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REVIEW

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Implementation Approaches of Thermoelectric Generator in Photovoltaic System: A Review

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Abstract: Solar energy is one of the viable solutions for global energy demand. To compete with traditional resources, solar cells have to be reliable and cost-effective. This paper reviews the basics of thermoelectric generators (TEGs), including their working principles and main physical properties. TEGs transform heat directly to electricity based on the Seebeck effect, which generates an electric voltage based on the difference in temperature of a material. It presents methods for energy harvesting by using TEGs integrated with photovoltaic (PV) systems and discusses the application and findings of this hybrid model. By converting solar system waste heat or primary heat flow into additional heating, cooling, and electricity, TEGs enhance PV system efficiency. This paper reviews the methods and effects of integrating thermoelectric devices with PV systems, summarizing key findings from previous studies. The paper concludes that the integration of TEGs significantly improves the functionality and efficiency of PV systems, as evidenced by previous studies.

Keywords: thermoelectric generators, thermoelectric materials, waste heat, hybrid PV/TEG

1. Introduction

Nowadays, the global energy system is transitioning from methods that are traditional and those that are based on fossil fuels [1] to those primarily powered by sources of renewable energy [2, 3]. As the world's population increases, traditional fossil energy sources have struggled to meet the rising demand, leading to a rise in global temperatures due to carbon dioxide emissions [4, 5]. Researchers across the globe have been concentrating more on sustainable solutions to solve the environmental issues brought about by large-scale fossil fuel utilization [6]. Additionally, solar photovoltaic (PV) systems are employed to provide clean electricity globally [7, 8].

Of all the renewable sources that are currently known [9, 10], solar is important because of the unlimited supply of the source of energy and recent significant technoeconomic developments in power generation technologies [11, 12]. Solar systems, in particular, could be highly efficient for supplying renewable energy in climate regions with high solar radiation potential throughout the year, such as hot and dry areas [13, 14]. Solar energy is a viable option for producing electricity through the use of PV modules [15–19], and for generating hot air through solar air heaters [20, 21]. It is also employed in solar air dryers for drying vegetables as well as other agricultural/horticultural products [22, 23]. Additionally, solar-powered desalination units provide drinking water [24–26], and solar cookers are used for cooking [24], Furthermore, since the oil crisis of the late 1970s, the consumption of solar energy, a renewable source of energy, for beneficial purposes has gradually increased. This has led researchers and decision-makers worldwide to focus on new methods to exploit solar energy more adequately and proficiently, especially in solar energy applications. Solar energy is used in two main ways on Earth: solar thermal systems that use collectors, heaters, and dryers and solar electricity systems that utilize solar PV technology [27–30].

Studies were selected based on publication date (2015–2025), relevance to hybrid PV/thermoelectric generator (TEG) systems, and focus on experimental or simulation-based results. Several research studies have been conducted, and continue to be undertaken, to enhance the efficiency of the aforementioned systems in various ways [31, 32]. Phase change materials (PCM) are one of these techniques; for example, PCMs also enhanced by nanotechnology [33–35], thermoelectric cooling [36, 37], thermoelectric generating [38, 39], coatings with nanotechnology [40], nanofluids [41], solar collector, and electrical heaters [42, 43]. The methods used are primarily determined by the solar system's specific design. PCMs are included in PV modules to improve the temperature of the module's outlet. Nanofluids are utilized in thermal or PVT

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collectors to increase the rate of heat transfer [44–46], or TEGs might be utilized to generate both heat and cold from PV or desalination units [47].

In contrast to the thermoelectric systems that were explained above, which use power to provide heating and cooling on both surfaces of the module (the Peltier effect), there is an alternative technique for utilizing thermoelectric modules that uses the difference in temperature between two heat sources to produce electrical power (Seebeck effect) [48]. This device is called a thermoelectric generator (TEG). An electricity flow could be produced by linking a hot source to one of the surfaces of the thermoelectric module and a cold source to the other one, both of which might be air, water, or something else. Montero et al. [49] investigated the impact of employing PCM to increase the rate of the generation of power of a solar thermoelectric generator (STEG). The STEG hot side was heated using solar radiation and an optical concentrator, while the cold surface's heat sink was a PCM. They demonstrated how the PCM increased the STE's power-producing rate by 0.6% at night. By using hot air and cool water to increase the difference in temperature between the two surfaces of the TEG. Luo et al. [50] improved the efficiency of a TEG. They demonstrated that, in comparison to the traditional ones, the modified TEG's electricity production increased by 5.9%.

Furthermore, Escobar et al. [51] enhanced the performance of the proposed system by employing an STEG hybrid system that collects the sun's rays via a thermosiphon while also producing electricity. While 0.118 kW was passed via the cartridge heater, their results indicated an output power of up to 96 MW and the rate of recovery of heat up to 0.06818 kW. Yakut et al. [52] used a connected six TEGs aimed at increasing the current and voltage. The experimental setup connected six TEGs in series and parallel and implemented a heat exchanger for proper cooling. The setup generated a maximum of 7.52 V and a solar irradiance value of 66 W/m^2. This resulted in a maximum output power of 5.236 W. He et al. [53] suggested and tested methods of restoring excessive heat from a diesel-powered engine using a TEG system for power generation. According to their findings, the efficiency of the electricity generation in this system can range from 1.41% to 4.12%. Furthermore, the Peltier and Seebeck effects have been repeatedly reported as acceptable strategies to increase the efficiency of PV modules of various concepts. In most situations, a PV system's efficiency is improved by employing cooling and heating techniques in thermoelectric modules to benefit from the Peltier effect or producing power by regaining the solar system's heat waste via the Seebeck effect [54].

Nonetheless, some recent review papers on the application of TE modules on various energy systems such as solar energy systems have been released, for example, one concentrating on the development of solar desalination systems using TE devices [55], TEG that generates electricity from solar ponds [56], TEGs that are used to generate electricity in solar thermal systems [57, 58], energy harvesting applications using TEG [39, 59], zero-energy buildings that require thermoelectric cooling [60], and hybrid systems [61, 62]. A system that combines PV cells and TEG to yield PV-TEG hybrid systems exhibits improved capabilities in transferring heat. Extensive experimental studies were conducted, and the results show that the hybrid configuration improves the amount of electricity produced by the PV cell. This is achieved by effectively regulating the heat in the device using a thermal lubricant [63]. Figure 1 [63] could include a brief description of the working principle and components of a PV-TEG system.

In addition, by integrating a solar cell with TEG to improve energy conversion efficiency, the temperature at which the solar panels operate can be reduced, and the power output increased. This is achieved by using the heat that would otherwise be wasted by the solar panels to generate power for the TEGs [64]. This technique boosts the total energy output and improves the sustainability of the system by making use of heat that was previously wasted. Nevertheless, there is a lack of a complete assessment of TE heating, cooling, and generators of electricity on a wide range of solar power systems, for example, PV panels, solar-powered desalination units, and solar water heaters. The proposed study seeks to address an empty space in the literature by presenting a comprehensive article to review in this area and imagining upcoming prospective works integrating many thermoelectric module solar energy systems. Figure 2 illustrates a classification of several PV systems that are integrated with TE cooling, heating, and power generators. PV systems with thermoelectric cooling, heating, and power generation mechanisms are categorized into two, namely: dynamic systems and static systems. Dynamic systems use moving components for the purpose of heat-to-energy conversion. The Stirling engine relies on gas compression and expansion, the thermoacoustic system utilizes sound waves from temperature gradients, the Brayton cycle compresses and expands gas in turbines, and the Rankine cycle generates energy via steam turbines in a closed loop. Static systems employ solid-state methods without moving parts. For thermoelectric systems, they convert temperature differences into electricity by the Seebeck effect. In thermionic systems, heat induces electron emission and, consequently, a current. However, in thermophotovoltaic systems, thermal radiation brings electricity through specially designed PV cells. Each of the sub-blocks represents one more way of converting heat into energy, fitted to some sort of operational requirement.

Integrating TEGs with PV systems has gained noteworthy attention due to their potential to enhance overall energy conversion efficiency by utilizing waste heat. Hybrid PV-TEG systems represent a very promising way to enhance renewable energy harvesting.

Figure 1
The hybrid PV/TEG system architecture, highlighting the integration of thermoelectric modules for enhanced efficiency

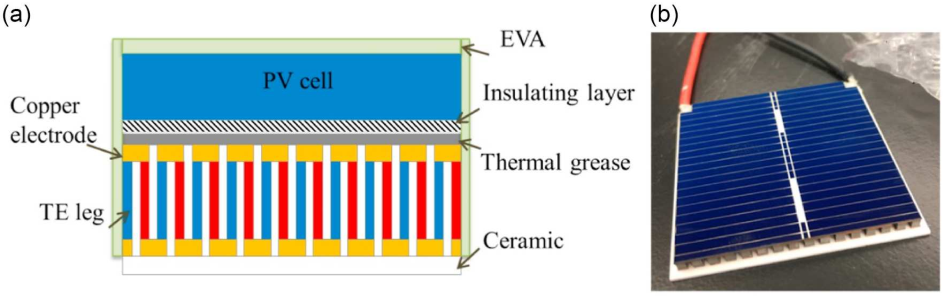
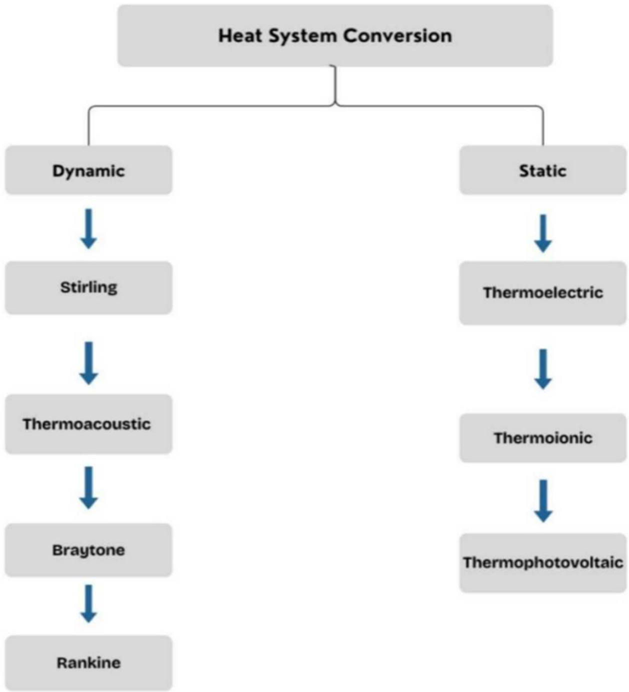


