVT unit during a typical summer month.

Ali Salari et al. [24] A 3D numerical model was developed to analyze a photovoltaic thermal system integrated with a thermoelectric generator module (PVT/TE). The study examined the effects of solar radiation, coolant flow rate, and temperatures on both PVT and PVT/TE systems. The findings revealed that the PVT/TE system achieved 6.23% and 10.41% higher electrical efficiency than the PVT system under solar radiation of 600 W/m^2 and 1000 W/m^2, respectively. An increase in the inlet fluid temperature from 26°C to 34°C resulted in a reduction of 2.58% in PVT efficiency and 4.56% in PVT/TE efficiency. Additionally, a higher ambient temperature (26°C to 34°C) led to a 1.43% decrease in PVT efficiency but a 0.82% increase in PVT/TE efficiency. Overall, the PVT/TE system demonstrated higher electrical efficiency, while the PVT system exhibited superior thermal efficiency. Figure 5 provides an overview of the developed PVT/TE model.

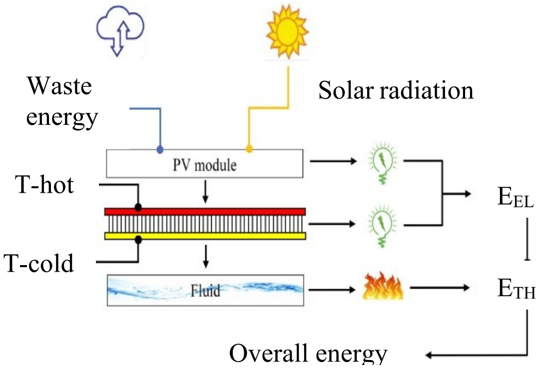

Figure 5. Overview of the developed PVT/TE model[24].

Abdelhak Lekbir et al. [25] It was found that electrical performance is almost 89% higher than in standard PV modules at an optimum solar concentration ratio of 14.6 within the hybrid system. The electrical performance improved by 13.9% compared to the CPV/TEG and 8.4% compared to the water-cooled CPV/TEG systems. Another 4.98% improvement was noted in thermal energy collection compared with the water-cooled system. The daily analysis of exergy demonstrated that the NCPV/T-TEG system gave, respectively, 92.47% more output compared to the standard PV cells, 41.06% compared to the CPV/TEG system, and 8.8% compared to.

Zhiying Song et al. [26] A study found that a nanofluid-based hybrid system for CPV/T-TEG realized approximately 89% better electrical performance than standard PV modules at the best value of 14.6 in solar concentration ratio. The designed device's electrical performance with CPV/TEG was raised by 13.9%, whereas 8.4% was achieved with water-cooled CPV/TEG. It also harvests around 4.98% more thermal energy. This may be fortified by the fact that the NCPV/T-TEG system produced 92.47% more exergy than standard PV cells and 41.06% and 8.8% more when compared with CPV/TEG and WCPV/T- TEG systems, respectively.

Xin Wen et al. [27] It was designed for a CSPV-TEG hybrid power generation system thermodynamic model, with a semi-transparent photovoltaic module attached to a thermoelectric generator to enhance overall efficiency using waste heat. They did simulations under different conditions and concluded that a maximum power of 219.75 W would be obtained at a concentration ratios 2 with 200 thermocouples. At the same time, the highest electrical efficiency reached 10.44% at a concentration ratio of 1 with 200 thermocouples. The results also identified that exergy efficiency outperformed electrical efficiency by 1.33%, proving the hybrid system has the potential to enhance power generation efficiency through effective heat management.

Abhishek Tiwari and Shruti Aggarwal [28] Two concentrated photovoltaic/thermal (PV/T) systems with thermoelectric generators were numerically compared; one had a gravity-driven heat pipe (GHP-LFPV/T-TEG) and another without it (LFPV/T-TEG). The results showed that, after seven hours of operation under the solar irradiation of 800 W/m^2, the GHP-LFPV/T-TEG system reached a 10.23% higher thermal efficiency than that of LFP. The gross total output of TEGs on the GHP LFPV/T-TEG was 13.64 kW, in comparison to 6.41 kW for LFPV/T-TEG, showing the benefits of GHP regarding the enhancement of thermal performance at the cost of electrical efficiency.

Milad Naderi et al. [29] integrated phase change materials and thermoelectric generators to enhance photocells (PV-PCM-TEG) to generate electricity 24 hours a day, increasing power generation and photocell efficiency. This managed to decrease the temperature of the solar cell from 74.43°C to 53.72°C, increase the output of electricity by 100%, and increase the efficiency of the solar cell by 1.38%. But it was generating power at lower rates during the night, producing electricity by thermal dissipation. Optimal performance was recorded at a packing factor 0.4; TEG efficiency decreased from 4.32 to 0.61 with higher packing factors. The efficiency increase in terms of the wind velocity and experimental validation, along with thermoeconomic studies, was suggested to carry Jinyoung Ko and Jae-Weon Jeong [30] evaluated a thermoelectric generator-assisted building-integrated photovoltaic system with phase change material to enhance energy generation efficiency. Simulations indicated that the optimal design with a PCM melting temperature of 35°C and thickness of 30 mm resulted in a 1.09% annual increase in energy generation compared to a standard BIPV system. Seasonally, the proposed system improved energy output by 0.91% in spring, 2.25% in autumn, and 3.16% in winter but saw a 1.32% decrease in summer due to high outdoor temperatures affecting PCM performance. The system's theoretical potential could achieve a 4.47% increase in annual energy generation with ideal TEG performance and reduced thermal resistance.

lvaro´Valera et al. [31] Investigated the efficiency improvement of passively cooled micro-scale hybrid CPV-TEG systems at ultra-high concentration levels up to 4,000 suns. Using a 3D finite-element method, the researchers found that incorporating a TEG module could enhance the efficiency of a CPV-only receiver by up to 10.8% relative magnitude. In a reference case with a concentration ratio of 2,000 suns, the hybrid system achieved a maximum cell temperature of 98°C and showed a 4.59% efficiency improvement compared to a CPV-only system. The efficiency of a thermoelectric generator increases with the hot side temperature when the cold side temperature is constant. A higher enhances the temperature difference, boosting the Seebeck effect and power output. However, the efficiency gain diminishes at higher temperatures due to material limitations and thermal losses.

