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A review of thermoelectric applications in photovoltaic modules: structure, performance, and optimization

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Highlights:

- PV-TEG, SSPV-TEG, CPV-TEG, and PV/T-TEG were reviewed.
- Economic feasibility of different coupling systems was discussed.
- An outlook on key aspects was presented, including environment and intelligent design.

Abstract: As the demand for renewable energy continues to grow, photovoltaic modules (PV) have attracted much attention as an important clean energy technology. The combination of thermoelectric generator (TEG) with photovoltaic (PV) systems offers significant benefits, such as using waste heat from PV to produce electricity, reducing the operating temperature of PV to extend its service life, and enhancing the efficiency of overall energy use. This review analyzes four main types of structural combinations: photovoltaic hybrid thermoelectric generation components (PV-TEG), split-spectrum photovoltaic hybrid thermoelectric generation components (SSPV-TEG), concentrating photovoltaic hybrid thermoelectric generation components (CPV-TEG), and photovoltaic/thermal hybrid thermoelectric generation components (PV/T-TEG) in order to obtain the latest relevant research developments. The structural design of the coupled system aims to optimize the integration of the TEG with the PV module for enhancing the heat transfer efficiency and power generation performance. The advantages of the PV/T-TEG system, which combines photovoltaic and thermoelectric conversion technologies, are likely to occupy an important position in the future solar energy market. While progress has been made in the application of TEG in PV, the challenges of efficiency, cost, and thermal management need to be overcome, and the opportunity to take advantage of developments in policy, innovation, and market demand will continue to improve performance through structural optimization.

Keywords: thermoelectric generations modules; photovoltaic modules; thermoelectric conversion; integrated energy utilization; optimized design

1. Introduction

As “carbon peaking,” “carbon neutrality,” and sustainable development strategies are being implemented, renewable energy is receiving greater emphasis [1]. Under the sustainable development strategy in recent years, renewable energy has developed greatly and is widely used in modern power systems [2]. By 2028, renewable energy is expected to account for 42% of global power generation [3]. This data clearly demonstrates the increasing trend of renewable energy in the global energy structure.

The global photovoltaic industry has accelerated, and between 2019 and 2023, the average yearly growth rate of the installed capacity for global photovoltaic power generation reached 28% [4]. It demonstrates the swift growth of photovoltaic technology within the renewable energy sector. The rapid growth of solar photovoltaic technology is basically in line with the expectations based on multiple aspects such as energy transformation needs, technological progress trends, market and policy factors, and industrial development laws. Its development is the result of the combined action of many positive factors, and it is expected to continue to maintain a rapid growth trend in the future. Solar photovoltaic technology, one of the fastest-growing sectors in the global energy field, is projected to lead global renewable energy production by 2100, supplying 20% to 29% of the world’s electricity needs, underscoring its pivotal role and vast potential in shaping the future energy supply system [5,6]. Moreover, solar devices can last for two decades with few performance declines or failures, and long-term data indicates that the annual output loss of photovoltaic panels is merely 0.5% [7,8]. These enduring and reliable characteristics highlight solar energy's role as a dependable global energy solution, providing a consistent and stable electricity supply, making it a highly practical solution capable of powering the entire planet [9]. Renewables are achieving an unparalleled penetration into the energy system, as more than 560 gigawatts (GW) of new clean energy capacity was added in 2023 [10].

At the same time, the mainstream PV market has become a mass-manufactured commodity market [11]. Photovoltaic devices can convert part of the solar spectrum directly, but much is absorbed as heat [12]. Thermal and photovoltaic systems are two ways to convert solar energy into electricity. A major inherent disadvantage of current photovoltaic technology is not absorbing the entire solar spectrum [13]. Photovoltaic cells, which function as efficient converters, are susceptible to heat influence. Their conversion efficiency declines with the increase in operating temperature [14]. Research indicates that with each 1 °C rise in cell temperature above the nominal value, the power output of a PV panel declines by approximately 0.5% [15].

As shown in Figure 1a, when sunlight reaches the photovoltaic panel, the P-N junction on the semiconductor and the photogenerated charge carriers in its vicinity are driven by the built-in electric field (which is formed due to the inherent properties of the semiconductor) to form a current from the N region to the P region. Specifically, it is the flow of electrons from the P region to the N region and the flow of holes from the N region to the P region. In detail, the photoexcited electrons and holes originally have a high probability of recombining on the spot, but in reality, due to the presence of the built-in electric field, the minority carriers are driven away, that is, electrons in the P region flow towards the N region, and holes in the N region flow towards the P region. At this point, as long as there is a metal contact at the outer ends of the P and N regions to form a complete circuit, the aforementioned current will flow continuously, which is the basic principle of photovoltaic power generation.

Silicon, due to its abundance, chemical stability, environmental friendliness, and excellent semiconductor properties, serves as the cornerstone material for the worldwide photovoltaic industry. The strategic introduction of impurities with a valence electron count differing from that of the semiconductor's base elements can significantly boost the concentration of electrons or holes within the semiconductor, thus improving its performance. Particularly, when pristine silicon—featuring 4 valence electrons—is alloyed with elements boasting 5 valence electrons, such as phosphorus, it results in the formation of an N-type semiconductor. On the other hand, incorporating elements with 3 valence electrons into pure silicon, like boron, leads to the creation of a P-type semiconductor.

In recent decades, with the diversified development of PV structure forms, a variety of structure forms such as photovoltaic/thermal components (PV/T), concentrating photovoltaic components (CPV), split-spectrum photovoltaic components (SSPV), have emerged.

Using Combined Heat and Power (CHP) systems can address power loss in PV systems caused by increased cell temperatures. Adding a temperature difference module is one form of combined heat PV system. The Seebeck effect is about the potential generation due to a temperature gradient between different electrical conductors or semiconductors [16]. As shown in Figure 1b, the operational mechanism of TEG rests upon the Seebeck effect. Whenever a temperature disparity exists between two distinct materials, a potential difference corresponding to it will be produced. Widely applied TEG is made up of a p-type and an n-type TEG component, in which the hot end is joined through metal conductor electrodes and the cold end is furnished with cold electrodes [17]. By absorbing heat from PV panels, temperature difference power generation overcomes the high-temperature constraint of PV panels and converts the heat into electrical energy, thereby improving the energy quality of the system. Though less efficient than photovoltaics, such devices are simple, quiet, and environmentally friendly [18]. TEG technology has been a hot research topic and widely used in recent decades [19]. In order to make full use of solar energy and avoid the waste of heat generated during the photovoltaic conversion process, many researchers suggest combining solar photovoltaic modules with TEG [20].

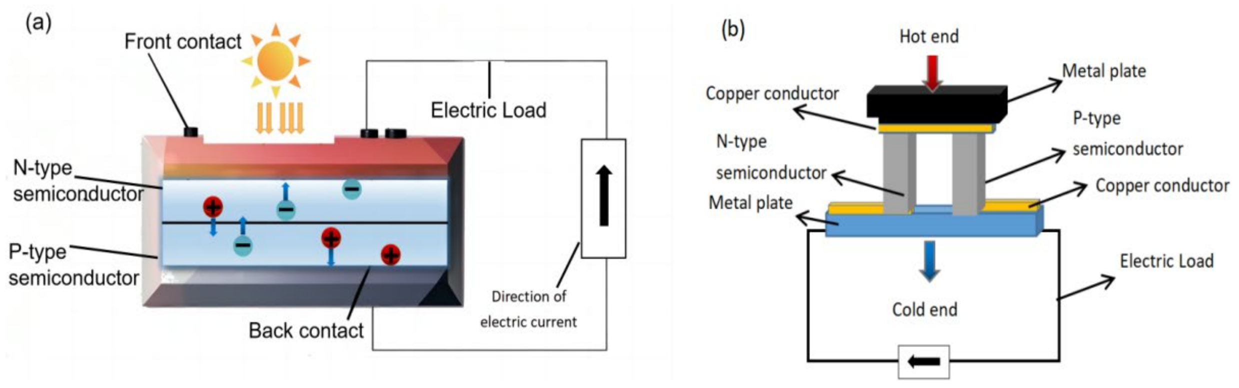

Figure 1. Schematic diagram of the working principle. **(a)** PV **(b)** TEG (authors' concept).

Although TEG technology is popular in PV cooling, its application in this field is hindered. The improper thermal coupling between the PV and the TEG leads to an unsatisfactory coupling effect [21]. The TEG must have a cold plate. According to the Seebeck effect, the higher the temperature difference between the cold plate and the hot plate, the more electrical energy will be generated. However, since the cold plate is very close to the hot plate, the dissipated thermal energy will also heat the cold plate.

This will then reduce the temperature gradient across the TEG, thereby decreasing the energy efficiency of the TEG. Therefore, the cold plate should be connected to a heat sink, which can be either active or passive, and then the system needs to be designed so that the overall system can achieve energy profit. Meanwhile, likePV, TEG have low conversion efficiency and high material costs, which hinder their wide application [22]. The structural optimization method of TEG has been proven to be an effective way to achieve remarkable thermoelectric performance advantages [23].

Therefore, researchers focus on using TEG with photovoltaics to improve overall efficiency due to the two technologies' complementary performance [24]. Although the above-mentioned technologies have improved the performance, the performance degradation of TEG from the material level to the system level and the relatively low overall conversion efficiency still limit its broader application and commercialization [25]. Thus, rationalizing the coupling of PV and TEG is a worthy research topic.

Therefore, this paper focuses on summarizing the application of TEG in PV in recent years, with the aim of providing valuable references and guidelines for the research and development of PV hybrid temperature difference power generation systems. In this comprehensive review, we first introduce the emergence of four important types of TEG coupled systems by recounting the development history of PV. Section 2 elaborates on the research methodology and research steps of this review. Through literature search, literature screening and analysis, and data processing and presentation, it finally presents the current significant literature regarding the application of TEG in PV. Section 3 also compares the thermoelectric performance of the coupled systems in different structural forms and relevant optimizations. Section 4 summarizes the various types of coupled systems mentioned above and also offers an outlook on the future application of TEG in PV.

2. Methods

2.1. Literature search

In this review work, the focus is on a comprehensive categorization and evaluation of existing thermoelectric generator coupled photovoltaic module technologies, as well as a survey of the latest research in the field. The specific time span of our research is from 2005 to 2024, which can be seen from Figure 2. For this purpose, recent articles on the development of TEG in PV applications were first read to understand the existing structure types and photothermal efficiencies, and to summarize the progress in the field, as well as to present an outlook on the future application of TEG in PV. The results of the survey are shown in Figure 2. The research steps in this paper are divided into three steps: literature searching, literature screening and analysis, and data organization and presentation.