Figure 2
Classification of heat to electricity conversion system



Several problems remain unaddressed. Existing research lacks thorough optimization techniques that adapt dynamically to changing environmental conditions, especially in maximizing power management and energy efficiency. While giant leaps have been achieved in thermoelectric materials, high-performance nanostructured materials offering improvements in electrical conductivity and minimal thermal losses remain largely unexplored. Another critical challenge is heating dissipation and thermal management, where conventional cooling techniques tend to limit system performance and therefore remain under further investigation, particularly for PCM and nanofluids that could improve efficiency. However, while a lot of theoretical and simulation-based studies have been conducted, there is a serious lack of experimental validation and on-field implementation; hence, this has caused challenges in ascertaining the practical feasibility of Hybrid PV-TEG systems. This review aims to address these knowledge gaps through a critical analysis of the recent progress, challenges, and opportunities in PV-TEG integration, focusing on material innovations, thermal management strategies, and optimization techniques to improve overall system efficiency.

2. Thermoelectric (TE)

In recent years, numerous research studies have been conducted on thermoelectricity. The study of thermoelectricity may be broadly categorized into three interrelated fields: The first field is material science, which focuses on developing novel materials that are thermoelectric, and engineering methods to enhance the nominal efficiency of current materials that are thermoelectric [65, 66]. The second is device-level design, which involves evaluating innovative methods to build and enhance devices that are thermoelectric in terms of the roles they can adapt to the least amount of degradation compared to their standard performance [67, 68]. Third, there is a level called system-level design, which mainly deals with implementations and methods to develop TEG systems while taking into account the demands and features of such applications [69–74].

As previously said, excellent evaluations have been done in every study field for TEG; nonetheless, it appears that there is a gap between the TEG uses and thermoelectric substances and the module designs. On the other hand, no review studies have provided a thorough picture of TEG. However, it is critical to gain a little knowledge about the kind of materials used, designing methods, and the procedures for the design to be able to evaluate and ascertain the viability of utilizing TEG in related fields, as well as fully comprehend the procedures in which TE methods may advance. Basically, the first and second parts of this paper provide a quick but comprehensive overview of the conceptual foundation, improvements in TE substances, and also their essential properties.

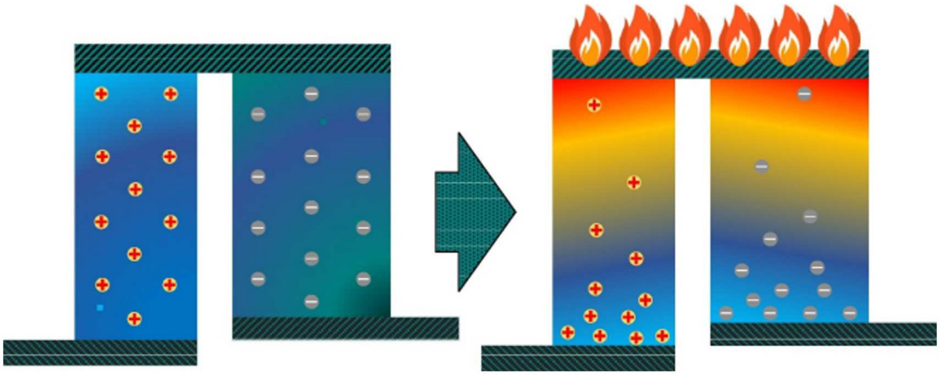
Following the establishment of this foundation, the major body of this paper provides a thorough examination of TEG's most popular uses. The abilities and limitations of the uses are concisely mentioned at each section's start, followed by an explanation of the benefits, problems, and overall practicality of using TEGs in these applications. In general, the current analysis offers a complete identification of TEG in the framework of modern power fields and attempts to convey a concise and accurate picture of TEG features and uses.

A straightforward conversion of the difference in temperature between two different substances into power is known as the thermoelectric (TE) phenomenon. The Seebeck effect was discovered by Thomas Seebeck in 1821. He demonstrated that if heating has been done to a junction of two different conductors, it can result in the generation of power. The Seebeck phenomenon is seen schematically in Figure 3 [75] in a thermoelectric uncouple; the modification of the free charge route distribution because of a thermal progression results in a voltage difference at the two ends of uncouple. The operation of a TEG is centered on the Seebeck effect, where a temperature differential between two sides of the generator leads to the generation of an electromotive force (EMF). Essentially, when heat is applied to one side, charge carriers move toward the colder side, creating a voltage difference that drives current around the external circuit, basically generating electricity from thermal energy. The process of energy conversion is very reliable, long-lasting, and flexible. The efficiency of a TEG is mainly attributed to the properties of the TE materials used. The Seebeck coefficient is a measure of the magnitude of the EMF developed per degree of difference in temperature; high electrical conductivity allows easy movement of charge carriers, while low thermal conductivity maintains the temperature difference. These properties collectively determine the efficiency of energy conversion, encapsulated by the dimensionless figure of merit, zT. As zT value increases, the performance and efficiency of TEGs increase.

Despite the potential of TEGs, there are practical problems. Materials that have a high Seebeck coefficient and balance high electrical conductivity with low thermal conductivity are not readily available. Proper heat flow management to maintain a significant temperature gradient is another critical challenge. Besides, there are critical obstacles when integrating TEGs into more complex systems and scaling up their production with regard to efficiency and cost. However, given these limitations in efficiency, TEGs stand out in applications where their unique properties are particularly advantageous, such as waste heat harnessing in industrial processes or power supply in remote or harsh environments. Under such conditions, their reliability and ability to utilize a free heat source make them priceless [76].

Thomson's study demonstrated that thermocouples can function as a heat engine, utilizing the Seebeck effect for energy

Figure 3
The contribution of different materials to the voltage difference caused by temperature differential



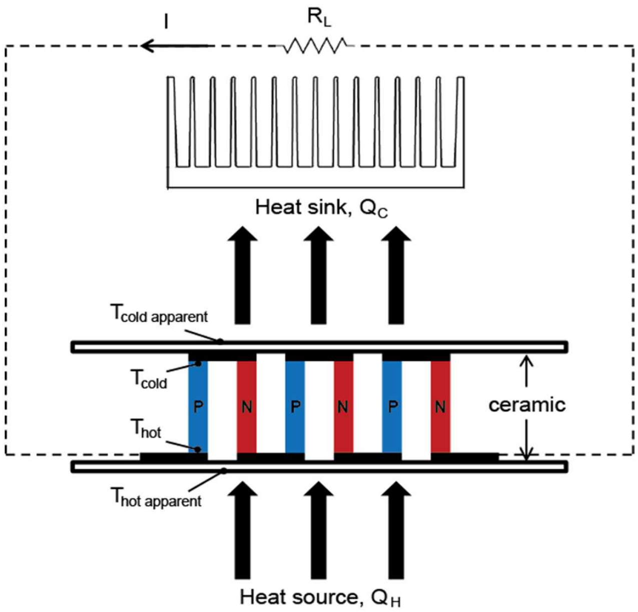
production from the difference in temperature or the Peltier phenomenon to produce a difference in temperature across both junctions. However, procedures like conduction of heat and Joule heating make thermocouples ineffective. Because of the dependency on thermoelectric materials' local temperature and transport characteristics, properly solving the mathematical equations regulating the processes in a TEG could be a difficult procedure [77]. As a result, several approximation approaches, such as numerical [78] and models that are analytically simplified [79], have been created to simulate the effectiveness of TEGs. TEG efficiency can be predicted with high precision using numerical algorithms, but this comes at the tradeoff of long processing periods and expensive computing costs. Analytical frameworks that use temp-averaged values for thermoelectric characteristics, on the other hand, can be useful for parametric investigation and development; but they can also not be accurate, particularly if the differences in temperature are high.

Catalan et al. [80] created a thorough mathematical system built on analogies that considered electrical for the transfer of heat and power, while also taking phase change exchangers for heat on the two surfaces of the TE modules into account. Qing et al. [81] explored the implementation of TEG being affected by varying factors of heat transfer on either side of a TEG using an analytical model. Various modeling methodologies may be used to simulate the effectiveness of TEGs, depending on the amount of accuracy and speed of analysis. Nevertheless, Tohidi et al. [75] reviewed several works on the subject to explore the concept and foundation of modeling a TEG. Figure 4 [82] shows the construction of a single pair of thermocouples used to generate energy. The typical thermocouple is made up of a semiconductor pair that yields (N-type) electrons excessively or a deficiency (P type) of electrons as a result of the heat flow. A thermocouple is placed between two ceramic plates that are highly effective thermal insulators and conductors of electricity. In practice, modular thermoelectric consists of multiple thermocouples coupled thermally in parallel and electrically in series. They may be utilized in this configuration between a source of heat and a sink to generate an appropriate voltage.