Muhammad Ahsan Iqbal Khan et al. [32] In another study conducted in Lahore, Pakistan, for ten days, it was concluded that embedding thermoelectric generators (TEGs) with a polycrystalline photovoltaic module rated at 10 W considerably enhanced performance. The hybrid PV-TEG system reduced the temperature of the operating photovoltaic module to 5.5%, from 55 °C to 52 °C. Added to this temperature drop, the added power developed by the TEGs sums up to a total increase in output power of 19% from 8.78 W to 10.84 W and an increase in efficiency of 17%, from 11.6% to 14%.

Bruno Lorenzi [33] Analyzed the hybrid thermoelectric-photovoltaic generators under adverse lighting or thermoradiative conditions. He combined a thermoradiative photovoltaic cell with a thermoelectric generator. He found that although the hybrid power density is generally lower than that of TR-PV alone, there may be efficiency gains. The results show that TR cells with less than 0.1 eV energy gaps displayed efficiency enhancements between 1% and 6%. Ideal TR cells with no loss in energy generation of up to 54 W/m^2 were produced. The study underlined that spectral matching and the proper emitter properties were necessary to optimize performance.

Dario Narducci and Bruno Lorenzi [34] evaluated the economic viability of hybrid thermoelectric-photovoltaic (HTEPV) solar harvesters that combine photovoltaic (PV) cells with thermoelectric generators (TEGs) for improved energy conversion. The result was that though hybridization increases solar power conversion, the associated power cost has often not justified deployment due to current technology limitations. An economic convenience index (EcCI) showed wide-gap PV materials to be profitable, along with high-performance TEGs with a figure of merit of around 0.003 K^-1. For example, polycrystalline silicon had an EcCI < 1, and the cadmium sulfide, which has an energy gap equal to 2.4 eV, achieved an EcCI of 1.05 under medium solar concentration, which means an efficiency enhancement of 5% at constant price. On the other hand, perovskite solar cells demonstrated an even more significant potential for hybridization, leading this technology onto a promising development road.

Nurul Syakirah Nazri et al. [35] studied a hybrid photovoltaic–thermal–thermoelectric (PVT-TE) system to achieve higher efficiency with a PV cell by adding a thermoelectric (TE) module for improved thermal management. The system's effectiveness has been analyzed by one-dimensional mathematical modeling and steady-state analysis; experimental tests were carried out at an intensity of solar radiation of 593.16 W/m^2 with a different air mass flow rate. The results indicate that a PVT-TE system can outperform conventional PVT systems and that its thermal and electrical efficiencies are better enhanced. The total system efficiency increased significantly, with theoretical improvements between 7.05% and 31.13% and experimental between 9.64% and 34.83%. It is emphasized that more research has to be done to optimize TE module performance and enhance the hybrid system.

M. Sheikholeslami and Z. Khalili [36] added a thermoelectric layer above the absorber to enhance electrical performance. The system had two regions for hybrid nanofluid flow: a circular duct with a turbulator and a mini channel with jet impingement, both operating in a laminar regime. The hybrid nanomaterial properties were modeled using a single-phase formulation. Selecting the turbulator with the highest rotation increased electrical efficiency by 1.41% and useful heat by 5.72%. The performance factor for the highest rotation case was 1.25, indicating good hydrothermal performance. This configuration included confined jets, achieving 15.50% electrical and 85.30% thermal performance. Temperature uniformity improved by 46.89%.

H.R. Fallah Kohan et al. [37] Integrating thermoelectric generator (TEG) modules into photovoltaic (PV) systems typically increases PV cell temperatures and reduces efficiency. Only two out of nine configurations showed marginal improvements, with the C-49 CPV-TEG system achieving a maximum performance increase of 0.57% under a cooling condition of h = 1000 W/m^2K and a concentration ratio of X = 500, while the C-71 system experienced a maximum performance decrease of 3.04%. Additionally, the one-day transient simulation revealed that the overall daily performance of PV-TEG systems remained almost unchanged compared to PV-only systems, with CPV-TEG systems performing better under weaker cooling conditions.

Adel Almarashi et al. [38] a photovoltaic (PV) unit was enhanced by incorporating a thermoelectric generator (TEG) and a triangular-shaped duct with ferrofluid cooling, augmented by magnetic forces. Dust reduced thermal (ηth), thermoelectric (ηTE), and electrical PV (ηPV) efficiencies by 3.98%, 6.96%, and 9.46%, respectively. Increasing the Hartmann number (Ha) improved ηth, ηTE, and ηPV by 6.68%, 19.16%, and 0.69%, respectively. At an inlet velocity (Vin) of 0.078 m/s, ηth, ηTE, and ηPV increased by 7.29%, 20.25%, and 0.72%, respectively. Higher Vin led to improvements of 10.19%, 29.14%, and 1% in ηth, ηTE, and ηPV, respectively, when Ha was zero. Nanoparticles enhanced performance, particularly in ηTE, but these improvements decreased by 13.37%, 9.91%, and 4.78% for ηth, ηTE, and ηPV, respectively, with higher Vin in the absence of Ha. Uniformity improved by 22.54% and 31.25% with increased Ha at Vin values of 0.078 m/s and 0.17 m/s, respectively.