Use of specialized academic databases (e.g., Web of Science, ScienceDirect, SpringerLink) ensures the coverage of high-quality literature and access to the latest results and technological developments. The use of keywords such as "TEG," "PV-TEG," "SSPV-TEG," "CPV-TEG," "PV/T-TEG," "PV/T-PCM-TEG," and other related terms was employed to expand the scope by adjusting the combinations, thus avoiding the omission of important documents. In order to comprehensively understand the development history and latest progress of TEG in PV, the scope of literature covering the past decade or even longer was set, and important early studies were searched retrospectively.

2.2. Literature screening and analysis

The literature is screened according to criteria such as the relevance to research topics, the authority and influence of the literature, and the scientificity of research methods, excluding irrelevant, low-quality, or innovatively lacking literature. This process includes extracting key data and conclusions, analyzing consistencies and differences, focusing on application cases and practical effects, and classifying and summarizing the current status of research, major advances, and problems according to different topics (e.g., the working principle of TEG, the integration method with PV, performance evaluation, and application cases).

2.3. Data organization and presentation

Firstly, key data are extracted from the literature, such as the performance parameters of TEG, the efficiency improvement data of PV, and cost analysis. Meanwhile, graphs and charts are used to present the results of the study and data trends, thereby enhancing the readability and visualization of the review. Finally, we explain the meaning of the data, analyze the relationships and differences, and present our opinions and conclusions. Citespace was used to analyze the keywords of the literature related to the development of TEG in PV (Figure 2). Through the above methods, the literature and information related to the development of TEG in photovoltaic modules are systematically collected, analyzed, and summarized to provide a comprehensive review and reference for research in this field.

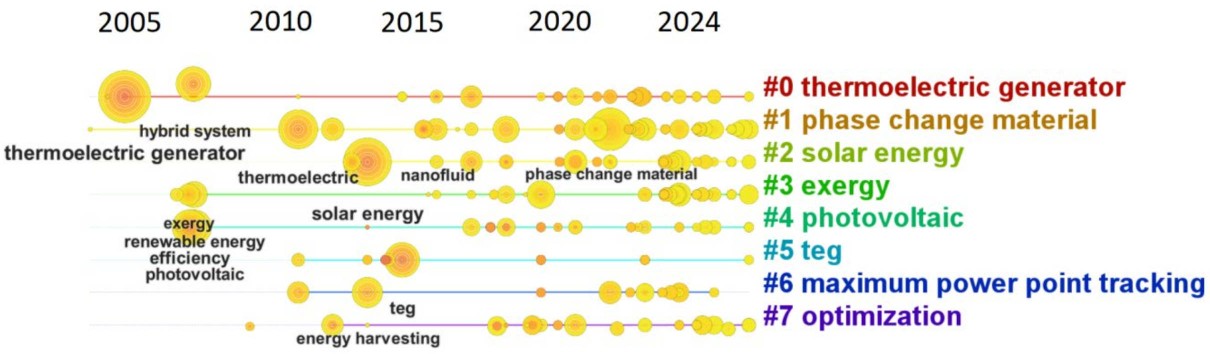

Figure 2. Linkage of different literature keywords with the earliest date of appearance (authors' concept).

3. Thermoelectric performance of different coupling assembly structure forms

3.1 Combinatorial history of coupled components

PV technology has traveled the initial development path from 1839, when Becquerel first discovered the photovoltaic effect and suggested that solar energy could be converted into electricity, to 1954, when Chapin *et al.* [26] first invented the solar cell with an efficiency of 6%. As researchers continue to learn more about PV, the average efficiency of the most commonly used solar panels on the market currently ranges from 15% to 20% [27]. However, according to the theoretical upper limit of solar cells, when silicon is used as the semiconductor material, the theoretical upper limit of the efficiency of a single-junction solar cell under non-concentration conditions is 33% [28]. Due to the aforementioned effect of temperature on PV efficiency, it's essential to dissipate the energy that the PV cell fails to transform into electricity to avoid overheating and performance degradation. Therefore, PV technology is developed based on how to cool the PV surface.

In the mid-1970s, Wolf *et al.* [29] introduced the concept of PV/T to improve PV efficiency by cooling the PV surface. Cooling is also categorized into active and passive cooling. In simple terms, active cooling involves the use of external energy, such as a fan or pumped fluid, to enhance heat dissipation, while passive cooling utilizes natural mechanisms like conduction, convection, and radiation without the consumption of additional energy. For both types of cooling, the media are mostly water or air. The first PV hot air collector was tested at the University of Delaware's Solar Energy Laboratory in 1973 [30].

Phase change materials (PCMs) are valued by many photovoltaic researchers for their ability to store usable thermal energy in an appropriate form and, when required, to store it in a suitable medium and extract it for later use [31]. Over the years, a great deal of research has been conducted to explore the application of PCM in PV, and many structural forms of PV/T-PCM have emerged [32]. Heat pipes are exceptionally efficient at transferring heat because they leverage the latent heat of vaporization, allowing them to move heat across long distances with minimal temperature differences [33]. The heat pipe operates on the principle that the working fluid within it vaporizes in the evaporation section when heated, and this vapor moves to the condensation section as temperatures rise. Subsequently, the condensed fluid returns to the evaporation section, perpetuating the cycle [34]. Modern heat pipes are also actively used in photovoltaic modules, and they have a great impact on the efficiency of photovoltaic modules [35].

In the year 1995, Choi and Eastman put forward the notion of nanofluids in light of their laboratory investigations [36]. From that moment on, the age of nanofluids was initiated. Nanofluids, which are essentially colloidal suspensions of nanoparticles within a base fluid, have emerged as a significant thermal management approach within energy systems, with particular emphasis in solar energy technologies [37]. Their relatively high thermal conductivity endows them with the suitability for cooling functions in photovoltaic and thermoelectric assemblies [38]. The incorporation of nanofluids into PV-TEG systems presents a novel opportunity to deal with the heat-associated performance problems that have chronically afflicted these systems [39].

With the continuous development of inexpensive optics, CPV technology has also started to concentrate solar radiation onto smaller photovoltaic cells by means of inexpensive optical devices, leading to the development of CPV technology [40]. Researchers have been engaged in concentrating solar energy-related developments since the late 1970s. Generally, the system consists of a PV subsystem, a thermal utilization subsystem, and a solar concentrator [41]. Heat management systems are of vital significance in concentrated photovoltaic (CPV) installations for a number of justifications. Initially, they are essential in managing the thermal energy generated by the intense sunlight hitting the photovoltaic cells. If suitable cooling techniques are not in place, the effectiveness of the cells may be severely diminished due to overheating. Additionally, the heat retrieved from the heat management system can be utilized for other functions, such as warming water or supplying heat to indoor spaces, thus enhancing the overall energy utilization rate and improving the system's operational proficiency. The merger of heat and electricity generation renders CPV systems more economically practical and environmentally sustainable.

One alternative means of exploiting solar energy is the split-spectrum photovoltaic (SSPV) system. This system functions by apportioning certain high-energy photons to the photovoltaic cells and directing a fraction of the low-energy photons towards other pieces of equipment [42]. The theoretical efficiency of the SSPV-TEG hybrid system is extremely high, showing its great potential for efficient solar energy utilization [43]. While the setup of the SSPV-TEG hybrid arrangement is more intricate compared to the directly-linked PV-TEG hybrid model, it exhibits the advantages of a reduced PV operational temperature and enhanced effectiveness [44]. Due to the complex structure of SSPV-TEG and the difficulty of conducting specific experiments with many relevant factors, many of the relevant studies are currently conducted based on simulations [45]. In 1955, Jackson [46] initially put forward the concept of capturing solar energy by partitioning the solar spectrum and channeling each spectral segment towards the most efficient converting device. However, the maiden experimental undertaking was carried through by Moon *et al.* in 1978. This specific methodology persists in being extensively utilized to tackle the spectral mismatch conundrum within solar cells.

Due to the characteristics of PV cells that decrease in efficiency with increasing temperature, cell thermal management is essential in PV installations to minimize the shortfall in PV module output power [47]. In the past decades, a diverse array of thermal regulation methodologies pertaining to PV systems have been suggested and appraised with regard to their practical viability. Among the proposed methods are air, liquid, heat pipe, phase change materials, thermoelectric devices. Hybrid photovoltaic-photothermal coupled temperature difference power generation systems provide a constructive approach to increase the power generation and heat recovery of PV cells, thus greatly improving the overall system efficiency, which is practically achievable [48].

3.2. Structure

As a result, many researchers have coupled TEG to photovoltaic modules in a number of different ways. These different structures produce different thermoelectric efficiencies, so in this paper we will categorize them into several groups and discuss them at the same time. At present, I have classified the TEG applications in PV found in published research papers into the following categories: PV-TEG, SSPV-TEG, CPV-TEG and PV/T-TEG. The four main coupling structures are analyzed in terms of structure, performance and optimization, respectively.

3.2.1. PV-TEG

PV panels have the potential to absorb approximately 80% of the incoming solar radiation. However, the conversion efficiency of the incident solar energy into electricity varies significantly depending on the specific photovoltaic cell technology employed. Crystalline silicon cells, which are widely used in the industry, typically convert no more than 20% of the incident energy into electricity under standard test conditions [16]. At a stage when PV technology cannot quickly break through the limitations of development, due to its low power generation efficiency, researchers proposed the PV-TEG coupling system based on the thermoelectric properties of TEG. Combining PV and TEG, the thermoelectric system has the dual function of cooling PV and improving energy utilization due to the complementary effects of the two devices [49]. The PV-TEG we mention here refers to the direct coupling of the PV to the TEG, the TEG is placed directly under the PV plate, and the two are in direct contact.

In 2024, Gopinath and Marimuthu [50] put forward a methodology to enhance the efficiency of PV panels through the integration of a thermoelectric generator (TEG) at the back of the PV panels. The paper further mentions that graphite flakes could serve as a heat dissipation component to augment the output of the PV-TEG system (Figure 3a). Zhu *et al.* [51] glued nine solar cells on a copper plate in series. On each flank of the copper plate, heat insulation material was affixed. Meanwhile, a thermally conductive silicone adhesive was employed to attach four series of TEG to the central area of the copper plate, with the aim of lessening the boundary thermal resistance. At the same time, a foam polymer was glued and filled in the circular gaps of the water blocks to avoid heat loss (Figure 3b). To minimize air convection, a polymethyl methacrylate (PMMA) shell was also designed, which manages the thermal aspects of all parts of the system to increase the power of the combined system. As shown in Figure 3c, heat pipe cooling is one of the passive cooling methods for PV, and the combination of PV system and heat pipe is beneficial to improve energy efficiency [33]. Rajpar *et al.* [52] developed a PV-TEG hybrid system, which is different from the previous one in that the TEG is placed directly behind the PV panels. This system connects the PV and the TEG in parallel by cooling water, realizing the utilization of the full solar spectrum and generating electricity from the secondary heat (Figure 3d). Channel cooling is also a type of active cooling for photovoltaics. Combining the photovoltaic system with channels is beneficial for improving the utilization rate of energy [53].