3. TE Materials

According to the efficiency relationship, a TEG's efficiency is exclusively determined by the zT value and the temperatures of the cold and hot connections. This indicates that one way to enhance the effectiveness of TEGs is to identify substances with qualities that contribute to a greater value of z or to alter current materials to increase the value of z (such as increasing thermal resistance as well as the conductivity of electricity).

Figure 4
How each thermocouple module is connected in series and parallel to generate electricity



Nonetheless, TEGs' great scalability might be a key quality to support their advancement. The article emphasizes the importance of developing novel TE substances and strategies to enhance the current ones. Despite the fact that it is not the major focus of this study, some data about the present status of material research on the topic of thermoelectricity may be useful. It is sufficient to show some significant developments related to this area.

Lee et al. [83] recently presented outstanding research. The research on tin selenide (SnSe) illustrates that by removing surface tin oxides, polycrystalline SnSe achieves near-single-crystal thermoelectric performance with a high zT value of around 2.5 at 773 K. The implication is great potential for high-efficiency thermoelectric modules for power generation from excess heat. However, the long-term stability and practical application of the results are uncertain. While it is promising in the laboratory, its cost, processability, and durability are in question. Synthesis via traditional techniques like ball milling and spark plasma sintering is relatively low-cost and scalable. Yet, the evaluation of the material's performance over time and under diverse environmental conditions is significant for practical use. In addition, addressing issues like surface oxidation and impurities will be significant for effective use in thermoelectric devices. Shi et al. [84] provided a thorough examination of advances that are related to TE materials and architectures and to the design of the device. Furthermore, some notable reviews on thermoelectric materials have recently been released, such as carbon allotrope hybrids [85], thermoelectric materials that are based on fibers [86], and thermoelectric materials and technologies that are flexible and portable [67].

Essentially, the topic of TE materials research is so extensive that addressing all of its various sections could be impractical, and not related to this review, and just repetitive. However, as stated before, a good knowledge about the thermoelectric materials and their development could be helpful for thermoelectric applications that also may assist to enhance the electric generation and power of PV systems.

4. Application

4.1. Hybrid PV/TEG systems

The combination of thermoelectric modules with PV panels shows a great advantage in getting rid of the heat waste from the PV panels in a useful way [87]. Due to this combination, the heat waste from solar panels is altered to an increase in electrical efficiency via thermoelectric modules. This highlights the beneficial impact of TEG integration, which improves the electrical efficiency of the PV module by reducing the panel surface's temperature.

4.1.1. Cooling applications

A study was conducted on coupling solar boards with a thermoelectric cooling system for developing more efficient energy systems by Liao et al. [88]. With solar irradiance of 200 W/m^2, they directly applied PV power to TE cooling. The impact of solar irradiance on the best performance and operating conditions is investigated to enhance the electrical and power efficiency. Their system results show that 13.9% was the energy efficiency of their study. Figure 5 [88] shows a schematic diagram of a PV-powered thermoelectric cooling system.

4.1.2. Power generation

A numerical study was done on a hybrid system that consists of a TEG and a concentrated photovoltaic (CPV) cell by Mahmoudinezhad et al. [89]. Both the TEG module and the CPV cell have a combined area of 1 cm × 1 cm. The TE elements in the TEG module have a sectional area of 0.04 m × 0.04 m. A heat exchanger is located beneath the TE modules to raise the variation between the hot and cold sides of the TEG while also keeping the cell's temperature below the critical operational temperature. Their outcomes demonstrated a direct correlation between the solar radiation fluctuations and the temperature of all components. In a study by Dimri et al. [90], an integrated PV/TEG system with an air duct was proposed to study how much the air duct and TEG will improve the overall electrical efficiency. Three experimental setups were tested: a PV panel with an air duct, a solar panel partially covered with a TEG, and a PV panel completely covered. The proposed system includes an opaque PV module combined with 36 TEG modules, each with a 4 cm × 4 cm area. They discovered that the solar modules' overall power efficiency that are completely covered outperforms solar panels that are partially covered by 4.46–6.23%. Figure 6 [90] illustrates the various PV panel cases using TEG.

Lekbir et al. [91] explored the effect of various cooling method configurations on PV module efficiency. TEG's hot surface is linked to the solar panel to utilize the panel's heat waste. The nanofluid acted as a coolant, absorbing temperature from the TEG module's backside, increasing its overall system performance. The PV panel had a surface area of 1 m^2 and a 0.0104 kg/s carbon nanotube-water nanofluid's mass flow rate as a cooling fluid. According to the findings, the solar panel and TEG's electrical efficiency while employing nanofluid was enhanced by 49.5% when compared to traditional PV systems. Dimri et al. [92] designed a three-layer feed-forward Artificial Neural Networks (ANN) model for a glass-Tedlar PV/T system with a TE module to study the total exergy and thermal energy gain. The ANN technique was applied to predict the system's thermal and electrical power generation. The PV module's waste heat is utilized by attaching the hot side of the TE module to the rear of the solar panel, and air cooling is used to lower the TE module's cold surface temperature. Their findings revealed that the daily thermal energy increased by 7.16% and the electrical energy increased by 6.03% of the system with the Tedlar cover when compared to the system with the glass cover. Throughout an experimental study by Rajaee et al. [93], the effectiveness of using the nanofluid and the improved PCM at the same time on the performance of the PV/TEG hybrid system was investigated. Under the PV module, the hot surface of the TE module was attached, and the cold surface of the TE module was linked to pipes made of copper.

Soltani et al. [94] used TEG and cooling methods to reduce the PV surface's temperature and to enhance its output of electricity and

Figure 5
The working process of a PV-powered thermoelectric cooling system

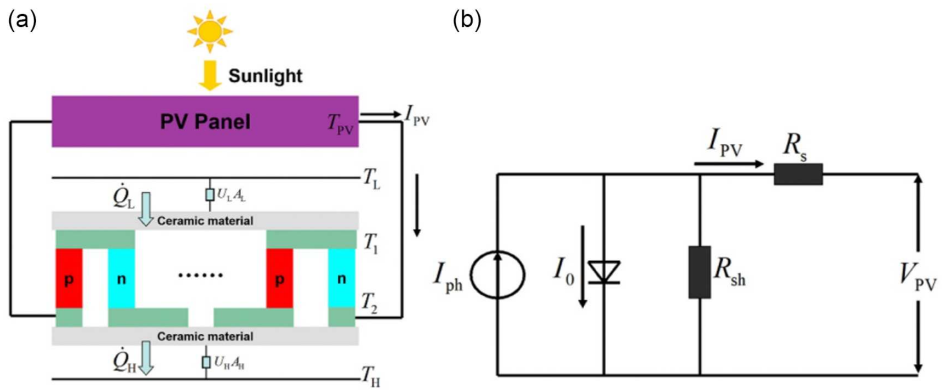
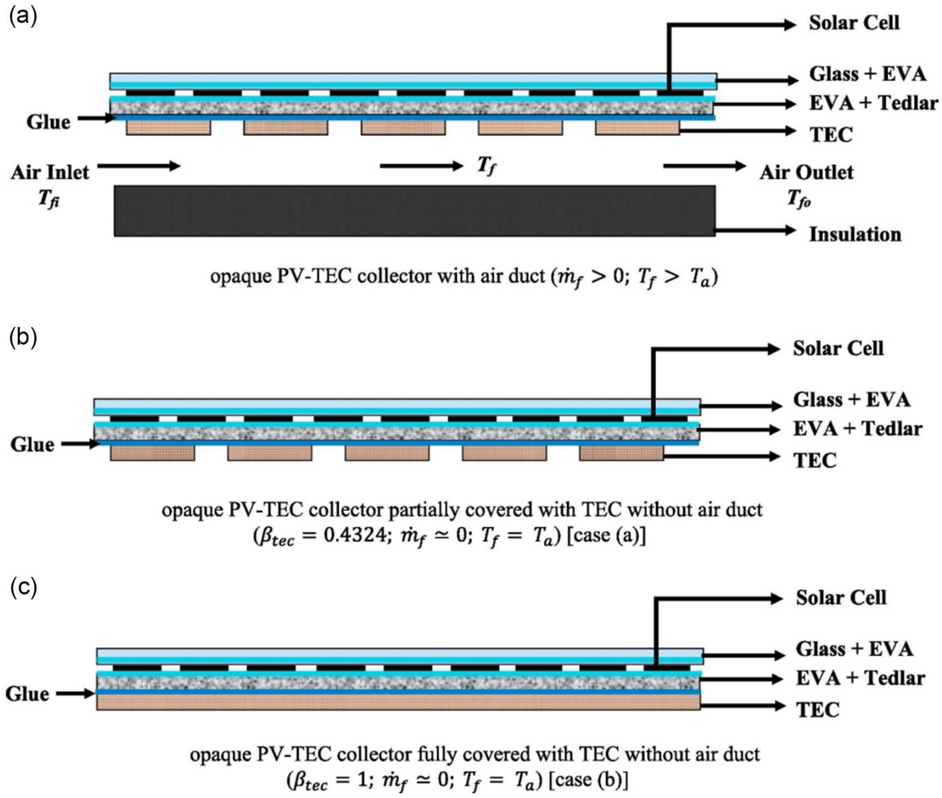