E. Azizi et al. [39] The productivity of a photovoltaic thermal (PVT) system under dusty conditions was enhanced. The system included a cooling tube with anchor-shaped fins, PV cells integrated with thermoelectric generator (TEG) modules, and a hybrid nanofluid (water and Fe3O4/SiO2 nanoparticles) for cooling. A self-cleaning SiO2 nanoparticle coating was used to reduce dust impact. Photovoltaic (ηPV), thermoelectric (ηTE), and thermal (ηTh) performances were evaluated for two configurations: case A (without fins) and case B (with fins). Using the hybrid nanofluid improved heat transfer and overall efficiency. Without fins, the impact of nanoparticles was approximately three times greater than with fins. Dust deposition in case B reduced ηPV, ηTE, and ηTh by 38.19%, 12.06%, and 14.05%, respectively. Coating the glass with nanoparticles improved ηPV by 8.07% in case A and 4.93% in case B.

Ammar A. Melaibari et al. [40] a new design for photovoltaic-thermal (PVT) systems featuring an elliptic cooling duct filled with ferrofluid and a thermoelectric generator (TEG) showed significant improvements. Dust accumulation decreased electrical efficiency by 23.5% and thermal efficiency by 9.07%. Introducing a magnetic field (Ha) improved temperature uniformity, raising electrical efficiency by 1.18% and thermal efficiency by 6.85%. Increasing the inlet velocity (Vi) enhanced cooling, leading to a 4.03% increase in electrical efficiency and a 30.26% rise in thermal efficiency. Adding nanofluid further boosted performance, with electrical efficiency increasing by 65.73% and thermal efficiency by 7.35%.

Adel Almarashi et al [41] It examined the consequences of using Fe3O4 nanoparticles and the effect of a magnetic field on the operation of PVT systems. Thus, it was determined that dust deposition had decreased proper heat by around 10.11%, with an actual electric productivity decrease of about 25.36%. Thermal performance improvement due to applying the magnetic field (MHD) is around 8.9 %, while electrical efficiency is about 1.8%. The silicon layer was well-cooled with the addition of Fe3O4 nanoparticles in the cooling fluid, improving its performance much better, particularly in the absence of MHD. In addition, increased inlet velocity improved electrical performance by up to 8.22%. It was demonstrated that this combined passive and active techniques, in fact, greatly enhanced both the electrical and thermal efficiencies of the PVT systems with high accuracy.

E. Azizi et al. [42] proposed a combination of finned tubes and enclosed jets to increase the efficiency of photovoltaic-thermal (PVT) systems. The authors used a hybrid nanofluid of Carbon Nanotubes

(CNT) and Fe3O4. They considered three scenarios: 1) a standard system with an ordinary cooling tube, 2) a finned-tube type cooling unit in a system, and 3) combined confined jetting with the finned tube. According to the findings, overall performance improved by about 2.64% if hybrid nanoparticles were introduced compared to the standard system. The performance of TEG increased by 86.13% due to integration of fins with confined jets, while thermal efficiency increased by 26.42%. Thermal performances were enhanced by greater inlet velocities, which also improved irradiance value by 8.66% and 3.48%, respectively. However, higher wind speeds decreased thermal efficiencies by about 12.8% and TEG efficiencies by approximately 7.5% while improving PV efficiency slightly

Selcuk Bulat et al. [43] evaluated the efficiency of photovoltaic–thermoelectric (PV-TE) hybrid systems using various cooling strategies. It tested seven different thermoelectric generators (TEGs) under conditions without cooling, with passive cooling using aluminum heat sinks, and with active cooling using water and nanofluids. Results showed that TEGs with ceramic plates performed better than those with graphite plates, particularly at higher temperatures. The active cooling system increased power output by up to 9.45% compared to no cooling. Notably, TEG4 with active cooling using nanofluids achieved the highest efficiency, providing a 9.45% increase in power output. This research highlighted the potential for cooling strategies to enhance the performance of PV-TE systems significantly.

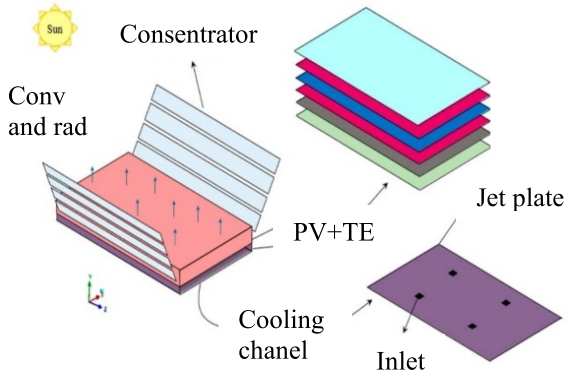

Figure 6. The CPVT system configuration uses a linear Fresnel concentrator [44].

M. Sheikholeslami and Z. Khalili [44] in this study, as shown in Figure 6, linear Fresnel concentrators enhanced CPVT unit productivity by increasing silicon layer temperature. However, non-uniform isotherms may shorten the panel's lifespan. Confined jets of alumina–water nanofluid were used for cooling. The numerical code validation showed good agreement. Various Tin and Vin were analyzed.

Concentrators improved overall performance and CO2 reduction. Increasing Vin enhanced thermal performance by 4.2% and uniformity by 13.91%. Thermal power increased 2.19 times, and PV power rose 86.22% due to reflectors. Higher Tin decreased thermal and electrical performance by 19.95% and 5.24%, respectively. Overall performance improved by 6.55% with concentrators. Over 10 years, the CPVT-TEG system was expected to mitigate 148.28 tons of CO2.

Abdulrahman M. Alajlan et al. [45] introduced a photovoltaic-thermoelectric hybrid system that improved both daytime and nighttime energy efficiency. The system achieved a notable power density of 0.5 W/m^2 at night by integrating water-passive cooling with thermoelectric generators. Experimental results showed a temperature reduction of over 10°C in the PV cells during peak solar exposure, which increased their efficiency by approximately 5%. The hybrid system provided a practical and cost-effective solution for off-grid electricity generation, demonstrating significant advancements in renewable energy technology.