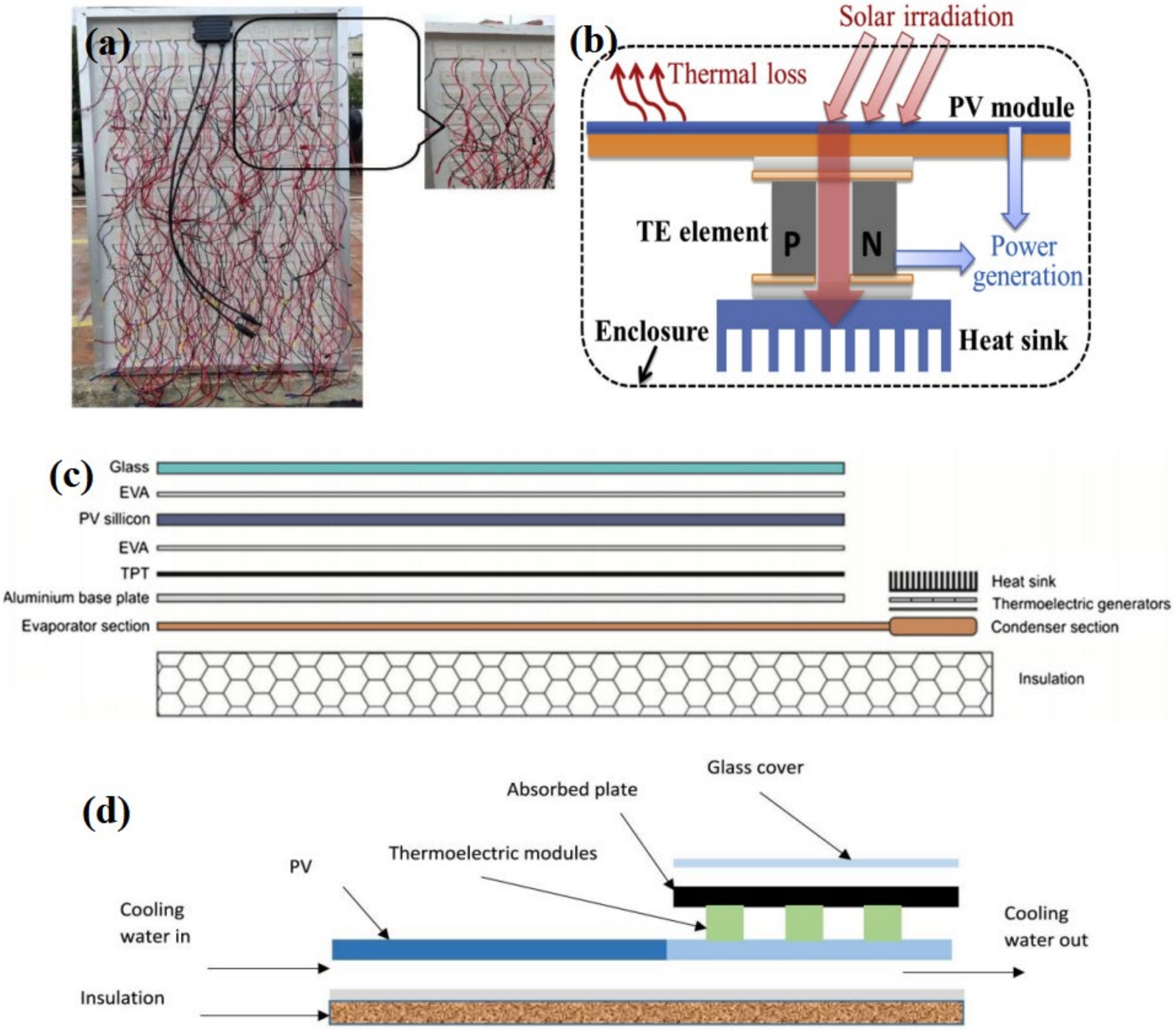

Figure 3. Schematic diagram of PV-TEG structure. **(a)** direct coupling [50]; **(b)** finned type [51]; **(c)** new heatpipe type [33]; **(d)** new water channel type [53]. Reprinted with permission. Copyright 2016 Elsevier.

3.2.2. SSPV-TEG

The direct coupling of PV and TEG is what PV-TEG represents. It is achieved by placing the TEG right under the PV plate so that they come into direct contact with one another. Moreover, there are other aspects as we described earlier. There is also a coupling method that utilizes the spectral splitting principle, a spectral beam splitter is used to split the sunlight into multiple parts, and the PV and the TEG absorb the energy of a certain part of it [54]. Compared with direct coupling, the structure of the spectrally split coupling system is more complex, and therefore receives less attention and research [55]. On the contrary, the thermoelectric analysis of directly coupled systems is of particular interest to researchers. However, the direct coupling of PV and TEG is limited in directly coupled systems due to the mutual mismatch of the efficiency-temperature characteristics of the two components, which restricts the further improvement of efficiency [56]. The fundamental principle underlying the SSPV-TEG hybrid system lies in the transfer of the solar spectral energy that remains unabsorbed by traditional PV to the TEG module, thus enhancing the overall energy utilization efficiency of the hybrid setup. A prevalent approach is to direct the high-frequency segment of the incident solar spectrum towards the PV and divert the residual low-frequency part to the TEG. This particular method of solar spectrum division is regarded as a prospective means to alleviate spectral mismatch and attain high levels of efficiency in solar energy conversion [57]. In the research conducted by Liang *et al.* [58], a two-axis tracking PV/T system integrated with a SiO2/TiO2 interference film was devised and fabricated (Figure 4a). Yin *et al.* [59] developed a coupled photoelectric thermal multiphysics field model of a spectrally split PV-T system combining microstructure and macroscopic properties in 2023, which utilizes a filter to split the sunlight spectrum and effectively improve the efficiency of the coupled system (Figure 4b).

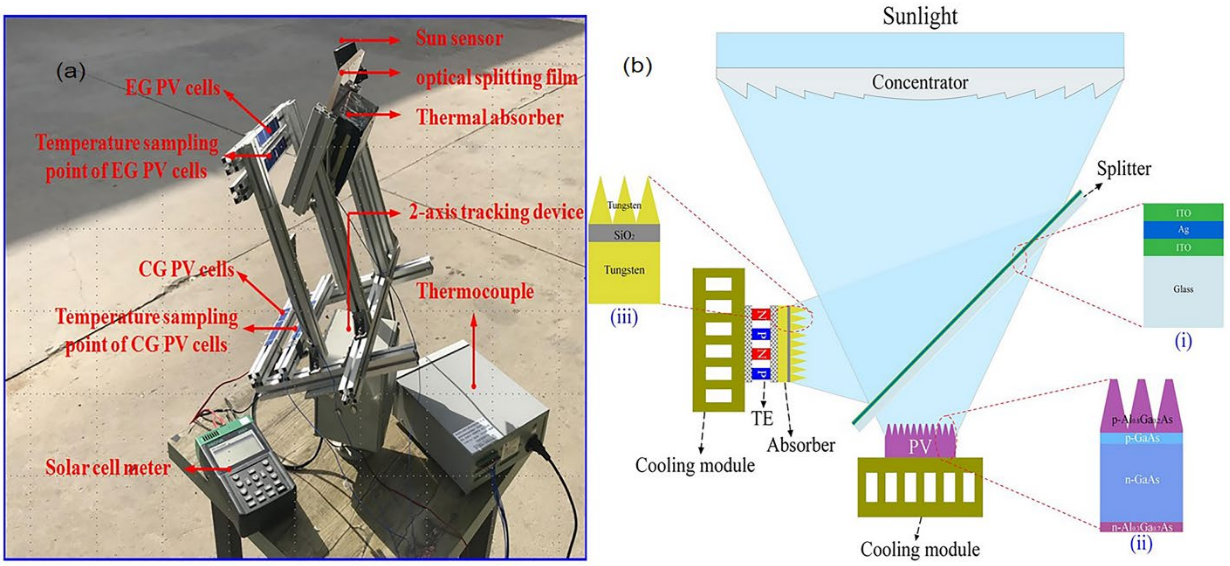

Figure 4. Schematic diagram of the SSPV-TEG structure. **(a)** tracking type coupling structure [58]; **(b)** diffuse coupling system [59]. Reprinted with permission. Copyright 2019, 2024 Elsevier.

3.2.3. CPV-TEG

Advanced solar energy conversion and utilization technology has perpetually constituted the central concern within the domain of solar energy research. This technological pursuit is advantageous for facilitating the progression towards high-quality and sustainable development of human society [60]. In recent years, concentrating solar thermal utilization has inspired many innovative designs and design improvements due to its flexibility, manufacturability, high efficiency, and multi-output characteristics [61]. Concentrating solar thermal technology has great potential for better energy and environmental returns as well as practical applications [62]. The amalgamation of solar concentrators and photovoltaic cells constitutes the most potent way to lower the cost of commercial photovoltaic cell power generation systems [63]. Combined CPV-TEG systems can be further categorized into two different types [64,65]: One method employs the technology of spectral beam splitting, while the other leverages the technique for recovering waste heat. The above-mentioned is the first type, the spectral beam splitting system. It can also be categorized into point focusing and line focusing by the focusing system of the concentrator [66]. Point focusing includes parabolic dishes and solar towers, while line focusing includes parabolic troughs and linear Fresnel reflectors. Mohsenzadeh *et al.* [67] proposed an innovative CPV/T solar system integrated with a thermoelectric module. In this system, PV monocrystalline silicon cells are fixed on the sidewalls of a triangular heat-absorbing duct. Meanwhile, the thermoelectric module is placed between the PV cells and the duct's cold surface. Finally, the whole assembly is installed at the focus of a linear parabolic concentrator with a polar solar tracker along the N-S axis, as shown in Figure 5a. Shadmehri *et al.* [68] built a novel concentrating photovoltaic thermal solar system with a triangular cross-section heat absorption duct as shown in Figure 5b. Flores *et al.* [69] proposed and implemented a design and optimization method for a hybrid energy harvesting system (Figure 5c).To sum up, the proposed approach enables the enhancement of the comprehensive performance of the energy harvesting system via a successive incorporation procedure of optimization strategies. A thorough energy balance examination is carried out to ascertain the influence on energy generation. Zhang [70] formulated a numerical paradigm of a low concentration photovoltaic/thermal (LCPV/T) collector interconnected with a thermoelectric generator (TEG), and the new coupled system has the potential for future development by concentrating photovoltaic to heat the water, generating a temperature difference with the original water temperature, and using it to generate electricity (Figure 5d). This structure is different from the one designed by Mohsenzadeh *et al.* because they took the TEG out separately and utilized the hot water to create the temperature difference.