Figure 6
PV panel diagrams utilizing (a) an air duct and a TE module, (b) a thermoelectric module partially covered, and (c) a thermoelectric module completely covered



efficiency. The cooling method that was applied on the cold part of the TE module has a remarkable impact on system performance and on the output power. Experimental research on Fe_3O_4/water nanofluid cooling, forced air cooling, SiO_2/water nanofluid cooling, water cooling, and natural cooling demonstrated the promise of SiO_2/water nanofluid cooling, which produced the most power production that was 52.29%, and the highest efficiency was 3.35% as improvements, in contrast to the natural cooling. In a study that was done by Gürbüz et al. [95], the action of heat on the PV panel with a capacity of 40 W was stored in the PCM that was connected to the back surface for passive cooling. The heat that was saved in the PCM was transferred to the hot surface of the TEG via the fluid circulated in the copper pipes inside the PCM to accomplish active cooling. It was possible to implement the base hybrid system (PV/T-PCM-TEG) design (Case 1), which increases cell thermal stability. TEG uses 20 thermoelectric modules. Additionally, a particular type of paraffin wax was used as a heat storage material in the empty space on the back of the PV panel. Furthermore, three modifications were made to enhance the system's efficiency: in Case 2, Al_2O_3 nanoparticles were added to the PCM, and in Case 3, copper fins were put on both sides of the copper pipes. This resulted in higher power output for the PV/T-PCM-TEG than that of a standard PV panel, with improvements of 10.29% in Case 1, 12.73% in Case 2, and 14.22% in Case 3. Also, the efficiency of PV/T-PCM-TEG grew to 32.8% in Case 1, 33.9% in Case 2, and 35.2% in Case 3. This contrasts with the regular PV panel's maximum efficiency of 30%. The technical drawing for the PV/T-PCM-TEG hybrid system is displayed in Figure 7 [95].

Yang et al. [96] connected the TEG module behind the PV module via direct coupling in the hybrid PV-TEG system. Figure 8 [96] illustrates the connection structure of the PV module. Connecting the TEG module behind the PV panels converts all losses of heat into power generation. The use of ceramic wafers enhances heat conduction efficiency. Furthermore, the heat sink reduces the hybrid system's overall temperature and keeps the hot and cold ends significantly different from one another.

Naderi et al. [97] did a study to improve the generation of power and ultimately enhance the efficiency of photocells through the use of PCM and TEG. The PV-PCM-TEG model is made up of one cover of glass, a solar cell, aluminum sheet, TEG, PCM, Tedlar film, air channel, insulation box, and two reflectors that are identical, as shown in Figure 9 [97]. The PV module's excess heat is transferred to the PCM and discharged at a low level of solar intensity by locating the PCM beneath the PV module. The TE's hot surface is attached below the PCM, and the TE module's cold side is cooled via an air channel. Their outcomes indicated the following: the system's electricity output was increased by 100%, and solar cell efficiency was increased by 1.38%. Kolahan et al. [98] aimed to combine PV modules with TEG and to use nanofluid as a cooling fluid to study their effect on the PV system. To decrease the temperature of the cold surface of the thermoelectric module, an aluminum-water nanofluid was selected as a working fluid. The equations were figured out using the tridiagonal matrix algorithm with a formulation and a center-difference method. According to their findings, they discovered that the adjusted system had a 2.5–4% higher total electrical power efficiency than the conventional module alone.

A hybrid system that integrates a TEG with a heat pipe to enhance the efficiency of the PV panel was theoretically discussed by Makki et al. [99]. In order to provide cooling and keep the solar cells operating at a lower temperature, a heat pipe is attached

Figure 7
A solar PV/T-PCM-TEG hybrid system experimental layout

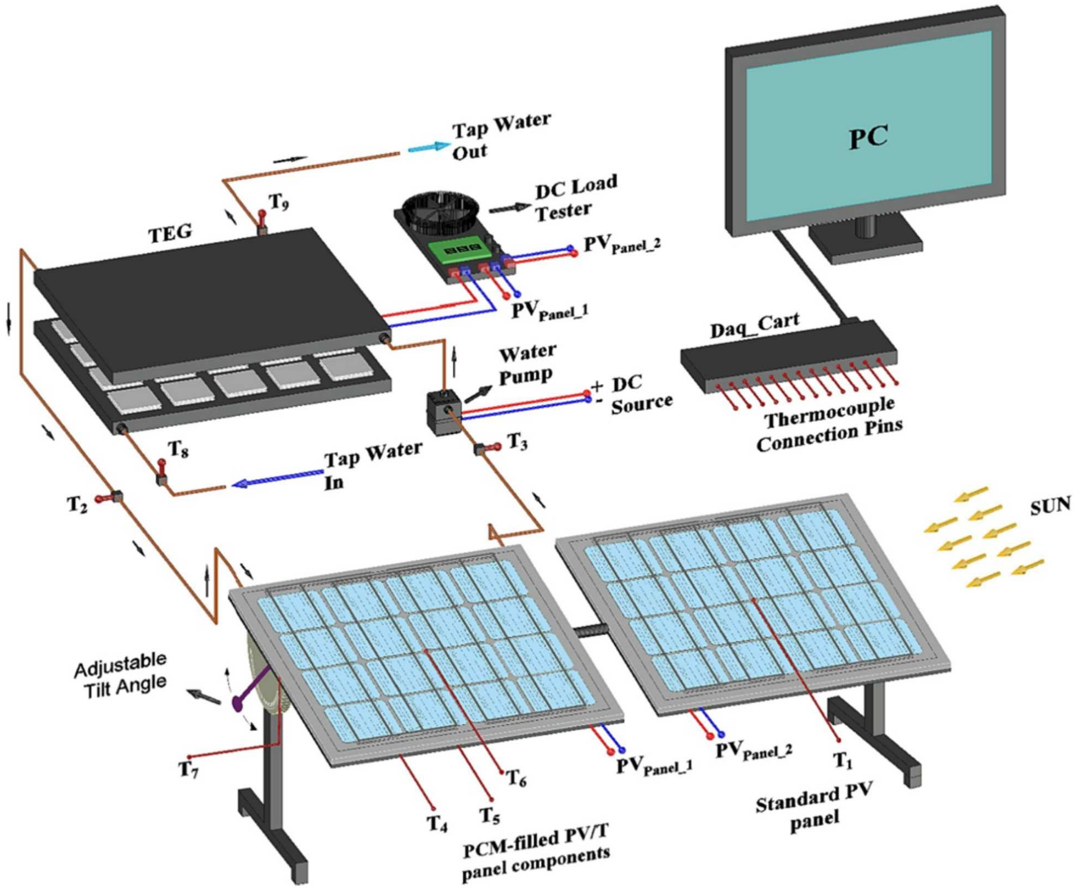


Figure 8
The connection structure of the PV-TEG module

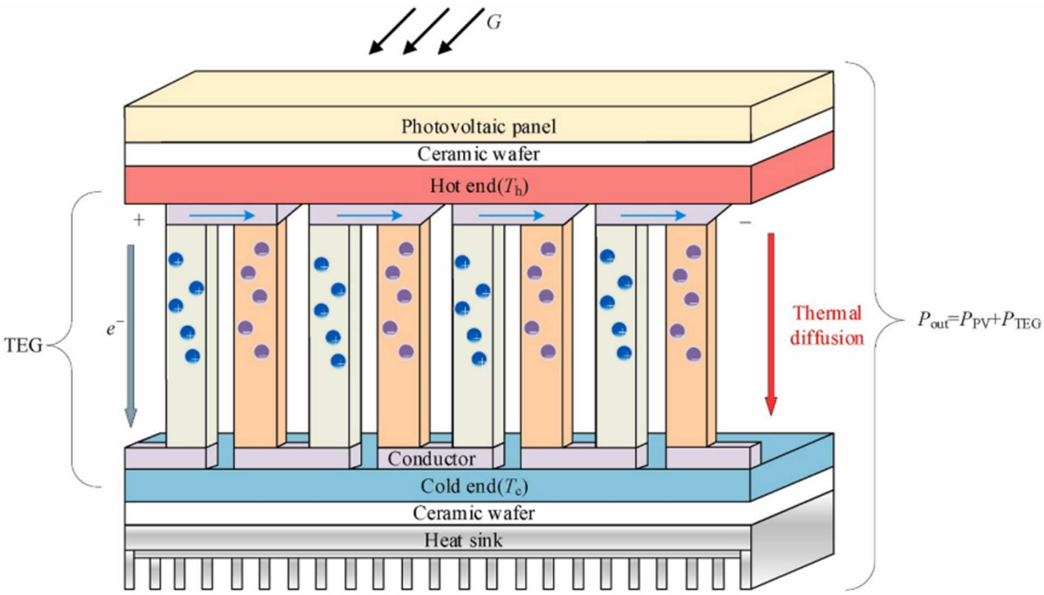
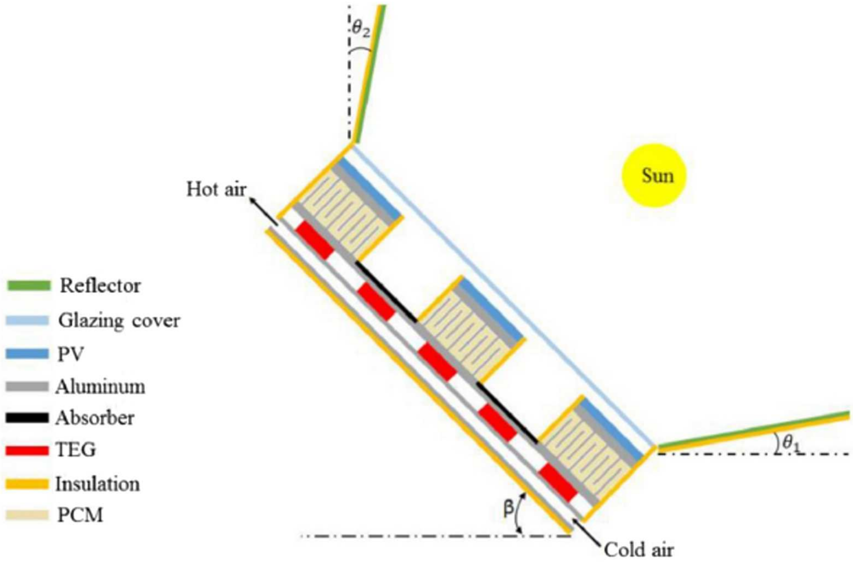


Figure 9
PV panel system diagram utilizing PCM and TEG



to remove excess temperature from the cells. The extracted heat was moved to a TEG through a boiling-condensing process, which was attached to the heat pipe's condenser section, and heat waste was used to transform the difference in temperature directly across the TEG's surfaces to electrical power. Their findings showed that the solar panel utilizing heat pipe and TEG had better energy efficiency than the traditional module.