2.2 The literature related to experimental photovoltaic-thermoelectric hybrid systems (PV-TEG)

J. Darkwa et al. [46] demonstrated that integrating phase change materials (PCMs) with photovoltaic (PV) cells in a combined system can enhance power output and efficiency. The best performance of the integrated PV/TEG/PCM system was observed under 1000 W/m^2 solar radiation, where the power output was 9.5% higher than that of standard PV systems. This was achieved using a PCM layer with a thickness of 50 mm, a thermal conductivity of 5 W/mK, and a phase change temperature range between 40-45°C, which was the most suitable configuration. Initial results indicated lower peak temperatures and improved conversion efficiency during the first one and a half hours of operation, with the peak TEG power output reaching 0.55 W/m^2, contributing to the overall efficiency increase. However, after five hours, the efficiency gain dropped to only 1.8%. The PCM used in the study was a paraffin-based n-

Octadecane, which has a latent heat of 123 kJ/kg and a phase change temperature range of 25.78°C to 31.28°C, further enhancing the system's thermal management and efficiency.

Ershuai Yin et al. [47] This report presented a detailed feasibility analysis of a tandem concentration photovoltaic-thermoelectric (CPV-TE) hybrid system and compared it with the single system CPV. The researchers then developed theoretical models and experimental installations to measure working temperatures and output power at different solar concentration ratios. Findings in the study revealed an improvement in output power of 8.7%, which translated from 1.38W produced by a single-junction GaAs PV cell at a 255:1 concentration ratio and increased it to about 1.5W in favor of the hybrid system. However, this was impossible for a double-junction GaAs PV cell since its efficiency was always lower than that of the single CPV system for all studied concentration ratios. This research also found that device performance parameters and system operating conditions were significant factors determining whether such hybrids could be considered feasible and their overall performance levels, respectively.

Ruzaimi et al. [48] analyzed the performance of a hybrid system that integrates photovoltaic (PV) and thermoelectric generators (TEGs) in non-uniform heat. The hybrid PV-TEG system was designed to use both light and heat from solar radiation to increase its energy output. It was noted that there had been an appreciable decrease of 33% in power produced due to the non-uniform heat distribution in TEG modules. Therefore, temperature variations influenced their consistency as power sources, which called for better thermal management. During the experiments, individual TEG module testing and their serial/parallel setup were conducted to optimize energy efficiency in PV-TEG systems by reducing non-uniform temperature impact on them.

Gideon Kidegho et al. [49] reported on their implementation of thermal interface materials (TIMs) as a practical remedy for temperature differences in thermal electric generators (TEG) and photovoltaic (PV) facilities. The TIMs came in such forms as graphite sheets, heat spreaders, and aluminum foils and were tested using two cooling methods, namely air and water. They were baffled about the temperature differences observed due to using the thermal interface materials(TIMs), but the heat spreader was the best performer. When working under the perfect conditions, the photovoltaic module gained extra power by 1.8% thanks to the air-cooling and 2.5% with water-cooling, and the TEG heat pump power generation also improved by 19.7% and 24.85%, respectively. The detailed evidence indicated that TIMs can be beneficial for developing the overall effectiveness of the PV-TEG systems.

Zakieh Gholami et al. [50] an L-shaped passive earthenware tank was used for cooling, and an ultrasonic humidifier was added to the tank for more active cooling. The ultrasonic humidifier works with a piezoelectric actuator to transform the cooled water in the tank into a cold mist located behind the PV module, using the cavitation phenomenon. This process facilitates heat transfer and conductivity, thereby reducing the temperature of the PV module surface. The temperature contrast between the PV module surface and the cold mist generates surplus electricity via a TEG. Three different cold mist production capacities (250, 400, and 550 mL/h) were examined, with the highest enhancement in solar energy utilization observed with a capacity of 550 mL/h. This capacity resulted in a PV section temperature decrease of approximately 5.2°C, a 5.1% increase in PV maximum power, and a total efficiency improvement of 4.96% compared to the control PV module.

Nurul Syakirah Nazri et al. [51]examined the hybrid photovoltaic–thermal–thermal (PVT-TEG) system's performance and found significant improvements over conventional photovoltaic–thermal (PVT) systems. Experiments demonstrated that the PVT-TEG system theoretically increased overall efficiency by 7.05% to 31.13% and experimentally by 9.64% to 34.83%. The thermal efficiency of the PVT-TEG system ranged from 21.19% to 57.08%, while its electrical efficiency increased to 14.19%. Integrating thermoelectric modules and air collectors enhanced energy conversion efficiency, reducing the temperature of PV panels and optimizing system performance.

M. Gopinath and R. Marimuthu et al. [52] This study investigated graphite sheets and heat sinks in Photovoltaic-Thermoelectric Generator (PV-TEG) systems. Under 823 W/m^2 of solar irradiation, the PV-TEG system without heat dissipation converted the heat from the PV backside into a TEG DC voltage of 0.727 V. With the addition of a graphite sheet, the generated voltage increased to 0.889 V. In contrast, using a heat sink resulted in a voltage of 1.476 V. The graphite sheet boosted the TEG voltage by 0.241 V, resulting in a 0.75 times increase in DC voltage compared to the standalone TEG, with a temperature difference of 3.92°C from the hot end to the cold end so that the heat sink became bigger than the 5.96°C hot end to the cool end of the TEG device. The heat sink system increased the TEG voltage by 0.749 V, thus providing a DC voltage gain of 1.78 times over the standalone TEG and enlarging the temperature difference to 5.96°C.

Seepana Praveenkumar et al. [53] performed a thermo-environmental-economic analysis of a hybrid photovoltaic (PVT)/thermoelectric generator (TEG) system and compared it with PV and PVT-water systems. Compared with the conventional PV panel, when it used PVT/Water and PVT/TEG/nanofluid systems to cool the panels, its results showed a reduction of temperatures at 25.1% and 41.2%, temperature drop, respectively, in addition to the electrical efficiencies increase by about (5.8%) and (8.5%). The PVT/TEG/nanofluid system achieved LCOE $0.051-$0.178/kWh, EPBT = 3.36 years, and CO2 mitigation of about 2 ton/year Anthropophysioeconomic parameter which reflects the diminution in GHGs emitted due to photovoltaic module If imaginary water released during a phase change is considered as real nanofluids from chemical forces where negative energy renders a repulsive outcome in form of carbon credit ($51Similar kind on yearly basis). While more equipment expenses were involved, the LCOE and EPBT of the PVT/TEG/nanofluid method seemed to be high.