3.2.4. PV/T-TEG

The use of water or air to cool PV can be effective in increasing power generation [71]. Researchers have investigated several PV/T-TEG conceptual designs that utilize different heat extraction mechanisms to achieve the maximum power of the coupled system. Maleki *et al.* [72] compared the performance of two systems, PV/T-TEG-2PCM and PV/T-TEG, in terms of heat, electricity, and exergy, and this particular system design can serve as a framework for the next step in the research to improve the hybrid efficiency of solar energy systems, especially for home applications where there is a special need for low maintenance, affordability, and durability (Figure 6a). Li [73] proposed a novel system combining photovoltaic (PV) panels, phase change materials (PCM), TEG, and a heat harvesting device (PV-PCM-TEG-T) (Figure 6b). Li *et al.* [74] presented the PV/2T-PCM-TEG coupled system with a novel PV/2T-PCM-TEG module design, featuring serpentine copper tubes at the cold part of the PCM layer and the TEG module (Figure 6c).

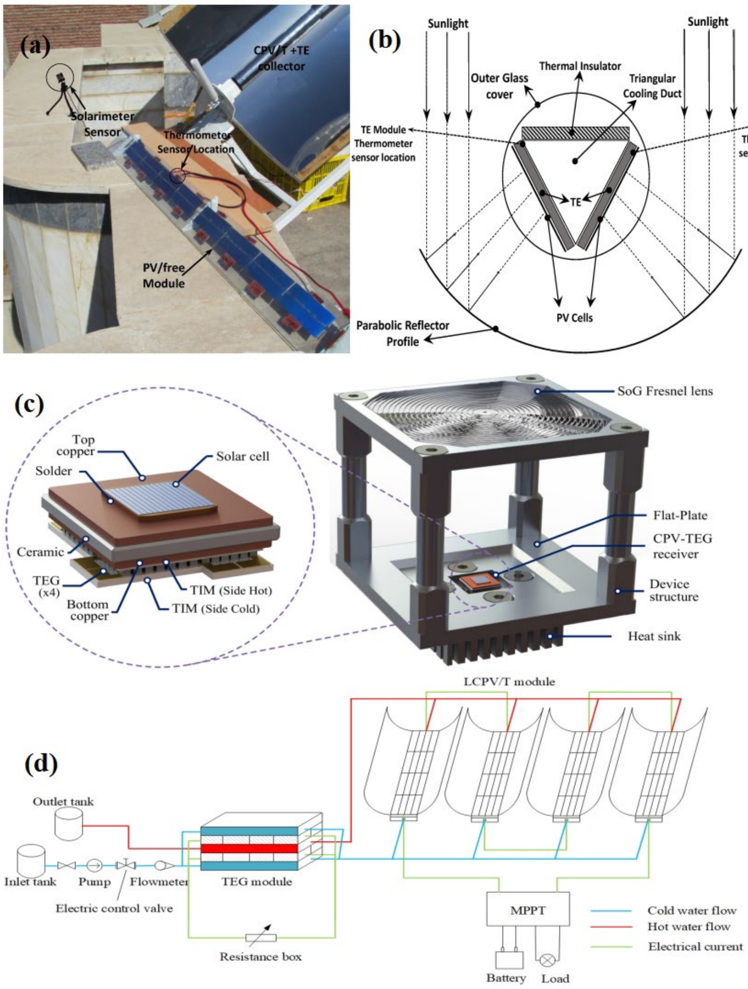

Figure 5. Schematic structure of CPV-TEG. **(a)** direct coupling [67]; **(b)** triangular cross section [68]; **(c)** thermo-interfacial material coupled type [69]; **(d)** LCPV/T-TEG [70]. Reprinted with permission. Copyright 2017, 2018, 2024, 2021 Elsevier.

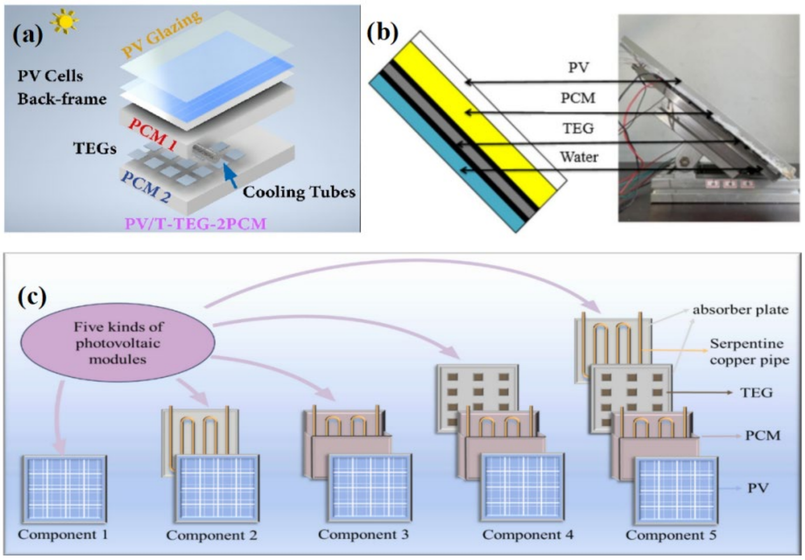

Figure 6. Schematic diagram of PV/T-TEG structures. **(a)** PCM type [72]. **(b)** PCM and water channel type [73]. **(c)** PV/2T-PCM-TEG structure [74]. Reprinted with permission. Copyright 2022, 2024 Elsevier.

3.3. Performance

Parthiban *et al.* [75] proposed a PV-TEG coupled system, and experimental validation showed a 15% space saving and an overall efficiency increase of 14%–16% compared to the use of PV panels alone. This clearly demonstrates the superiority of the coupled system compared to ordinary PV systems. The effectiveness of the PV panels was boosted by attaching a thermoelectric generator (TEG) to their back. The results revealed that with the TEG's hot side at 37.937 °C and the cold side at 31.255 °C, the maximum TEG voltage achieved via this method was 13.515 V and the largest temperature gap was 6.682 °C [50]. For a PV-TEG hybrid system modeled in MATLAB for energy simulation, the PV efficiency was only 12.0% while the TEG efficiency reached 4.7%. Significantly, the TEG assembly's efficiency was highly affected by weather factors, inlet cooling water temperature, and fluid flow speed [53]. Fatih *et al.* [76], in their study on how to improve the coupled PV-TEG assembly's energy and exergy performance, proposed an approach to utilize different shapes of nano-enhanced cooling channels. They used finite element computational simulation to numerically analyze different cooling channel (L-, T-, and U-shaped) pairs. Among the various cooling channels, the U-shaped channel had the best cooling performance, the T-shaped channel had the worst cooling performance, and the U-shaped channel had an exergy efficiency of up to 14.6%.

Wei and Lin *et al.* [77] proposed a PV-TEG power supply system for bridge safety monitoring microsystems, with 132 Wh of PV power and 0.9 W of TEG power. Zhang *et al.* [78] used Simulink to study insulation's effect on TEG efficiency; the PV-MCHP-TEG system's insulation efficiency was 19.32%, 2.41% higher than the non-insulated PV-TEG system. Zhu *et al.* [51] developed a PV-TEG hybrid system by optimizing thermal management, achieving 23% peak outdoor efficiency, 25% higher than PV cells (Figure 7a). Farhani *et al.* [79] designed a PV-TEG system for low power thermal energy harvesting, with the TEG harvesting nearly 7 mW. Mohsenzadeh *et al.* [67] devised a system and evaluated its performance. The system with a polar one-axis solar tracker shows the daily average electrical efficiency can reach 4.83%. But due to solar irradiation, the CPV-TEG hybrid system's surface temperature is high and its power generation efficiency is lower than that of a normal PV system. (Figure 7c). Li *et al.* [74] built PV/T, PV/T-PCM, and PV/T-PCM (50% paraffin + 50% petrolatum, R22 as heat transfer fluid) experimental platforms (Figure 7d).

Studies on tandem photovoltaic thermoelectric systems typically examine high-temperature performance with the TEG placed under photovoltaic panels. Gao *et al.* [80] compared conventional and bifacial PV-TEG structures under uniform and non-uniform radiation, finding the bifacial structure increased cell output power by 9.28%. He and Ji *et al.* [81] modeled a bi-directional PV-PCM-TEG system, their findings indicated that the PV achieved a maximum output power of 0.16 W and an efficiency of 16%, while the TEG had a maximum output power of 0.08 W and an efficiency of 1%. It was also noted that thicker PCMs contributed to the improvement of the overall performance. Wei *et al.* [82] introduced a 24-hour coupled system with a phase change material, achieving peak efficiency at 38 °C and 30mm thickness, with efficiencies of 19.6% for PV, 1.2% for TEG, and a total of 20.8%. Khan *et al.* [83] integrated PCM and TEG into a PV module, reducing the average temperature by 9.28 °C and increasing output power by 9.69%.

Alnahhal *et al.* [84] demonstrated that a hybrid PV-TEG system achieved 32.10% efficiency at 10-sun concentration, surpassing the 26.34% of a standalone PV cell. Eke *et al.* [85] reported a 42% efficiency for spectrally split chalcogenide/silicon solar cells integrated with TEG devices, which is 1.8 times more efficient than a standalone solar cell at an 800nm separation wavelength. Yang *et al.* [86] enhanced a concentrating solar spectrum splitting PV-TEG system model, achieving a maximum efficiency of 40.2%, with a focus on the collector PV cell area ratio's impact on system performance. Chen *et al.* [87] derived mathematical models for a coupled system's efficiency and power output, showing improvements of 9.89% and 9.87% respectively over standalone PV, and a 10.4% increase in reactive energy efficiency. Wang *et al.* [41] introduced a novel solar concentrator system with a beam splitter, achieving 30.5% PV conversion and 26.6% total energy efficiencies, both higher than conventional standalone systems, by optimizing incident light angle and solar thermal tube operating temperature.

Yin *et al.* [59] used thermodynamic analysis to reveal energy and loss distribution in the system. Results showed that the largest losses in energy conversion were in concentrating and splitting, with a 33.3% light loss of total input energy. The photovoltaic conversion process had a 51.5% energy loss, and the thermoelectric conversion process had an 87.8% loss. The study results are significant for understanding the spectral photothermoelectric system’s working principle, optimizing performance, and advancing its application. Liang *et al.* [58] experimentally showed that using the SiO_2/TiO_2 interfering thin film increased PV cell power generation by 10% (Figure 7b). Cuce *et al.* [88] showed that compared to the pure parabolic trough PV system, the parabolic trough PV thermoelectric hybrid system’s total thermal efficiency can increase by 70% and electrical efficiency by 5%. Mohsenzadeh *et al.* [67] proposed a new integrated design for a concentrating photovoltaic/thermal solar system with a thermoelectric module. The mean daily electrical and thermal efficiencies attained were 4.83% and 46.16% correspondingly.