Furthermore, Yang et al. [100] identified that the issue of partial shielding condition (PSC), which involves reduced power and component inconsistency in a PV-TEG hybrid system, is a significant challenge. PSC refers to a situation where only a portion of a system or device is shielded from electromagnetic interference or radiation, leaving other areas exposed or less protected. In this study, a reconfiguration technique for the hybrid PV-TEG system using artificial rabbit optimization (ARO) was introduced. This method modifies the system's switching matrix to optimize the electrical connections between PV arrays and TEG arrays, resulting in increased power output. Their study uses various measures such as mismatch loss, standard deviation for evaluation, maximum output power, and average output power.

They extensively analyze four different algorithms: genetic algorithm (GA), particle swarm optimization (PSO), whale optimization algorithm, arithmetic optimization algorithm (AOA), and ant colony algorithm, through simulation tests conducted on arrays of sizes 4 × 4 and 20 × 15, respectively. The outcomes of the simulation show that the hybrid system's output power improves by 34.05% in the 4 × 4 array and 23.10% in the 20 × 15 array after ARO algorithm-based reconfiguration.

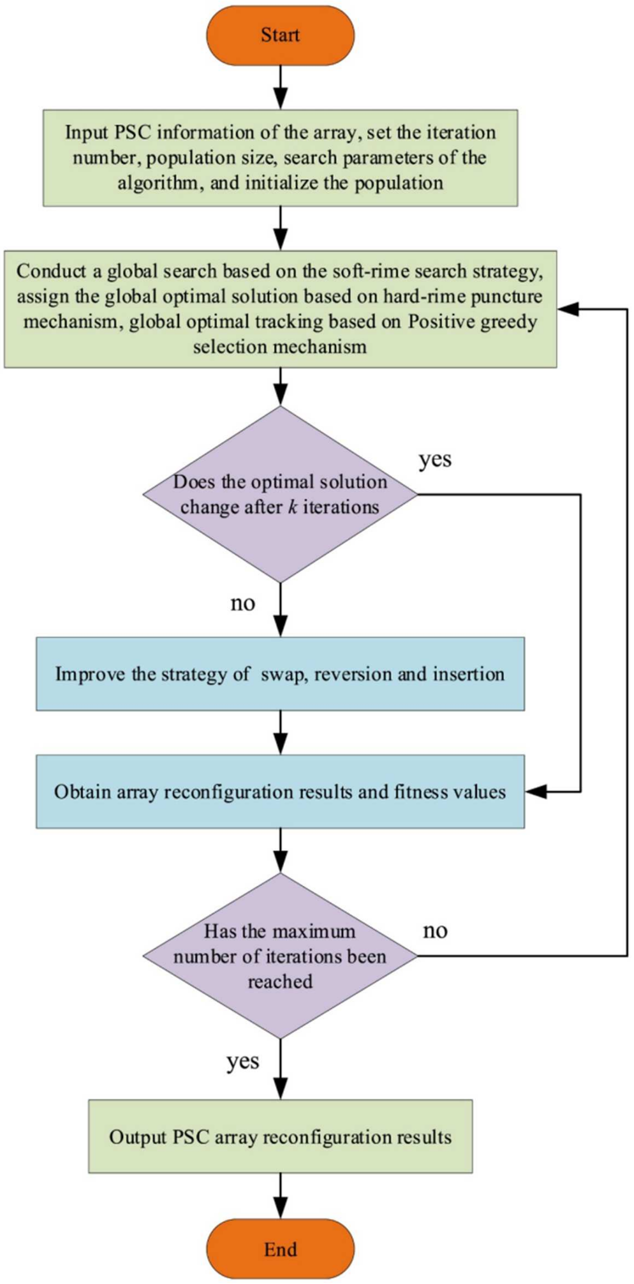
On the other hand, Yang et al. [101] designed an array module for a stacked PV-TEG hybrid power generation system. To address the issue of PSC and potential power generation reduction due to component mismatch, a reconfiguration method using the improved RIME (IRIME) in the hybrid PV-TEG system was proposed through simulation. Figure 10 [101] shows the array reconfiguration of PV-TEG hybrid system based on IRIME algorithm. To test the viability of IRIME algorithm, simulations using ten PSCs on two PV-TEG hybrid systems of varying scales were conducted. The findings from the simulation show that after reorganization, the average generated energy of the hybrid system increased by 26.76% on the 6 × 6 scale and 30.47% on the 6 × 10 scale. This improvement in energy generation showcases the success of the IRIME algorithm in optimizing PV-TEG hybrid systems.

Previous studies, like the one by Mirza et al. [102], have noted that traditional optimization approaches are insufficient for reaching the maximum possible power because of the nonlinearity of the composite hybrid power system. They proposed an innovative approach to power management in the PV-TEG system by employing an active Maximum Power Point Tracking (MPPT) controller based on an AOA.

To verify the viability and efficacy of the suggested AOA approach for practical uses, five scenarios utilize actual atmospheric data and experimental setup. The findings were correlated to those obtained using successful intelligent strategies, such as gray wolf optimization, cuckoo search algorithm, PSO, and optimized perturb and observe. The suggested technique's robustness has been verified by quantitative and statistical analyses. AOA achieves an energy reduction of 8% and a power tracking efficiency of 99.86%. During changing operating conditions, the tracking time remains below 0.1 s, with a typical settling time of 0.280 s. The results of the study, comparative analysis, and statistical indices demonstrate that the proposed AOA optimization achieved superior performance, enhancing the environmental friendliness of the PV/TEG module.

A study by Paquianadin et al. [103] suggested another method for obtaining the most power from the hybrid PV-TEG system. The paper discussed a 48 V isolated DC microgrid that is powered by a hybrid solar PV-TEG and suitable power electronic controllers. To extract the maximum power from this hybrid solar PV generator-TEG, a new controller is proposed that uses a current sensor to track the maximum power point. The proposed controller in the study tracks the maximum power points by monitoring the current in the DC microgrid and calculating the duty cycle of the boost converters connected to the solar PV-TEG. Simulation and experimentation have been used to validate the effectiveness of the proposed MPPT controller. Moreover, to extract maximum power from the hybrid solar PV generator TEG, the suggested MPPT controller is compared to two independent MPPT controllers. Based on the comparison results, the suggested MPPT controller is 50% more reliable and 50% less expensive than the two independent

Figure 10
PV-TEG hybrid system array reconfiguration using the IRIME algorithm



controllers. Additionally, the proposed MPPT controller has 50% less power loss compared to the two independent controllers.

4.1.3. Combined cooling and power generation

Photoelectric-thermoelectric cooling and power-generating technique's ability to gather energy were investigated by Cai et al. [61]. The PV energy was collected on the solar panel using a concentrator. The TE device employed in the mentioned study was an energy converter, which is sandwiched between the PV and heat sink and was made up of p-n thermocouples that are arranged in series, along with ceramic and conducting plates. Excess heat in the thermoelectric device's dissipative end was dispatched via various cooling methods in which water or air could be used as a coolant. According to this, concentrator photovoltaic/thermoelectric (CPV-TEC) systems were classified into two types: CPV-TEC systems, in which the thermoelectric device acts as a thermoelectric cooling module, and CPV-TEG systems, in which the thermoelectric device acts as a TEG module. The total electricity output of the CPV-TEC system was the difference between the PV output power and the TEC input power, whereas the total electricity output of the CPV-TEG system was the sum of the electricity output from the PV panel and the TEG. At a solar intensity of 1000 W/m², they found that the exergoeconomic value of the CPV-TE cooling system was 0.266 \$/kWh, while that of the CPV-TEC system was 0.263 \$/kWh.

4.2. Thermoelectric module-equipped solar water heaters

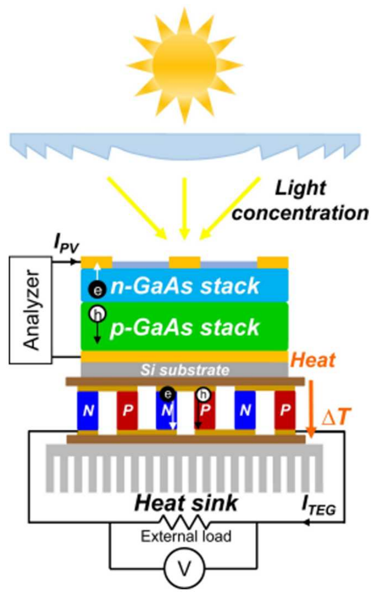
The improvement in temperature of the water in the solar water heater can be greatly impacted by the application of thermoelectric heating. The water heater tank is equipped with thermoelectric heating, which raises the water's temperature. The thermoelectric generators in solar water heaters generate electricity by the difference between the hot water temperature and that of the surrounding areas. Efficiency in this case is determined by heat conduction and their ability to maintain a good temperature gradient.