M. Gopinath and R. Marimuthu [54] This study suggested an approach that improved the efficiency of current photovoltaic (PV) panels by embedding a thermoelectric generator (TEG) on their back sides. In other words, sunlight exposure on PV panels heated their backs, which not only stripped a significant amount of temperature from any electrical production capacity at that DC level to the grid conversion stage but also sometimes required expensive cooling systems. They required an easier, more affordable solution with simple installation requirements. The thermoelectric generator offered a simple solution to harness wasted heat to minimize power consumption while providing high reliability and fast start-up. The output of the graphite-based PV-TEG system was enhanced; when a graphite sheet served as a heat dissipator, it reached a maximum voltage of 13.515 V and outputted maximum power at approximately 5 W. Moreover, the temperature difference in °C between the graphite sheet and the PV panel back was found to peak at 6.682°C.

5. Conclusion

This comprehensive review highlights the potential and challenges of integrating thermoelectric generators (TEGs) with photovoltaic (PV) systems to enhance solar energy utilization. Hybrid PV-TEG systems offer a promising approach to improving energy conversion efficiency by utilizing the waste heat generated in PV modules. However, several factors, including the complexity of system integration, cost implications, and dependency on environmental conditions, play critical roles in the overall performance of these systems.

Advanced cooling techniques have significantly enhanced hybrid systems' efficiency, such as using phase change materials (PCMs), nanofluids, and optimized thermal interface materials (TIMs). Nonetheless, the added thermal resistance introduced by TEGs can sometimes offset the benefits, particularly in environments with less than optimal solar intensity. The review also emphasizes the need for further research into the material science aspects of TEGs and PVs and the necessity for robust mathematical models that can accurately predict real-world performance.

In conclusion, while integrating TEGs with PV systems holds considerable promise for enhancing solar energy harvesting, its widespread adoption is contingent upon overcoming technical and economic barriers. Future research should optimize the design and configuration of PV-TEG systems, particularly in the context of varying environmental conditions, to maximize their practical application and commercial viability.

The survey imposes the following remarks:

5.1. Limitations

1-Ali Salari et al.'s [24] study supports the point that the performance of PV-TEG systems is highly dependent on environmental conditions. Their research showed that variations in solar radiation and ambient temperature significantly affect the efficiency of these systems. Specifically, while higher solar radiation improved the system's efficiency, increased ambient temperatures could decrease it.

2- H.R. Fallah Kohan et al. show that the presence of TEGs can prevent the PV module from cooling properly, resulting in decreased efficiency of the PV cells. The study supports this, showing that degradation often outweighs the potential gains from the TEG, making the combined system less effective than a standalone PV system in certain configurations. [22] They found that integrating TEGs into PV systems typically increased the temperature of the PV cells, reducing their efficiency. Only in very specific conditions did the combined system show marginal improvements, with most configurations resulting in little to no net gain in overall system performance

3- Ruzaimi et al. [48] which analyzed the performance of a hybrid PV-TEG system under non-uniform heat conditions. The study found that the power produced by the TEG was significantly reduced by about 33% due to the non-uniform distribution of heat across the modules. This highlights the importance of managing temperature differences effectively to optimize the performance of PV-TEG systems.

4- H.R. Fallah Kohan et al. [22] investigates the performance of hybrid PV-TEG systems. It highlights that while these systems can potentially achieve higher power output under certain environmental conditions, they often face a significant challenge: the temperature difference across the TEG is typically minimal. This limited temperature difference reduces the TEG's efficiency, making it less effective at generating power.

5-Dario Narducci and Bruno Lorenzi [34]although hybrid thermoelectric-photovoltaic (HTEPV) systems can improve solar power conversion, the high costs associated with these systems often make them economically unfeasible.

5.2. Assess PV-TEG system performance and efficiency under different solar concentrations, cooling methods, and materials.

Research on solar concentration ratios, cooling methods, and materials in PV-TEG systems reveals significant findings. Dianhong Li et al. observed that higher concentration ratios notably enhance system efficiency, with a CIGS-TE hybrid system achieving a 21.6% output electric power efficiency at a concentration ratio 200, marking a 4.1% increase [18]. Abhishek Tiwari and Shruti Aggarwal compared two CPV-TEG systems. The GHP-LFPV/T-TEG system exhibited a 10.23% higher thermal efficiency than LFP after seven hours of operation under 800 W/m^2 solar irradiation [28]. Regarding cooling methods, Ershuai Yin et al. highlighted water cooling as the most effective, significantly boosting overall system efficiency [19]. At the same time, Selcuk Bulat et al. demonstrated that active cooling using nanofluids could increase power output by up to 9.45% compared to systems without cooling [43]. Regarding materials, R. Bjørk and K.K. Nielsen found that crystalline Si, CIGS, and CdTe cells produced lower power and efficiency than standalone PV due to the TEG's low efficiency. However, amorphous Si (a-Si) slightly improved [14]. Koushik S et al. also reported efficiency gains of 10.74% for monocrystalline cells and 20.79% for multifunction cells in PV-TEG hybrid systems [21].

5.3. Assess the impact of PCM, cooling methods, and advanced thermoelectric materials on PV-TEG system performance and reliability in real-world applications.