Sabry *et al.* [89] utilized finite element analysis to study a CPV-TEG hybrid system, finding a 7.4% power generation increase over CPV with a radiator. Zhang *et al.* [70] observed a 1.68 W, or 2.85%, power boost in summer with a TEG module in LCPV/T systems, analyzing environmental impacts, economic aspects, and seasonal energy savings. Wu *et al.* [90] introduced a self-cooling CPV system with thermoelectric modules, reducing temperatures by 39% and enhancing the CPV plant's efficiency over passive cooling methods. Wen *et al.* [91] implemented a micro-channel heat pipe and TEG in a CPV/T system, increasing average electrical efficiency from 7.62% to 8.95% and averaging 8.33 W of TEG power over 4 hours. Kohan *et al.* [92] developed a numerical model showing that a CPV-TEG system benefits from a weaker cooling system due to increased TEG efficiency from higher CPV surface temperatures. Shadmehri *et al.* [68] optimized thermoelectric properties with an aperture width of 1.6–2.2 m and a vertex angle of 80°–120°.

Maleki and his colleagues [72] ascertained that the PV/TEG-2PCM configuration surpassed the PV/T-TEG arrangement. Precisely, it curtailed the mean temperature of the solar cell by a considerable 89.4% and amplified the temperature disparity of the TEG by 1.2%, resulting in an 8.1% augmentation of the mean electrical efficacy and a 9.9% enhancement of the overall efficacy. Meanwhile, Rajaee [93] contrived a hybrid PV/T-TEG setup integrating Co_3O_4/water nanofluid and phase-transition material. The experimental outcomes signified that when implementing 1% nanofluid-amplified PCM for cooling, the electrical efficiency was amplified by 12.28% relative to water-cooling, and the PV/T-TEG efficiency experienced an increment of 11.6%. To sum up, these innovative systems and techniques markedly magnify the utilization of solar energy, eclipsing solitary PV panels and presenting promising prospects for the development of solar energy utilization technology.

Lekbir *et al.* [94] developed a MATLAB simulation for a concentrating photovoltaic-nanofluid-photothermal coupled system, achieving an average exergy efficiency of 15.28% and reducing CO2 emissions by up to 1208.9 kg annually per 1 m2. Shoeibi *et al.* [95] proposed a solar collector integrating PV panels, heat pipes, and TEG, with maximum hourly power generation of 68 W, 69 W, 73 W, and 75 W for different configurations, and electricity costs of \$0.061/kWh, \$0.141/kWh, \$0.128/kWh, and \$0.147/kWh, respectively. Fini *et al.* [96] presented a hybrid system with polycrystalline PV panels, a thermoelectric module, and a water-cooled heat exchanger, based on a one-year finite element simulation. This system showed an average maximum PV temperature of 44.2 °C, compared to 57.1 °C for standalone PV, with power generation of 9.49 W, significantly higher than the 8.48 W of standalone PV.

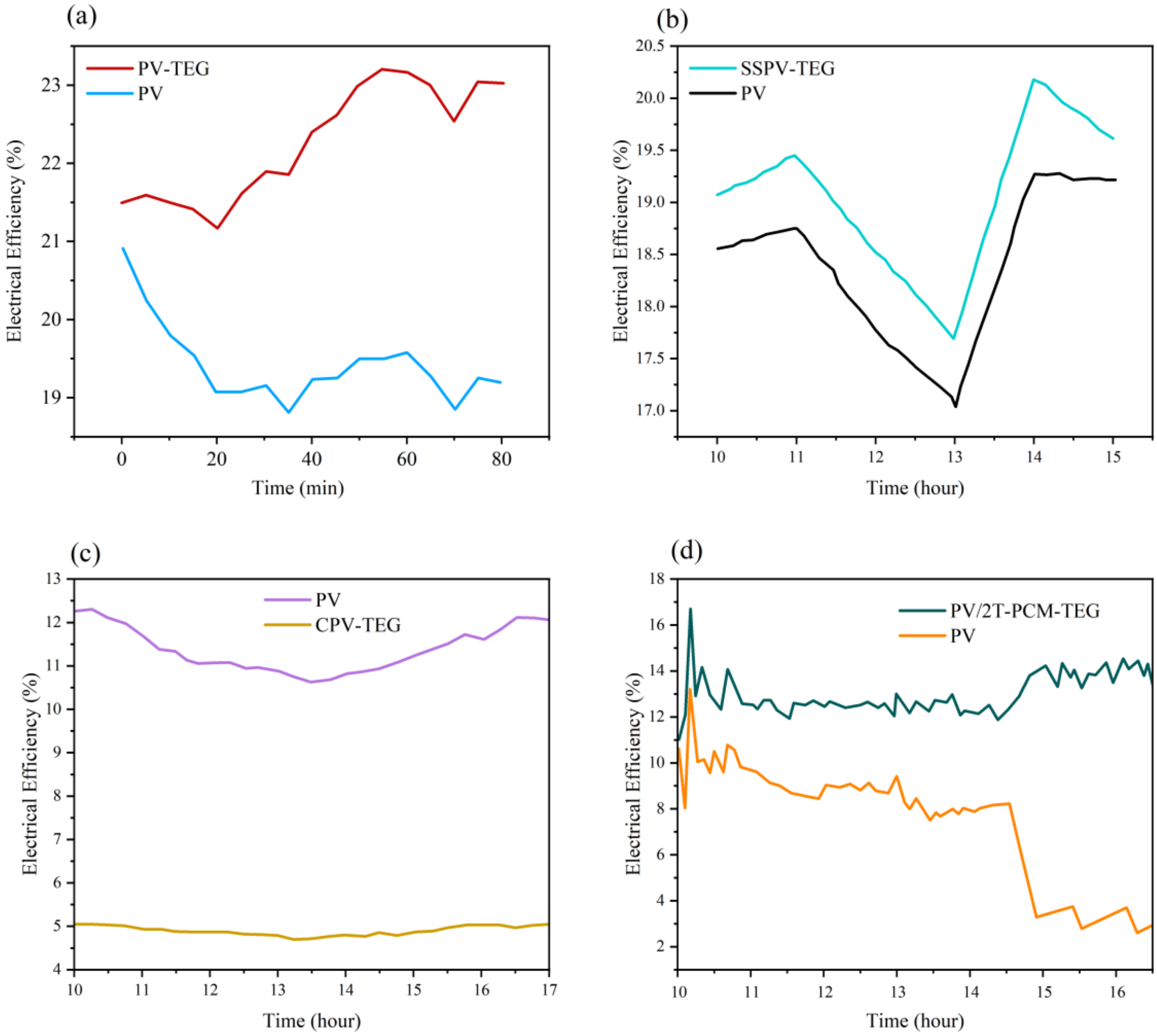

Figure 7. Partial structural properties of **(a)** PV-TEG [51] **(b)** SSPV-TEG [58] **(c)** CPV-TEG [67] **(d)** PV/T-TEG [74].

3.4. Optimization

The hybrid system must encounter partial shading conditions caused by some other factors during the actual operation, and the temperature of some components of the hybrid system will increase dramatically under partial shading conditions, which is called the hot spot effect [97]. It also leads to an uneven temperature distribution of the TEG coupled to the PV, so this is also known as non-uniform thermal distribution (NTD) [20].

Wang *et al.* [98] proposed a Chaos Driven Dynamic Interactive Whale Optimisation Algorithm (CDI-WOA)-based multi-optimization strategy for PV-TEG systems, enhancing maximum power output by 32.02%. This is because under partial shading conditions and non-uniform heat distribution, multiple local maximum power points occur in hybrid systems, where maximum power point tracking techniques (MPPT) play a crucial role [99]. Yang *et al.* [100] developed an MPPT design for PV-TEG systems under partial shading using the Salp swarm algorithm, achieving up to 43.75% higher energy output and effective power fluctuation suppression. Mirza *et al.* [101] introduced an intelligent control system for hybrid PV-TEG, achieving a power tracking efficiency of 99.86% under dynamic conditions. Xiong *et al.* [102] optimized a PV-TEG system with a genetic algorithm, increasing theoretical average power to 0.343 W (2.69% more than a single PV cell) and average power to 0.317 W (0.32% more), offering insights for solar energy applications in Northwest China. Kidegho *et al.* [21] improved PV module power by 2.5% and TEG power by 50.6% by optimizing thermal interface materials.

Jamali *et al.* [103] proposed a flat reflector-enhanced PV-TEG system, which combines a flat reflector with a PV-TEG system to improve solar energy utilization with a daily thermal efficiency of 42%. Meanwhile, the rise of flexible thermoelectric materials has become a major driving force for the development of PV-TEG hybrid systems into wearable electronics [104]. Zhang *et al.* [105] achieved high thermoelectric performance through combining dimethylsulfoxide doping and NaBH4 regulation with a composite film having an output power of 391 nW at a temperature difference of 20 K and high thermal and electrical performance. A passive heat transfer device, known as the microchannel heat pipe, transfers heat over long distances by taking advantage of the latent heat of vaporization [106]. Zhang *et al.* [78] proposed a novel PV-MCHP-TEG system integrating a photovoltaic (PV) cell, a microchannel heat pipe (MCHP) array, and a thermoelectric generator (TEG) module component with an insulating layer strategically placed for year-round, day and night power generation.

PCM-based TEGs outperform those without PCM, positively affecting power output compared to standard PV and PV/TEG systems. The complexity of PV-TEG systems has led researchers to propose various optimization methods. Deep learning, increasingly emphasized in solar energy utilization, has also been highly regarded by an increasing number of researchers and applied to predict the performance of PV-TEG systems[107]. Zhu *et al.* [108] developed a 3D artificial neural network model predicting a 6.4% increase in total power output (265 kWh/m^2) compared to standalone PV systems, with 97.6% accuracy and 6000 times faster simulation speed than COMSOL. Twelve PV-TEG configurations were subjected to tests by Alghamdi *et al.* [39]. It was found that in the system with the best performance, there was a 12% increase in power output. Additionally, the superiority of graphene nanofluid in thermal management at the optimal flow rate of 2 m/s was highlighted. Kohan *et al.* [92] found that the daily performance of PV-TEG systems remained unchanged under constant cooling conditions due to insufficient temperature difference for TEG efficiency enhancement.