There are two common integration modes for TEGs in solar water heating. Mounting TEGs on the heater surface directly is the contact mode, to enhance heat collection but degrade in the long run by heat exposure. The heat exchanger-assisted method installs TEGs within a heat exchanger, to enhance the heat transfer in control, leading to longer life and the facility for constant difference in temperature, suitable for the long-term purpose.

Solar water heating energy was converted into electrical energy using a TEG. Faddouli et al. [104] examined the comparative evaluation of a solar water heater with a planar TEG and another with a thermal device and tubular and planar TEGs. The TEG area was $16 \times w10^{-4}$ m^2, and the setup of the surface was approximately 1.75 m^2. The findings indicated that the updated system produced approximately 161 W of electrical energy.

Kil et al. [105] made a CPV/TE hybrid generator. Figure 11 [105] shows the schematic diagram of the CPV/TE hybrid generator. The hybrid generator includes a Fresnel lens, a GaAs-based

Figure 11
CPV/TE hybrid generator schematic diagram



(Gallium Arsenide-based) single-junction PV cell, a TE module, and a heat sink. The light from the xenon lamp of a solar simulator is concentrated by the Fresnel lens. A commercial TEG (RMT, 1MC04-030-05TEG) is positioned on top of a single-junction, GaAs-based CPV cell. This setup was implemented to address the thermal degradation issue in the traditional CPV cell. As a result, at a solar concentration of 50 suns, their hybrid generator achieves a conversion efficiency 3% higher than that of a single CPV cell. Their findings show that CPV/TE hybridization is a promising method for efficiency improvement. Additionally, controlling heat flow and utilizing the Peltier cooling effect of TEG are crucial for achieving a highly efficient hybrid generator.

4.3. Solar desalination and water purification systems

Water scarcity is a worldwide issue, particularly in arid and semi-arid areas. Solar-powered water treatment and desalination systems are green technologies since they utilize solar energy to drive the desalination process. System efficiency can be enhanced by using TEGs, which recover waste heat and generate additional electricity or supply auxiliary thermal energy to enhance evaporation.

4.3.1. Thermoelectric-assisted desalination

TEGs can be incorporated into solar desalination systems in several ways:

Waste Heat Utilization: TEGs recover excess heat from solar collectors or distillation units and convert it into electricity to power auxiliary components, such as pumps.

Direct Thermal Enhancement: TEG modules can provide additional heating to evaporate seawater efficiently in humidification-dehumidification desalination systems.

Assareh et al. [106] proposed an energy system for producing cool water, hot water, and desalinated water. The systems operate on a steam Rankine cycle and make use of a reverse osmosis desalination unit. The proposed integrated system is shown in Figure 12. To increase the electricity output of the system, TEGs are used in place of a condenser. For water desalination, the system makes use of the reverse osmosis process. This technique separates water and dissolved substances by passing the liquid through a partially permeable membrane and filtering out the unwanted substances. After comparing TEGs against condensers for the proposed system, the results show that using TEGs reduces the total cost rate to 10.41 $/GJ and improves the exergy efficiency of the system. The system generated 240.226 m^3 of fresh water and 9146.7 kW of electricity.

A novel TEG-based water desalination system was discussed in Shoeibi et al. [107]. The study concentrated on improving the performance of a solar desalination system with mirrors, waste material as a heat storage medium, and TEGs for the harnessing of waste heat. Two mirrors were used to heat water by concentrating solar radiation on the absorber sheet. Black-painted iron scraps were used as storage materials in the basin to increase evaporation rates. The study compared various experimental setups with a setup comprising solar still with TEG, iron scraps, and mirrors (SS-TEG-WI-M), yielding the best results, as shown in Figure 13. The SS-TEG-WI-M configuration produced 0.796 L of freshwater per meter squared and showed an improvement of 24.5% in CO_2 over other configurations.

4.3.2. TEGs in solar water purification

Beyond desalination, TEGs also enhance solar water purification by:

Boosting UV Sterilization: By generating additional power, TEGs can help run UV purification units in remote locations.

Powering Filtration Systems: Small-scale solar TEG hybrids can be used for off-grid filtration, providing clean drinking water where traditional infrastructure is lacking.

A study investigates the integration of a double-sided PV-TEG system with water treatment, photocatalysis, and photo-Fenton

Figure 12
The main components of the proposed integrated system by Ehsanolah et al. [106]

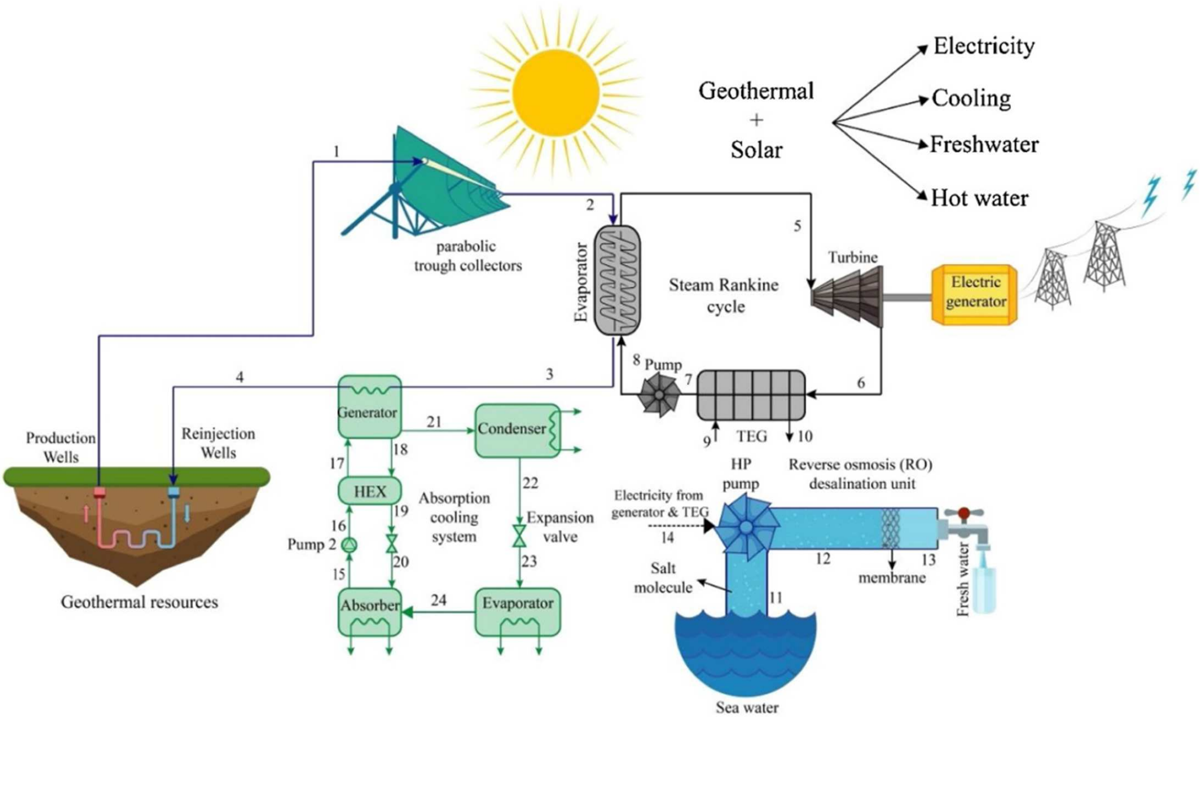


Figure 13
A sketch view of typical solar still and a solar still utilizing mirrors, iron scraps, and TEG [107]

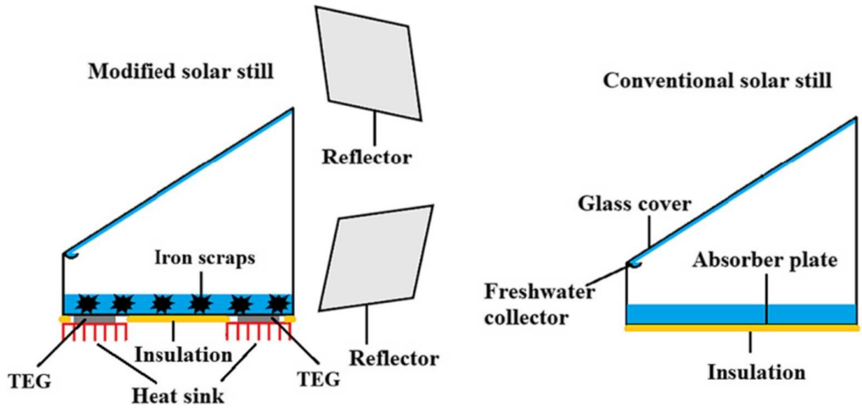
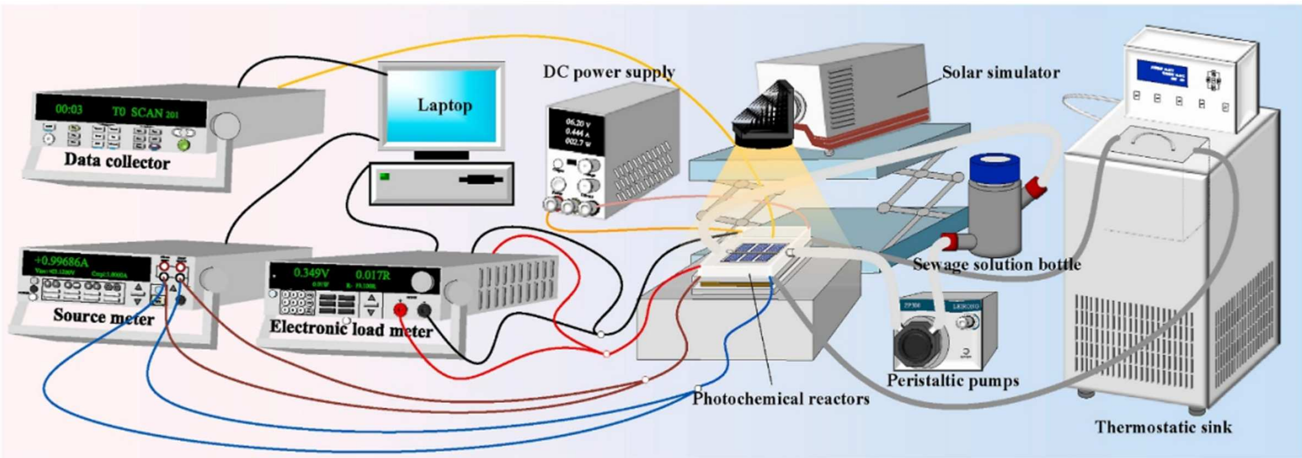