Phase Change Materials (PCM) have proven to be effective in enhancing the efficiency of PV-TE systems. Tengfei Cui et al. [17] designed a novel concentrating PV-TE system incorporating PCM, which maintained a constant temperature and improved the system's daily total efficiency to 26.57%, compared to 25.55% for a single PV system. Similarly, J. Darkwa et al. [46] found that integrating PCMs with PV cells improved power output and efficiency, especially under high solar radiation, with a 9.5% higher power output than standard PV systems. Regarding cooling techniques, M. Gopinath and R. Marimuthu [52] demonstrated that using graphite sheets and heat sinks in PV-TEG systems significantly increased the TEG voltage, enhancing heat dissipation and system efficiency. Ershuai Yin et al. [19] further confirmed that water cooling is particularly effective in boosting PV-TE system efficiency. In addition, Muhammad Ahsan Iqbal Khan et al. [32]

highlighted the benefits of advanced thermoelectric materials, reporting that their use in PV-TEG systems led to a temperature reduction of the PV module, resulting in a 19% increase in output power and a 17% increase in efficiency. This is illogical, as the legs of thermoelectric generators are made of semiconductive material, which adds thermal resistance to the solar panels=

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Conflicts of Interest

The authors declare no conflict of interest.

References

[1] T. T. Chow, “A review on photovoltaic/thermal hybrid solar technology,” *Appl. Energy*, vol. 87, no. 2, pp. 365–379, 2010, doi: 10.1016/j.apenergy.2009.06.037.

[2] P. M. Rodrigo, A. Valera, E. F. Fernández, and F. M. Almonacid, “Performance and economic limits of passively cooled hybrid thermoelectric generator-concentrator photovoltaic modules,” *Appl. Energy*, vol. 238, no. October 2018, pp. 1150–1162, 2019, doi: 10.1016/j.apenergy.2019.01.132.

[3] M. H. Ahmadi *et al.*, “Renewable energy harvesting with the application of nanotechnology: A review,” *Int. J. Energy Res.*, vol. 43, no. 4, pp. 1387–1410, 2019, doi: 10.1002/er.4282.

[4] A. Z. Sahin, K. G. Ismaila, B. S. Yilbas, and A. Al-Sharafi, “A review on the performance of photovoltaic/thermoelectric hybrid generators,” *Int. J. Energy Res.*, vol. 44, no. 5, pp. 3365–3394, 2020, doi: 10.1002/er.5139.

[5] E. Yin, Q. Li, and Y. Xuan, “Feasibility analysis of a concentrating photovoltaic-thermoelectric-thermal cogeneration,” *Appl. Energy*, vol. 236, no. September 2018, pp. 560–573, 2019, doi: 10.1016/j.apenergy.2018.12.019.

[6] S. Jena and S. K. Kar, “Demonstrating the benefits of thermoelectric-coupled solar PV system in microgrid challenging conventional integration issues of renewable resources,” *Int. J. Energy Res.*, vol. 44, no. 2, pp. 950–976, 2020, doi: 10.1002/er.4953.

[7] S. Jena and S. K. Kar, “Employment of solar photovoltaic-thermoelectric generator-based hybrid system for efficient operation of hybrid nonconventional distribution generator,” *Int. J. Energy Res.*, vol. 44, no. 1, pp. 109–127, 2020, doi: 10.1002/er.4823.

[8] X. Lu, X. Yu, Q. Wang, Y. Chen, and T. Ma, “Numerical study on nonuniform segmented enhancement method for thermoelectric power generator,” *Numer. Heat Transf. Part A Appl.*, vol. 76, no. 8, pp. 605–627, 2019, doi: 10.1080/10407782.2019.1644909.

[9] M. Teymori-Omran, A. Motevali, S. Reza Mousavi Seyedi, and M. Montazeri, “Numerical simulation and experimental validation of a photovoltaic/thermal system: Performance comparison inside and outside the greenhouse,” *Sustain. Energy Technol. Assessments*, vol. 46, no. May, p. 101271, 2021, doi: 10.1016/j.seta.2021.101271.

[10] W. He, G. Zhang, X. Zhang, J. Ji, G. Li, and X. Zhao, “Recent development and application of thermoelectric generator and cooler,” *Appl. Energy*, vol. 143, pp. 1–25, 2015, doi: 10.1016/j.apenergy.2014.12.075.

[11] H. S. Yousif and S. M. JALIL, “Optimum Load of the Non-Uniform Heat Flux on Thermoelectric Generator (TEG) with Plate-Pin Heat Sink,” *Salud, Cienc. y Tecnol. - Ser. Conf.*, vol. 3, p. 829, 2024, doi: 10.56294/sctconf2024829.

[12] H. R. Fallah Kohan, M. Eslami, and K. Jafarpur, “A hybrid analytical-computational method for three-dimensional modeling of thermoelectric generators,” Int. J. Energy Res., vol. 45, no. 2, pp. 2680–2693, 2021, doi: 10.1002/er.5960.

[13] S. Singh, O. I. Ibeagwu, and R. Lamba, “Thermodynamic evaluation of irreversibility and optimum performance of a concentrated PV-TEG cogenerated hybrid system," *Sol. Energy*, vol. 170, no. June, pp. 896–905, 2018, doi: 10.1016/j.solener.2018.06.034.

[14] R. Bjørk and K. K. Nielsen, "The performance of a combined solar photovoltaic (PV) and thermoelectric generator (TEG) system," *Sol. Energy*, vol. 120, pp. 187–194, 2015, doi: 10.1016/j.solener.2015.07.035.

[15] R. Lamba and S. C. Kaushik, "Modeling and performance analysis of a concentrated photovoltaic-thermoelectric hybrid power generation system," *Energy Convers. Manag.*, vol. 115, pp. 288–298, 2016, doi: 10.1016/j.enconman.2016.02.061.

[16] H. Hashim, J. J. Bomphrey, and G. Min, "Model for geometry optimization of thermoelectric devices in a hybrid PV/TE system," *Renew. Energy*, vol. 87, pp. 458–463, 2016, doi: 10.1016/j.renene.2015.10.029.