Elsarrag *et al.* [109] found that selective absorbent materials and beam splitters enhance TEG performance and overall PV efficiency by reducing convective heat loss. Yin *et al.* [42] optimized a centralized beam splitting PV/T system, suggesting lower thermal resistance in TEG for optimal operation. Yang *et al.* [43] experimentally determined that an 880 nm cutoff beamsplitter maximized the output power of a PV/T hybrid system, 1.5 times that of a single PV system, and identified factors improving coupling performance. As the concentration ratio grows, the system's total power ascends and the thermoelectric power's share in the total power also rises. In this experiment, when the heat-to-electricity relative ratio is less than 0.5 at high temps, the SSPVT collector with the optimal filter has a much better overall effective efficiency than the similar regular solar collector. The photovoltaic bandgap, splitter cutoff wavelength, concentration ratio, thermal features, and thermoelectric structural elements are the main aspects that strongly affect the SSPV-TEG coupled system's performance [110].

Mahmoudinezhad *et al.* [111] modeled a CPV-TEG system, showing power generation increased with solar radiation but CPV efficiency decreased; system optimization was achieved through TEG geometry and material properties. The results show that increasing convective heat transfer increases the power generation and efficiency of CPV and TEG, while the rate of this increment decreases at higher convective heat transfer, so the optimal convective heat transfer must be found [112].

Alghamdi *et al.* [113] achieved 14.2% efficiency with a CPV-TEG module using PbTe, with significant energy and carbon savings, utilizing genetic algorithms for material optimization. Sarabi and Hekmat [114] demonstrated that PCMs, particularly those with higher latent heat, significantly increased CPV power output. Akbar *et al.* [115] evaluated PV/T-TEG, finding Ag-H_2O increased efficiency by 20.68% and genetic algorithms optimized hybrid power and efficiency. Gharapetian *et al.* [116] integrated nanofluid-cooled TEG with PV panels, with CuO-Fe/W nanofluid enhancing PV and TEG power output by 65.9% and 187%, respectively. Azizi *et al.* [117] combined finned tubes and restricted jets, improving TEG and thermal performance by 86.13% and 26.42%, respectively. Rejeb *et al.* [118] modeled CPV-TEG-PCM systems, showing efficiency in hot climates with moderate melting temperatures. A numerical model for a PV-PCM-TEG-T system was developed by Li [73]. Subsequently, through experimental verification, it was determined that this system exhibited lower temperatures and a higher TEG power generation in comparison to standard PV panels. In parallel, an environmental and economic analysis was carried out by Kan *et al.* [119]. The results indicated that the PV-PCM-TEG-T system possessed better energy savings and conversion efficiency when contrasted with both the PV and PV-PCM-T systems.

3.5. Discussion

3.5.1. Comparison between structures

As shown in Table 1, Marandi [120] proposed a hybrid PV-TEG module consisting of five photovoltaic panels filled with solar cavities for better utilization of solar energy compared to conventional systems. Although the direct coupling of PV and TEG improves the energy utilization, the uneven temperature distribution of the PV cells leads to coupling difficulties. Optimization of the performance of PV-TEG coupled systems is an ongoing process that requires innovative and strategic design as well as good thermal management in order to achieve large-scale applications.

Table 1. Performance of some coupled systems.

Reference	Methods	PV	TEG	System performance	Highlights	Type
Marandi *et al.* [120]	experiment	NA	TGM-127-1,4-2,5	System power: 1008 mW Efficiency: 21.9%	Power at 5 × 5 aperture: 15% reduction Power at 2.5 × 2.5 aperture: 33.6% reduction	PV-TEG
Alghamdi *et al.* [113]	simulation	NA	Bi_2Te_3	Coupled system power increase: 12%	Configurations tested; Nanofluids evaluated: graphene; TEG design: assessed	PV-TEG
Kohan *et al.* [92]	simulation	SolarTech SPM020P-BP	GM200-71-14-16 GM200-127-14-16 GM200-49-45-25	C-49 system: 0.57% performance gain C-71 system: 3.04% performance loss	TEG models compared: TEG71, TEG127, TEG49	PV-TEG
Chen *et al.* [87]	simulation	NA	Bi_2Te_3	Max power output increase: 9.87% Max energy conversion efficiency Increase: 9.89%	Two-stage TEG Energy and exergy efficiency improved Optimal design and operation	SSPV-TEG
Huang *et al.* [121]	simulation	Si and CdTe	NA	PV efficiency up to 49.5%	Optimal filter configurations; SSPVT Collector; Solar energy systems	SSPV-TEG
Yin *et al.* [59]	simulation	GaAs	1MD04-031-03TEG	PV conversion efficiency: 42.3% TEG conversion efficiency: 7.4%	Energy loss distribution PV and TEG conversion losses	SSPV-TEG
Liang *et al.* [58]	experiment	polycrystalline silicon	NA	Energy efficiency with film: 22.72% Exergy efficiency with film: 18.81% Increase in energy efficiency: 4.94% Increase in exergy efficiency: 1.03%	Two-axis tracking PV/T system Interference thin film; Temperature control Solar energy utilization: promising solution	SSPV-TEG
Singh *et al.* [122]	simulation	Siemens SP75	Bi_2Te_3	PV max efficiency: 10% Coupled system max efficiency: 12%	Hot spot formation	CPV-TEG
Mahmoudinezhad *et al.* [111]	simulation	Multi-junction Cells	NA	TEG max efficiency: 1.8% CPV max efficiency: 40.5%	TEG geometry optimization; Better heat sinks	CPV-TEG
Rejeb *et al.* [123]	simulation	NA	RT26	Dubai summer system CPV peak power: 170 W/m^2 Dubai summer system TEG peak power: 1.317 W	CPV-TEG-CM Integration; Performance optimization across climates	CPV-TEG
Shoeibi *et al.* [95]	experiment	NA	TEG1-12611–6	Power generation increase: 20.9% Thermal efficiency: 47.9% Electrical efficiency increase: 5.2%	Heat pipes and TEG application; Solar still performance enhancement	PV/T-TEG
Ahmadlou *et al.* [124]	experiment	Crystalline Silicon Photovoltaic Panel	1206-TEC	Max electrical power of PV panels: 4.46 W Max electrical power of TEG module: 4% at 13:00	SWCNT/Water nanofluids	PV/T-TEG
Li *et al.* [73]	experiment	single crystal silicon	TEM1-12706	PV panel power increase: 10.4% PV panel efficiency increase: 1.9% TEG max output power: 0.94 W	Temperature drop: 10.1 °C; Integrated PV-PCM-TEG-T system	PV/T-TEG
Li *et al.* [74]	experiment and simulation	GHGN-D50WK	SP1848–27145	Max power efficiency: 12.97% Avg total exergy efficiency: 55.11% Increase over first four: 42.61%, 11.39%, 5.92%	Temperature drop: 10.8 °C compared to Previous designs; PV/2T-PCM-TEG design	PV/T-TEG

Conventional photovoltaic cells are susceptible to heat loss, can only absorb spectral energy at specific frequencies, and cannot be fully converted into electrical energy [125]. The SSPV-TEG system separates the spectra through a spectral beam splitter for PV and TEG respectively, which improves the efficiency of solar energy utilization [126]. The SSPVT collector model proposed by Huang [121] has a significant effect on the spectral and energy distribution of the collector by moving the filter to adjust the relative ratio of thermal and electrical energy.

While CPV technology is driving the popularization of PV, it requires cooling to maintain performance, and active cooling is power-consuming and complex. The use of TEG not only cools the solar cells but also utilizes the waste heat. The economics of CPV-TEG are low and need to be further improved. Strategies to solve the CPV waste heat problem include TEG, microchannel heat pipes, and nanofluid cooling to absorb and utilize the thermal energy. The advent of TEG has provided a fresh solution for addressing the overheating problem that CPV encounters. Further research will be required in the future to optimize the coupling [127]. As shown in Table 1, Rejeb *et al.* [123] conducted a finite element method study using COMSOL and developed a polynomial statistical model, which revealed that the maximal electrical efficiency of the CPV-TEG was 17.448% when certain operating parameters were applied.

PV/T systems generate both electrical energy and low-grade thermal energy, which have multiple applications, like space heating, industrial process heating, the preheating of fluids used in industrial or domestic settings, and crop drying [128]. However, due to practical obstacles, the optimization of PV/T-TEG systems also requires cost reduction and efficiency improvement on one hand and cost reduction on the other. Only when these two objectives are achieved, the wide application of the coupled system will be truly realized. Li *et al.* [74] developed PV/2T-PCM-TEG. It enhanced PV power output and thermal energy capture, with average and optimal exergy efficiencies of 14.86% and 18.50%. Thus, the module offers a design reference for PV/T-TEG by improving thermoelectric performance. Typical PV-TEG systems place the TEG directly behind the PV plate (Figure 8a); SSPV-TEG systems use a beam splitter to split the spectrum to make full use of the spectrum to utilize the TEG separately from the PV (Figure 8b); CPV-TEG systems use a concentrator system to increase the concentration of the TEG under the PV (Figure 8c); PV/T-TEG systems are an expression of maximizing the use of solar energy by utilizing the solar thermal The PV/T-TEG system is a way to maximize the use of solar energy, utilizing the solar thermal and photovoltaic effects, and the typical structure also places the TEG under the PV device while increasing the temperature gradient (Figure 8d).

3.5.2. Economic feasibility analysis

(1) Analysis of TEG cost trends

Bi_2Te_3 has long been used as a thermoelectric material and is widely recognized as one of the most excellent and commonly utilized thermoelectric substances in the near-room-temperature region. However, the traditional methods for manufacturing Bi_2Te_3-based thermoelectric materials are fraught with significant drawbacks, which seriously impede their progress towards commercial production.

When it comes to the synthesis time, taking a typical traditional process as an example, the process from the initial processing of raw materials to obtaining thermoelectric materials with specific performance features usually requires a long time span. In some cases of preparing Bi_2Te_3 by the solid-state reaction method, the raw materials such as bismuth (Bi) and tellurium (Te) must first be carefully ground and thoroughly mixed, a process that may take several hours. Then, a long sintering reaction in a high-temperature environment is generally needed, often lasting more than ten hours or even longer, to achieve a relatively good crystalline structure for the material. The entire synthesis process incurs an extremely high time cost.

During the raw material preparation stage, it is crucial not only to ensure the extremely high purity of elements like Bi and Te but also to meet strict requirements regarding their particle size distribution and crystalline shape. This requires the implementation of multi-step pretreatment procedures, including purification and screening. In the synthesis process, many parameters such as reaction temperature, heating speed, holding time, and reaction atmosphere require precise control. The precision requirements for these parameters are extremely high. Even a slight deviation can lead to significant fluctuations in the material's performance, thus affecting the uniformity and stability of the final product. Currently, the main costs of TEG mainly come from raw materials and the relatively complex manufacturing processes. The specific costs can be seen in Figure 9.