Figure 14
The proposed test rigs [108]



processes to harness the full spectrum of solar energy (infrared, visible, and ultraviolet) [108]. The experimental setup, shown in Figure 14, comprises two double-sided PV-TEG modules and a system for emitting light, systems for recording data, and a water circulation arrangement. The experiment researched the impacts of using UV/Fenton on the efficiency of degradation for RhB and Orange II in different lighting. Results showed that illumination drastically improved the pollutant degradation efficiency, with an improvement of 51% for RhB. This underscores the feasibility of using PV-TEG systems with water purification systems.

Research conducted by Zhang et al. [109] depicts the production of a dual-purpose device in the form of solar-thermal-driven water purification and thermo-driven power generation. The device is fabricated by polydopamine (PDA) coating on melamine sponges (PDA@Sponge) via hydrogen bonds, along with a TEG (PDA@Sponge/TEG). The design is highly solar-thermal-driven and dual-functional. The PDA@Sponge suppresses interfacial hydrogen bonding between water molecules, enhancing water evaporation. The optimal serrated geometry achieves a rate of water evaporation of ~1.50 kg/m^2/h with an efficiency of ~94.04% at one sun. This study stimulates the fabrication of multifunctional devices for seawater desalination, wastewater cleaning, and low-energy electronic powering, especially in remote areas without power plants or water treatment facilities.

Hybridization of TEGs with solar desalination and water treatment is the way to go for enhanced efficiency and sustainability in dry regions. Due to ongoing advancements in thermoelectric materials and system design, hybrid technologies hold promise to be among the future water security solutions.

5. Discussion

After reviewing different studies that were done on thermoelectric module integration with solar systems, it also provides valuable insight into recent developments and potential applications of this novel approach. Also, all the studies that were mentioned in the literature showed that the combination of the PV system with TEGs has enhanced its thermal and electrical efficiency and provided great advantages to the conventional PV system. Excess heat from PV modules is being strategically used to power TEGs, which is a smart and efficient measure. This method not only demonstrates the interconnectedness of various solar technologies, but it also provides an opportunity to maximize power output in solar-thermoelectric systems.

TEGs prove to be a versatile solution for harnessing the waste heat generated by solar systems. The frequent utilization of TEGs to convert excess heat into power not only enhances overall system efficiency but also contributes to the sustainable utilization of energy resources. The literature is rich with articles that show the benefits of connecting TEGs to the PV system to reduce heat loss by attaching the hot surface of the TEG beneath the PV cell. As mentioned in one study, three diferrent cases were studied: PV using an air duct, PV panel that was partially covered with TEG, and PV panel completely covered with TEG. The last case recorded the highest power efficiency improvements among the three cases. These studies prove the benefits and the positive effects of TEG on solar PV systems. Table 1 compares various integrations of TEGs into PV systems discussed in this study.

Some articles combined PCM with the hybrid PV/TEG system that showed in all of them higher efficiencies than the conventional system [110]. To mention, one study that used PCM in addition to a certain component showed a great enhancement in power production efficiency and electrical efficiency. Not only that, another one used PV with PCM and TEG systems in three different cases; one of them included Al_2O_3 nanoparticles into PCM in this system, which raised the maximum efficiency of the based PV/T-PCM-TEG, and this shows the effectiveness of implementing PCM in PV/TEG hybrid systems. In other studies, they combined the nanofluid applications with PCM, which also boosted efficiency. In one study, they used nano-enhanced PCM and Co_3O_4-water nanofluid that improved the electrical efficiency.

The introduction of Ag/Fe_3O_4-water hybrid nanofluid and SiO_2-water nanofluid demonstrates the potential for advanced coolant technologies to significantly improve productivity and power generation capacity. For example, several articles investigated the use of different types of nanofluids in their systems. One study used an aluminum-water nanofluid, which showed a notable improvement in performance. Others used graphene-water nanofluid as a cooling medium, which also enhanced power output. In another study, a carbon-based nanofluid was employed and demonstrated better electrical performance compared to the previous ones. Not only that, the one article that the SiO_2-water nanofluid was used recorded the highest enhancement in power efficiency among the previous articles compared to natural cooling techniques.

Thermoelectric can be used in enhancing the efficiency of solar desalination systems since the combination of TE cooling/heating

Table 1
Comparative table

Author's Name and Years of Publication	Methodology	Key Findings	Limitations	Reference
Kil et al. (2017)	Developed an experimental CPV/TE hybrid generator using a Fresnel lens, a GaAs-based CPV cell, and a commercial TEG; addressed thermal degradation issues.	At a solar concentration of 50 suns, the hybrid generator achieved a conversion efficiency that was 3% higher than that of a single CPV cell.	High solar concentration is required, and the system's complexity (especially thermal management) may pose challenges for widespread adoption.	[105]
Dimri et al. (2018)	Carried out experimental investigations on an integrated PV/TEG system using an air duct configuration; compared three setups (PV with air duct only, partially covered with TE module, and fully covered by TE module).	The fully covered PV/TEG configuration outperformed the partial cover by 4.46–6.23% in terms of power efficiency.	Increased design complexity and potential issues with uniform cooling/control over larger areas.	[90]
Lekbir et al. (2018)	Evaluated a PV module cooled by attaching a TEG whose cold side was cooled using an aluminum-water nanofluid.	Found that nanofluid cooling improved the PV/TEG system's electrical efficiency by 49.5% relative to a conventional PV system.	Use of nanofluids may introduce higher cost and maintenance challenges.	[91]
Faddouli et al. (2019)	Conducted a comparative evaluation of a solar water heater integrated with planar TEGs versus a system with a tubular TEG; the system featured a modest TEG area relative to the collector surface.	The enhanced system generated approximately 161 W of electrical energy.	The limited TEG area and system design constrain the overall efficiency improvements, and further scaling is necessary.	[104]
Luo et al. (2020)	Modified the design of a TEG and compared its performance to that of traditional TEGs under similar conditions.	Recorded a 5.9% increase in electricity production over conventional designs.	Details on cost–benefit analysis and scalability were not fully addressed.	[50]

(*Continued*)

Table 1
(*Continued*)

Author's Name and Years of Publication	Methodology	Key Findings	Limitations	Reference
He et al. (2020)	Tested a TEG system designed to recover waste heat from a diesel engine exhaust.	Reported electrical generation efficiencies ranging from 1.41% to 4.12%.	Efficiency remains low and is very specific to engine waste heat conditions; further optimization is needed.	[53]
Rajaee et al. (2020)	Experimentally investigated a hybrid PV/T-PCM-TEG system combining nanofluid cooling and improved phase change material in three different design cases.	Reported power output increases from 10.29% to 14.22% and efficiency improvements from 30% (standard PV) up to 32.8–35.2%.	The integration of multiple advanced components (PCM, nanofluids, TEGs) adds system complexity and demands precise control.	[93]
Montero et al. (2021)	Experimentally integrated PCM into a STEG; heated the hot side via solar radiation with an optical concentrator while using PCM as the heat sink for the cold side.	Increased the power production rate by about 0.6% at night.	Improvement was modest; performance is closely tied to PCM behavior and may not scale substantially.	[49]
Escobar et al. (2021)	Developed an experimental hybrid system where a solar TEG was combined with a thermosiphon for heat collection and recovery.	Demonstrated enhanced heat recovery (with reported output power improvements) when integrating a TE module with solar collectors.	Data interpretation was somewhat ambiguous (e.g., unusually high output values), and the system's complexity may affect scalability.	[51]
Liao et al. (2021)	Experimentally coupled a PV board with a thermoelectric cooling system powered directly by the PV output (tested at 200 W/m^2 irradiance).	The integrated system achieved an overall energy efficiency of 13.9%.	Results depend on specific solar irradiance levels and testing conditions; further real-world validation is required.	[88]
Mirza et al. (2021)	Proposed an active MPPT controller based on an AOA for hybrid PV/TEG systems; validated with experimental data and comparative simulations.	Achieved a 99.86% tracking efficiency, reduced energy loss by 8%, and exhibited a fast-settling time (~0.28 s).	Testing was performed under specific atmospheric datasets; broader field testing is required to generalize the findings.	[102]
Yang B et al. (2023)	Employed simulation-based reconfiguration techniques using algorithms (ARO and enhanced RIME) to optimize PV-TEG arrays under partial shading conditions.	Simulations showed output power improvements up to 34.05% (ARO) and energy generation improvements of 26.76–30.47% (IRME) in different array configurations.	Results are based on simulations; experimental validation is needed, and algorithm complexity may hinder practical implementation.	[101]
Paquianadin et al. (2023)	Developed a 48 V isolated DC microgrid powered by a hybrid PV/TEG system and introduced a novel single MPPT controller based on the SGSS algorithm; compared performance with two independent MPPT controllers.	The proposed controller was 50% more reliable, 50% less expensive, and resulted in 50% less power loss compared to independent controllers.	Results are specific to a microgrid scenario; additional work is needed to confirm scalability and integration into larger systems.	[103]