[17] T. Cui, Y. Xuan, and Q. Li, "Design of a novel concentrating photovoltaic-thermoelectric system incorporated with phase change materials," *Energy Convers. Manag.*, vol. 112, pp. 49–60, 2016, doi: 10.1016/j.enconman.2016.01.008.

[18] D. Li, Y. Xuan, Q. Li, and H. Hong, "Exergy and energy analysis of photovoltaic-thermoelectric hybrid systems," *Energy*, vol. 126, pp. 343–351, 2017, doi: 10.1016/j.energy.2017.03.042.

[19] E. Yin, Q. Li, and Y. Xuan, "Thermal resistance analysis and optimization of the photovoltaic-thermoelectric hybrid system," *Energy Convers. Manag.*, vol. 143, pp. 188–202, 2017, doi: 10.1016/j.enconman.2017.04.004.

[20] J. Zhang and Y. Xuan, "Performance improvement of a photovoltaic - Thermoelectric hybrid system subjecting to fluctuant solar radiation," *Renew. Energy*, vol. 113, pp. 1551–1558, 2017, doi: 10.1016/j.renene.2017.07.003.

[21] S. Koushik, S. Das, V. Sharma, P. Walde, and N. Maji, "PV and TEG Hybrid Power Generation for Enhancement of Efficiency," *India Int. Conf. Power Electron. IICPE*, vol. 2018-Decem, pp. 1–6, 2018, doi: 10.1109/IICPE.2018.8709422.

[22] H. R. Fallah Kohan, F. Lotfipour, and M. Eslami, "Numerical simulation of a photovoltaic thermoelectric hybrid power generation system," *Sol. Energy*, vol. 174, no. September, pp. 537–548, 2018, doi: 10.1016/j.solener.2018.09.046.

[23] B. Kılkış, "Development of a composite PVT panel with PCM embodiment, TEG modules, flat-plate solar collector, and thermally pulsing heat pipes," *Sol. Energy*, vol. 200, no. October, pp. 89–107, 2020, doi 10.1016/j.solener.2019.10.075.

[24] A. Salari, A. Parcheforosh, A. Hakkaki-Fard, and A. Amadeh, "A numerical study on a photovoltaic thermal system integrated with a thermoelectric generator module," *Renew. Energy*, vol. 153, pp. 1261–1271, 2020, doi: 10.1016/j.renene.2020.02.018.

[25] A. Lekbir, S. Hassani, S. Mekhilef, R. Saidur, M. R. Ab Ghani, and C. K. Gan, "Energy performance investigation of nanofluid-based concentrated photovoltaic / thermal-thermoelectric generator hybrid system," *Int. J. Energy Res.*, vol. 45, no. 6, pp. 9039–9057, 2021, doi: 10.1002/er.6436.

[26] Z. Song, J. Ji, J. Cai, Z. Li, and Y. Gao, "Performance prediction on a novel solar assisted heat pump with hybrid Fresnel PV plus TEG evaporator," *Energy Convers. Manag.*, vol. 210, no. September 2019, p. 112651, 2020, doi: 10.1016/j.enconman.2020.112651.

[27] X. Wen, J. Ji, Z. Song, Z. Li, H. Xie, and J. Wang, "Comparison analysis of two different concentrated photovoltaic/thermal-TEG hybrid systems," *Energy Convers. Manag.*, vol. 234, no. February, p. 113940, 2021, doi: 10.1016/j.enconman.2021.113940.

[28] A. Tiwari and S. Aggarwal, "Thermal modeling, performance analysis and exergy study of a concentrated semi-transparent photovoltaic-thermoelectric generator (CSPV-TEG) hybrid power generation system," *Int. J. Sustain. Energy*, vol. 40, no. 10, pp. 947–976, 2021, doi: 10.1080/14786451.2021.1887187.

[29] M. Naderi, B. M. Ziapour, and M. Y. Gendeshmin, "Improvement of photocells by the integration of phase change materials and thermoelectric generators (PV-PCM-TEG) and study on the ability to generate electricity around the clock," *J. Energy Storage*, vol. 36, no. February, p. 102384, 2021, doi: 10.1016/j.est.2021.102384.

[30] J. Ko and J. W. Jeong, "Annual performance evaluation of thermoelectric generator-assisted building-integrated photovoltaic system with phase change material," *Renew. Sustain. Energy Rev.*, vol. 145, no. April, p. 111085, 2021, doi: 10.1016/j.rser.2021.111085.

[31] Á. Valera, P. M. Rodrigo, F. Almonacid, and E. F. Fernández, "Efficiency improvement of passively cooled micro-scale hybrid CPV-TEG systems at ultra-high concentration levels," *Energy Convers. Manag.*, vol. 244, 2021, doi: 10.1016/j.enconman.2021.114521.

[32] M. A. I. Khan *et al.*, "An Experimental and Comparative Performance Evaluation of a Hybrid Photovoltaic-Thermoelectric System," *Front. Energy Res.*, vol. 9, no. September, pp. 1–9, 2021, doi: 10.3389/fenrg.2021.722514.

[33] B. Lorenzi, "Hybrid thermoelectric-photovoltaic generators under negative illumination conditions," *ACS Appl. Energy Mater.*, vol. 5, no. 5, pp. 5381–5387, 2022, doi: 10.1021/acsaem.1c02710.

[34] D. Narducci and B. Lorenzi, "Economic Convenience of Hybrid Thermoelectric-Photovoltaic Solar Harvesters," *ACS Appl. Energy Mater.*, vol. 4, no. 4, pp. 4029–4037, 2021, doi: 10.1021/acsaem.1c00394.

[35] N. S. Nazri *et al.*, "Analytical and experimental study of hybrid photovoltaic–thermal–thermoelectric systems in sustainable energy generation," *Case Stud. Therm. Eng.*, vol. 51, no. September, p. 103522, 2023, doi: 10.1016/j.csite.2023.103522.