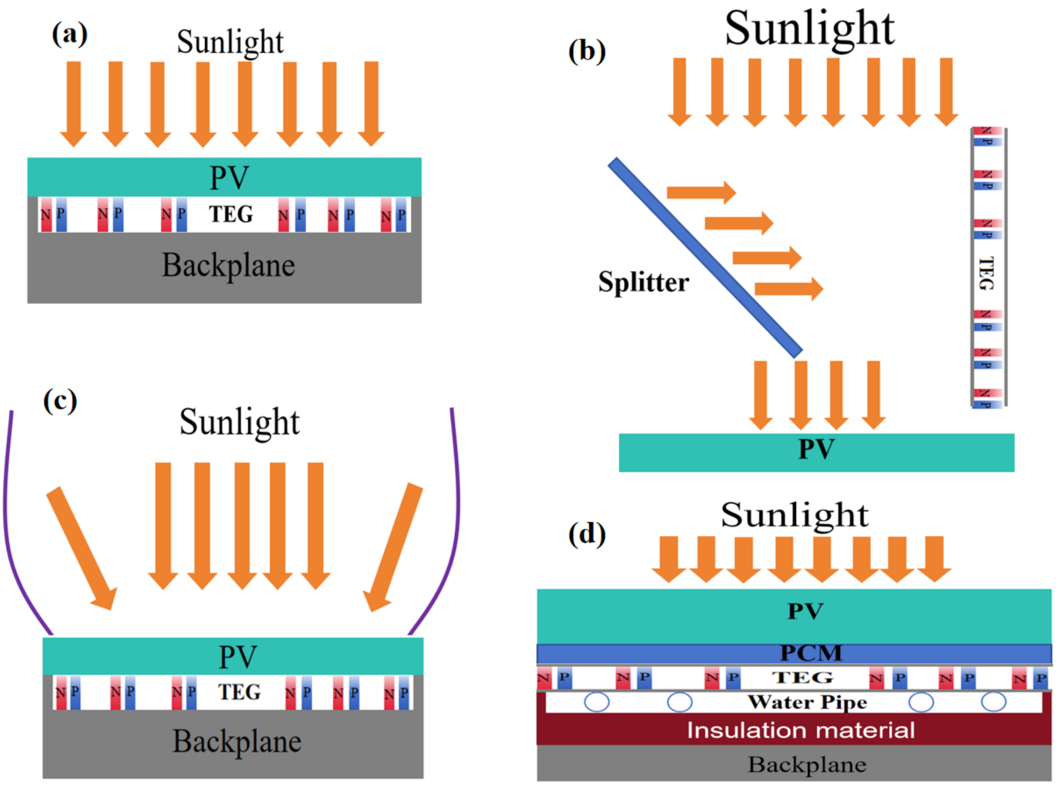

Figure 8. Schematic diagrams of four typical structures **(a)** PV-TEG; **(b)** SSPV-TEG; **(c)** CPV-TEG; **(d)** PV/T-TEG (authors'concept).

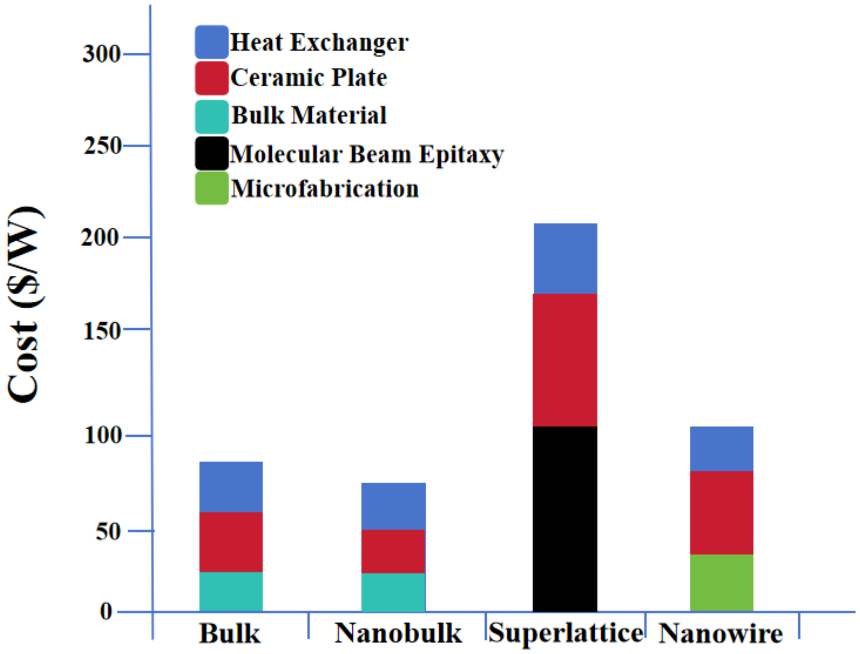

Figure 9. TEG Cost Composition [129]. Reprinted with permission. Copyright 2014 Elsevier.

High-pressure approaches possess remarkable strengths in the synthesis of thermoelectric substances, yet they are accompanied by certain drawbacks. The production can be finalized within a single hour, which brings about a significant boost in production efficiency in comparison with traditional techniques like melt crystallization. High-pressure apparatuses are capable of accurately regulating pressure and temperature, leading to high experimental reproducibility and stable sample qualities, which is advantageous for subsequent examinations and device manufacturing. It can augment the compactness of materials, allowing the sample to transfer heat and charge more effectively, enhancing the thermoelectric performance and evading issues such as porosity that exist in materials prepared by traditional means. Moreover, it can modulate the material properties, optimize the carrier concentration and mobility, and elevate the thermoelectric figure of merit. However, high-pressure methods also have limitations: they demand advanced equipment with high procurement costs, and their maintenance and operation require professional staff and additional inputs, thereby augmenting the labor and resource expenditures. To realize the extensive utilization of TEG in the photovoltaic realm, cost reduction is a crucial problem that demands immediate attention. In the future, it is essential to carry out in-depth investigations into alternative raw material options and explore more economical and sustainable material origins. Concurrently, endeavors should be made to streamline the manufacturing process, enhance production efficiency, and curtail the manufacturing cost of TEG through technological innovation and large-scale production.

(2) Analysis of PV-TEG cost trends

The expenditure of the PV-TEG system is comprehensively affected by a variety of elements. The variation of raw material prices has a significant effect on the system expenditure.

Precisely, changes in the price of silicon substances within the photovoltaic module and the unsteadiness of thermoelectric material prices in the TEG component directly affect the total outlay of the PV-TEG system. The possibility of improving the manufacturing process is a critical factor in the cost trend. If more proficient and economical manufacturing methods were devised, along with the streamlining of the integration between the TEG and the photovoltaic module and a cutback in energy consumption and material waste during production, it would assist in reducing the system cost. Market rivalry also has a crucial part to play in the cost trend. In light of the surging demand for clean energy in the market, the PV-TEG system is faced with competition from other renewable energy technologies. To boost market competitiveness, cost reduction has turned into an indispensable option. At present, although the PV-TEG system has merits in comprehensive energy utilization, its comparatively high cost limits its wide application. In the future, with the continuous progression of technology and the development of the market, it is expected that costs can be cut down through mass production, industrial chain consolidation, and technological innovation. Mass production can bring down the production cost per unit item, industrial chain consolidation can optimize resource distribution and reduce intermediate link costs, and technological innovation might introduce more efficient and inexpensive materials and manufacturing processes, allowing the PV-TEG system to become more cost-competitive and gradually access a broader application market.

(3) Analysis of SSPV-TEG cost trends

The SSPV-TEG system, because of the utilization of spectral splitting methodologies, displays a relatively elaborate configuration, thus resulting in a significantly increased initial expenditure. The production and setup of spectral separation devices demand additional expenditures, heightening the total cost of the system. Nonetheless, this system has the potential to boost the effectiveness of solar energy utilization, which could potentially bestow certain cost advantages during an extended period of operation. By exploiting the solar spectrum more skillfully and enhancing the power generation efficiency, the initial investment cost can be distributed to some extent. Currently, though, since the relevant technology is still in a nascent stage and large-scale manufacturing has not been achieved, the cost of such equipment remains comparatively high. The impact of oscillations in raw material prices on the cost of the SSPV-TEG system is also not negligible, particularly with respect to the specialized materials used for spectral separation and high-performance photovoltaic cells. As the technology advances and the market size expands, it is expected that the manufacturing process will be improved, the supply of raw materials will become more reliable, and the cost is predicted to decrease gradually. Simultaneously, by refining the system design and augmenting the performance and compatibility of each component, the maintenance cost of the system can also be reduced, further strengthening its economic practicality.

(4) Analysis of CPV-TEG cost trends

The cost of the CPV-TEG setup is under the convergent impact of assorted factors. The vacillation of raw material prices imposes a conspicuous influence thereon, specifically in relation to the high-performance materials employed in both the concentrated photovoltaic constituents and the TEG. The concentrated photovoltaic technology calls for exceedingly accurate optical parts and highly productive photovoltaic cells, which not only incur substantial costs but also display price instability. There is considerable scope for the amelioration of the manufacturing process. Currently, the fabrication protocols for the CPV-TEG system are elaborate, involving the exacting assembly of sundry components such as the optical focusing apparatus, the heat dissipation setup, and the electrical linkages. By heightening the technical proficiency of the process, expenditures can be efficaciously reduced. By means of implementing more sophisticated automated manufacturing methodologies, the production efficiency can be amplified, resulting in a diminution of labor outlays and material squandering. With regard to market competitiveness, although the CPV-TEG system presents an advantage in power generation efficiency within zones of high solar irradiation, its presently relatively high cost confines its market portion. Nevertheless, with technological progressions and the emergence of economies of scale, costs are expected to dwindle, and market competitiveness will incrementally enhance. Additionally, policy support and research and development investment will also exert a favorable influence on molding the cost trend of the CPV-TEG system, expediting its acquisition of a more distinguished position within the renewable energy market.

(5) Analysis of PV/T-TEG cost trends

Principal components that make up the expenditure of the PV/T-TEG system are the photovoltaic assembly, the TEG component, the thermal regulation system (encompassing phase change substances, heat tubes), along with the cost related to system integration. The outlay of each constituent part is affected by the oscillation of raw material prices. To illustrate, changes in the prices of photovoltaic cell materials, thermoelectric substances, and phase change materials carry considerable weight. Great significance is attached to the enhancement of the manufacturing technique when it comes to reducing costs, especially in terms of boosting the photovoltaic/thermal conversion efficacy and enhancing the performance of the TEG. Optimizing the design and fabrication process of the thermal management system can lead to an elevation of the system's overall efficiency, a reduction in the quantity of materials used, and as a result, a cut in the cost. Regarding market rivalry, the PV/T-TEG system is capable of generating electrical and thermal energy simultaneously and boasts a relatively high comprehensive energy utilization rate. This feature bestows upon it a latent advantage in specific scenarios where diverse energy requirements are present. However, currently, its relatively high cost imposes restrictions on its extensive application. Looking ahead, with the advent of technological innovation and the realization of mass production, it is predicted that the cost will experience a gradual decline. By developing novel low-cost materials, improving the manufacturing process, and optimizing the system design, the PV/T-TEG system is expected to enhance its cost-benefit ratio while meeting energy needs and strengthen its competitiveness within the renewable energy market.