(*Continued*)

Table 1
(*Continued*)

Author's Name and Years of Publication	Methodology	Key Findings	Limitations	Reference
Yusuf Yakut (2024)	Constructed an experimental setup with six TEGs connected in series and parallel and integrated a heat exchanger for effective cooling.	Achieved a maximum voltage of 7.52 V and a power output of 5.236 W under a solar irradiance of 66 W/m².	Overall power output was relatively low, and the performance is highly dependent on irradiance levels.	[52]

and TEGs shows that it is a promising strategy for increasing the efficiency of solar desalination systems. Several articles in the literature reported the benefits of this combination. In one study, they discussed hybrid solar-natural-gas power plant, Rankine cycle, TEG to generate electricity and distilled water, they reported a raise in overall energy efficiency and exergy efficiencies. Several studies have explored humidification-dehumidification (HDH) desalination systems coupled with thermoelectric generators (TEGs), as well as the impact of integrating TEGs with solar collector tubes on freshwater production. All of them showed an enhancement in the production of water and electricity. For example, in one study, they investigated a solar multi-generation system using TEG, which resulted in the generation of electricity, fresh water, and hot water. There was one study that created, built, and tested a desalination system with TEG. The most interesting finding was that it showed the highest water productivity in a system using both thermoelectric heating and cooling with a solar panel, which was much more than traditional solar desalination.

Finally, the combination of solar systems and thermoelectric technologies holds great promise for long-term energy production and water desalination. The discussed findings, however, also point to the need for ongoing research and optimization to address challenges and realize the full potential of these integrated systems. As the search for cleaner, more efficient energy sources continues, the insights provided by this review add to the ongoing discussion about advancing solar-thermoelectric technologies for a greener, more sustainable future.

5.1. Insights into PV-TEG systems

To further improve PV-TEG performance, various cooling methods are employed. Table 2 below summarizes the major cooling methods applied in PV-TEG and their respective properties.

In order to efficiently manage power in hybrid PV-TEG systems, various strategies are applied. These strategies are summarized into three categories.

MPPT: This ensures optimal power extraction from both PV and TEG components.

Reconfiguration Algorithms: Algorithms such as ARO, GA, and PSO improve the power flow efficiency of PV-TEG.

Machine Learning Models: Adaptive AI-based controllers dynamically adjust system parameters to maximize energy output.

The cost of the material is a major issue that influences the economic and practical viability of thermoelectric solar water heaters. Most TEGs rely on expensive materials like bismuth telluride, which influences cost. Advancements in material development can reduce the cost, but current systems are high in price when compared to traditional solar water heaters. The second issue is the return on investment (ROI) time. ROI depends on energy conservation and system lifespan. Although TEGs improve energy efficiency, initial high investment can prolong ROI time, making mass adoption less attractive.

Scalability is also important. In order to be applied on a large scale, cost minimization, high efficiency, and long-term stable performance are necessary. If the material and manufacturing costs are minimized and efficiency is increased, thermoelectric-equipped solar water heaters can be a competitive choice for heating and electricity generation.

5.2. Climatic conditions' effect on the performance of thermoelectric modules

The efficiency and power output of TEGs in solar water heaters are very much influenced by climatic conditions like solar radiation, ambient temperature, and season. As TEGs operate on a temperature

Table 2
Comparative analysis of cooling methods

Cooling Method	Working Principle	Effect on Efficiency	Optimal PV Type	Limitations
Passive cooling	Uses natural convection and radiative cooling	Moderate improvement	Standard PV panels	Limited heat dissipation
Air cooling	Fans circulate air to remove heat	5–10% increase	Rooftop PV systems	Requires external power
Water cooling	Water channels absorb excess heat	15–30% increase	Solar farms	Requires water supply
Nanofluid cooling	High thermal conductivity fluids enhance heat transfer	Up to 50% increase	High-performance PV-TEG	Expensive implementation

difference to produce electricity, any change in these parameters can greatly affect their power output and efficiency.

5.2.1. High-solar-radiation conditions

TEG-based solar water heaters demonstrate optimal performance in regions characterized by high solar irradiance, such as deserts and tropical areas. Under concentrated solar input, the following key effects are observed:

Increased Water Temperatures: Elevated solar radiation results in higher temperatures on the hot side of the TEG module. This amplifies the temperature differential across the TEG, leading to enhanced power output.

Enhanced Thermal Conversion Efficiency: The improved heat absorption capacity of the TEG, facilitated by the solar heater, promotes a more stable and pronounced temperature gradient, thereby increasing overall system efficiency.

Risks of Overheating: Prolonged exposure to extreme heat may accelerate material aging in TEG modules. To mitigate this, advanced heat dissipation techniques, such as PCMs or nanofluid cooling systems, are employed to maintain operational integrity.

5.2.2. Cold and low-radiation conditions

In contrast, TEG performance in cold climates or regions with partial cloud coverage is influenced by the following factors:

Reduced Temperature Gradient: Diminished solar input results in a smaller temperature difference between the hot and cold sides of the TEG, directly reducing power output.

Heat Retention Challenges: Low ambient temperatures exacerbate heat loss from the system, further compromising efficiency.

To address these challenges, several optimization strategies have been proposed:

Insulation Methods: The use of vacuum-insulated or thermally insulated hot water storage tanks minimizes heat loss, preserving system efficiency.

Heat Exchanger-Sustained TEGs: Incorporating heat exchangers ensures greater thermal stability and uniform temperature gradients, even under fluctuating solar conditions.

Hybrid Systems: Auxiliary heat sources, such as electric or geothermal backups, can supplement thermal gradients during periods of low solar radiation, ensuring consistent performance.

5.2.3. Seasonal variations and long-term performance

TEG-based systems exhibit distinct seasonal performance characteristics:

Summer Efficiency: During summer months, heightened solar radiation ensures optimal heat production, enabling peak TEG operation.

Winter Performance: In winter, reduced ambient temperatures and lower solar radiation diminish the temperature gradient, resulting in decreased overall system efficiency.

To achieve year-round optimization, the following techniques are recommended:

Thermal Energy Storage: Excess heat generated during sunny periods can be stored and utilized during cloudy conditions or nighttime, ensuring continuous operation.

Adaptive Control Systems: Real-time monitoring and control of heat flux enable dynamic adjustments to TEG output, maximizing efficiency under varying weather conditions.

With these flexibility measures, the TEG-based solar water heaters can operate more efficiently and stably in various climatic conditions with continuous hot water and electricity supply throughout the year.

6. Conclusion

Solar energy has been greatly attractive on the basis of its environmental benefits, better efficiency, and low cost. This review focuses on TEGs, their operation, and their physical characteristics. TEGs are devices that transform heat into electricity using the Seebeck effect to produce electricity directly from heat by causing an electric voltage because of a temperature gradient across a material. The combination of TEGs and PV systems has high potential, particularly for efficiency enhancement through waste heat recovery and cost reduction of the system.

Integration of TEG is possible in two ways: either by power supply through Seebeck effect-based TEGs or by utilizing Peltier effect-based thermoelectric heating and cooling devices to regulate temperature. Although the focus is primarily on the utilization of the Seebeck effect for power supply, there have been instances where the Peltier effect is utilized to regulate temperature in hybrid systems for enhanced system performance and stability.

This paper reviews recent research and classifies them into three categories: hybrid PV-TEG systems, solar water heating systems, and solar desalination and water purification systems. A hybrid PV-TEG system integrates TEGs and PV panels to harvest waste heat and improve the net energy conversion efficiency. Due to the nature of PV cells, where decreasing temperature means becoming less efficient, the integration of TEGs minimizes the energy loss and generates extra electricity. Solar water heaters use TEGs to reclaim solar collector waste heat. This setup incorporates auxiliary electrical generation with optimal thermal efficiency and achieves maximum energy efficiency for solar water heaters. TEG integration enhances solar desalination systems by applying waste heat from solar thermal systems for driving desalination operations. This introduces system autonomy and energy efficiency to support the sustainable production of freshwater in the desert and in remote areas. For every category, the process of adding TEGs for solar system performance enhancement is elaborated. The paper gives an overview of the key results of these studies, which reflect considerable improvement in energy conversion efficiency and system performance.

Future research ought to consider innovative trends in constructing such hybrid systems, such as exploring new materials for TEGs, cost-effective cooling system designs, and real-case situation application factors. The application of TEGs significantly improves the performance of PV systems through increased efficiency, which makes them innovative and relevant in the energy sector. Ongoing improvements in solar PV systems combined with thermoelectric devices are very promising toward improving the world's energy requirements and increasing the sustainability of solar power.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data available on request from the corresponding author upon reasonable request.

Author Contribution Statement

Oluwasegun Henry Jaiyeob: Conceptualization, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Mohammad Karimzadeh Kolamroudi:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Cemal Kavalcioglu:** Validation, Investigation, Writing – original draft, Writing – review & editing. **Çağrı Özkan:** Software, Writing – original draft, Writing – review & editing. **Said EL Khatib:** Conceptualization, Resources, Writing – original draft, Writing – review & editing.

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