[36] M. Sheikholeslami and Z. Khalili, "Investigation of a solar photovoltaic-thermoelectric system for building unit in presence of helical tapes and jet impingement of hybrid nanomaterial," *J. Build. Eng.*, vol. 74, no. May, p. 106871, 2023, doi: 10.1016/j.jobe.2023.106871.

[37] H. R. Fallah Kohan, M. Eslami, and K. Jafarpur, "Thermal influence of thermoelectric modules on the performance of hybrid PV-TEG systems: Effects of TEG type, arrangement and working condition," *Int. Commun. Heat Mass Transf.*, vol. 147, 2023, doi: 10.1016/j.icheatmasstransfer.2023.106969.

[38] . Almarashi *et al.*, "Photovoltaic thermal solar system in presence of nanofluid cooling analyzing environmental parameter in the existence of TEG module," *J. Therm. Anal. Calorim.*, vol. 149, no. 6, pp. 2739–2747, 2024, doi: 10.1007/s10973-023-12827-5.

[39] E. Azizi, Z. Khalili, and M. Sheikholeslami, "Simulation of solar photovoltaic system integrated with TEG in presence of hybrid nanomaterial," *J. Therm. Anal. Calorim.*, no. 0123456789, 2024, doi: 10.1007/s10973-024-13192-7.

[40] A. A. Melaibari, N. H. Abu-Hamdeh, A. S. Alorfi, H. A. Z. AL-bonsrulah, and A. M. A. Elsiddieg, "New design for PVT system with elliptic cooling duct involving nanofluid in existence of MHD and utilizing TEG," *Case Stud. Therm. Eng.*, vol. 53, no. October 2023, p. 103815, 2024, doi: 10.1016/j.csite.2023.103815.

[41] A. Almarashi *et al.*, "Effect of loading Fe3O4 nanoparticles on the electrical performance of solar panel utilizing numerical modeling," *Case Stud. Therm. Eng.*, vol. 55, no. February, p. 104165, 2024, doi 10.1016/j.csite.2024.104165.

[42] E. Azizi, Z. Khalili, and M. Sheikholeslami, "Simulation of the integration of PVT and TEG with a cooling duct filled with nanofluid," *Case Stud. Therm. Eng.*, vol. 59, no. February, p. 104504, 2024, doi 10.1016/j.csite.2024.104504.

[43] S. Bulat, E. Büyükbicakci, and M. Erkovan, "Efficiency Enhancement in Photovoltaic–Thermoelectric Hybrid Systems through Cooling Strategies," *Energies*, vol. 17, no. 2, 2024, doi: 10.3390/en17020430.

[44] M. Sheikholeslami and Z. Khalili, "Energy management of a concentrated photovoltaic–thermal unit utilizing nanofluid jet impingement in the existence of thermoelectric module," *Eng. Appl. Comput. Fluid Mech.*, vol. 18, no. 1, 2024, doi: 10.1080/19942060.2023.2297044.

[45] A. M. Alajlan, S. Dang, and Q. Gan, "Enhanced nighttime power generation and photovoltaic cooling in photovoltaic-thermoelectric hybrid systems," *Energy Convers. Manag. X*, vol. 22, no. March, p. 100580, 2024, doi: 10.1016/j.ecmx.2024.100580.

[46] J. Darkwa, J. Calautit, D. Du, and G. Kokogianakis, "A numerical and experimental analysis of an integrated TEG-PCM power enhancement system for photovoltaic cells," *Appl. Energy*, vol. 248, no. January, pp. 688–701, 2019, doi: 10.1016/j.apenergy.2019.04.147.

[47] E. Yin, Q. Li, and Y. Xuan, "Feasibility analysis of a tandem photovoltaic-thermoelectric hybrid system under solar concentration," *Renew. Energy*, vol. 162, pp. 1828–1841, 2020, doi: 10.1016/j.renene.2020.10.006.

[48] A. Ruzaimi *et al.*, "Performance analysis of thermoelectric generator implemented on non-uniform heat distribution of photovoltaic module," *Energy Reports*, vol. 7, pp. 2379–2387, 2021, doi: 10.1016/j.egyr.2021.04.029.

[49] G. Kidegho, F. Njoka, C. Muriithi, and R. Kinyua, "Evaluation of thermal interface materials in mediating PV cell temperature mismatch in PV–TEG power generation," *Energy Reports*, vol. 7, pp. 1636–1650, 2021, doi: 10.1016/j.egyr.2021.03.015.

[50] Z. Gholami, M. H. Rahmati, A. Arabhosseini, and M. Gharzi, "Combined cooling of photovoltaic module integrated with thermoelectric generators, by using earthenware water tank and ultrasonic humidifier: An experimental study," *Sustain. Energy Technol. Assessments*, vol. 53, no. October 2022, doi: 10.1016/j.seta.2022.102601.

[51] N. S. Nazri *et al.*, "Analytical and experimental study of hybrid photovoltaic–thermal–thermoelectric systems in sustainable energy generation," *Case Stud. Therm. Eng.*, vol. 51, no. September, p. 103522, 2023, doi: 10.1016/j.csite.2023.103522.

[52] M. Gopinath and R. Marimuthu, "PV-TEG output: Comparison with heat sink and graphite sheet as heat dissipators," *Case Stud. Therm. Eng.*, vol. 45, no. March, p. 102935, 2023, doi: 10.1016/j.csite.2023.102935.

[53] S. Praveenkumar, E. B. Agyekum, A. Kumar, and V. I. Velkin, "Thermo-enviro-economic analysis of solar photovoltaic/thermal system incorporated with u-shaped grid copper pipe, thermal electric generators, and nanofluids: An experimental investigation," *J. Energy Storage*, vol. 60, no. September 2022, p. 106611, 2023, doi: 10.1016/j.est.2023.106611.

[54] M. Gopinath and R. Marimuthu, "Experimental study of photovoltaic-thermoelectric generator with graphite sheet," *Case Stud. Therm. Eng.*, vol. 54, no. December 2023, p. 103982, 2024, doi: 10.1016/j.csite.2024.103982.