3.5.3. Application challenges

(1) Matching problem

The efficiency of the Thermoelectric Generator (TEG) is commonly low, which may fail to match efficiently with the power generation capability of the high-performance Photovoltaic (PV) module, thereby resulting in a decrease in the overall system's efficiency. The output of the temperature difference generator is greatly influenced by the variations in ambient temperature. When the ambient temperature fluctuates, the temperature differential across the TEG will alter, and this subsequently impacts its power output. This instability in the TEG's power generation will lead to an imbalance in the power flow within the hybrid system, eventually causing the power generation capacity of the PV to become unstable. Such fluctuations will have an impact on the overall power supply of the system. The temperature difference generator demands a particular temperature differential for optimal operation. Nevertheless, excessive heat can have negative consequences. High temperatures might speed up the aging process of PV materials, lowering their conversion efficiency and operational lifespan. This, in turn, will influence the PV's performance and further affect the stability and output of the entire system.

To address these issues, more understanding regarding thermal management techniques is required. Generally, the utilization of heat radiators can augment the dissipation of surplus heat. Heat radiators are typically composed of materials with high thermal conductivity, like aluminum or copper, with the aim of absorbing and transferring heat away from the components. On the other hand, cooling ducts can be incorporated into the system to provide a continuous stream of coolant, which assists in maintaining a steady operating temperature. Phase Change Materials (PCM) have also been utilized. Phase change materials are capable of absorbing and releasing a substantial amount of heat during the phase transition, thus functioning as a thermal buffer. They can store the excess heat during high-temperature periods and release it when the temperature drops, helping to stabilize the temperature within the system and sustain the optimal operating temperature of the PV components.

In addition, a more thorough analysis of the diverse factors contributing to the mismatch problem has been performed. The disparity in temperature coefficients between the PV and TEG components plays a vital role. The temperature coefficient of the PV dictates how its performance varies with temperature. If the operating temperature of the TEG makes the PV deviate from its optimal operating temperature, the efficiency of the entire system will be affected. Moreover, the differences in power generation attributes, such as the voltage and current output characteristics of the PV and TEG, also need to be carefully examined. These differences may lead to inefficiencies in power conversion and distribution within the hybrid system, further worsening the mismatch problem. Comprehending and resolving these factors is essential for optimizing the performance and stability of the PV-TEG hybrid system.

(2) Mounting location and layout

Installation of TEG needs to be in the optimal location for the particular PV module, as the range of PV cells affected by TEG is limited.

(3) Long-term operational stability

After a long period of operation, the performance of photovoltaic cells and thermoelectric modules may decline, affecting its long-term stability. How to ensure that the system can work stably for a long time under extreme environmental conditions (such as high temperature, humidity) is a key issue in the promotion of this technology.

3.5.4. Outlook

Although the application of TEG in PV has achieved some success, it is undeniable that a number of challenges remain. However, these challenges also present many opportunities.

(1) Material innovation and technology integration

From the perspective of technical hurdles, augmenting the efficiency of thermoelectric conversion represents a pivotal mission. This calls for unremitting endeavors in the exploration and innovation of novel thermoelectric materials. Precisely, it entails the search for new materials with improved thermoelectric capabilities. Researchers are perpetually seeking substances that exhibit a more advantageous blend of electrical conductivity, Seebeck coefficient, and thermal conductivity. This demands the examination of a diverse array of materials, such as but not restricted to complex oxides, sulfides, and nanostructured composites.

Furthermore, the refinement of material structures holds great significance. Doping methodologies are extensively utilized to insert alien atoms into the lattice of the base material, thus modifying its electronic and phonon transmission traits. By accurately regulating the kind and quantity of dopants, it becomes feasible to boost the carrier mobility and modify the carrier concentration, culminating in an enhancement of the overall thermoelectric performance. Additionally, nanostructuring techniques play a vital part. Through the formation of nanostructures like nanowires, nanotubes, and quantum dots, the scattering of phonons can be efficiently augmented, while the electron transport is minimally impacted. This leads to a decline in thermal conductivity and a rise in the thermoelectric figure of merit.

Moreover, a thorough evaluation of the potential of these materials to heighten the efficiency of TEG is indispensable. This necessitates the execution of detailed experimental investigations and theoretical simulations to fathom how the altered material properties translate into enhanced power output and conversion efficiency. It also entails contemplating the congruence of these materials with prevailing manufacturing procedures and device architectures.

Simultaneously, it must be integrated with advanced manufacturing processes to enhance the quality and stability of the materials and attain higher conversion efficiency.

This mandates technological breakthroughs, large-scale production, and the optimization and integration of the industrial chain to curtail costs and augment the market competitiveness of TEG. Sophisticated manufacturing processes such as molecular beam epitaxy, atomic layer deposition, and chemical vapor deposition can be employed to precisely govern the growth and composition of thermoelectric materials at the atomic or molecular scale. These approaches permit the fabrication of materials with high purity, uniform composition, and well-defined nanostructures, which are essential for realizing outstanding thermoelectric properties.

In the realm of large-scale production, attempts should be made to devise cost-effective and scalable manufacturing techniques. This encompasses optimizing production parameters, increasing the production yield, and diminishing waste generation. Also, the integration of the industrial chain is requisite to guarantee a stable supply of raw materials, efficient manufacturing processes, and reliable product distribution. By coordinating the undertakings of diverse stakeholders in the supply chain, ranging from material suppliers to device manufacturers and end-users, it is possible to actualize a smooth flow of products and services, thereby cutting costs and strengthening the market competitiveness of TEG.

(2) Sustainability of materials and disposal

In the present age, with the global attention increasingly centered on environmental safeguarding and the quest for sustainable progress, the evaluation of the environmental implications of TEG technology has become a matter of prime importance. This mounting concern necessitates a thorough and painstaking scrutiny, with particular emphasis on two pivotal facets: the viability of the materials utilized in the fabrication of TEGs and the protocols for their end-of-life handling.

The materials engaged in TEG manufacturing encompass a wide variety, each bearing its distinct consequences for the environment and the availability of resources. For example, some thermoelectric materials may comprise elements that are either rare in the natural world or procured through procedures that impose substantial stress on the ecological system. The retrieval of these elements might involve operations like extraction, which frequently gives rise to habitat disturbance, soil deterioration, and water contamination. Moreover, the production processes involved in converting these raw materials into operative TEG constituents can be highly energy-consuming, relying on non-renewable energy resources and thus contributing to the emission of greenhouse gases. This not only affects the proximate surroundings but also presents enduring challenges within the framework of climate change.

Likewise significant is the contemplation of the situation when a TEG arrives at the conclusion of its functional life. Unsuitable disposal means, such as landfill deposition, can lead to the seepage of noxious substances into the soil and underground water, polluting these essential resources. On the other hand, incineration might discharge poisonous fumes and particulate matter into the atmosphere, further aggravating air pollution. Consequently, there is an urgent necessity to investigate and execute more sustainable end-of-life resolutions, such as effective recycling procedures that can reclaim valuable materials and curtail waste generation, or inventive reuse tactics that prolong the lifespan and usefulness of TEGs in alternative applications.

All in all, a comprehensive and all-encompassing methodology for appraising the environmental imprint of TEG technology is indispensable. By meticulously addressing the material sustainability and end-of-life elements, we can aspire to a future where TEGs not only achieve efficient energy conversion but also do so in an environmentally conscientious and sustainable fashion, conforming to the global aspirations for a more verdant and sustainable planet.

(3) Intelligent system design

In the domain of TEG and PV technologies, the idea of intelligent system design has come to the fore as a significant and prospective future development trend. This methodology entails the combination of state-of-the-art sensors and intricate control systems, which collaboratively facilitate the intelligent and synchronized operation of TEG and PV components.

The sensors perform a vital function in constantly overseeing diverse parameters, including temperature gradients, light intensity, electrical output, and heat flux within the system. Such real-time data is subsequently conveyed to the control system, which serves as the “core” of the intelligent configuration. Relying on the obtained data and pre-set algorithms, the control system is capable of making well-grounded decisions and automatically adjusting the operational parameters of both the TEG and PV elements.

When there is high solar irradiance, the control system may boost the voltage or current output of the PV cells to achieve maximum power generation. Simultaneously, it could refine the thermal management of the TEG by modifying the flow rate of cooling fluids or adjusting the electrical load to augment its thermoelectric conversion efficiency. In conditions with low light or fluctuating environments, the system can flexibly alter its operational mode to guarantee a stable and efficient energy output. This adaptable adjustment not only boosts the overall energy conversion efficiency but also lengthens the operational lifespan of the components by averting overheating or underutilization.

Looking into the future, the forthcoming development of intelligent systems in this regard will unavoidably be intertwined with the capability of artificial intelligence algorithms. These algorithms can manage enormous quantities of data more effectively and make more precise predictions and decisions. For example, machine learning algorithms can examine historical performance data of the TEG-PV system under various weather conditions, seasons, and usage patterns. Based on this examination, they can anticipate future energy generation trends and optimize the system's operation beforehand.

Furthermore, artificial intelligence（AI） can heighten the reliability and stability of the system by detecting and diagnosing potential faults or malfunctions before they intensify. By continuously observing the system's performance and comparing it with normal operational ranges, the AI can spot anomalies and initiate appropriate corrective actions or maintenance warnings. This preventive approach curtails downtime, boosts the availability of the energy generation system, and ultimately contributes to a more sustainable and dependable energy supply.

In conclusion, intelligent system design has considerable potential for transforming the operational mode of TEG and PV systems, resulting in enhanced energy utilization, superior reliability, and a more sustainable energy future.

(4) System integration

In the realm of system integration, the combined design and enhancement of TEG and PV systems have emerged as a central focus within research and development initiatives. The integration undertaking is a sophisticated and multifarious pursuit, intending to harmonize the distinctive traits of both TEG and PV technologies.

Firstly, on the electrical front, state-of-the-art power electronics and control circuitry are utilized to administer and amalgamate the power outputs from the TEG and PV constituents. This entails the application of intelligent maximum power point tracking (MPPT) algorithms, which are capable of adaptively modulating the operating parameters of both systems to guarantee their optimal performance under fluctuating environmental circumstances like alterations in sunlight intensity, temperature, and load requirements. For example, during periods of intense solar irradiation, the MPPT algorithm might give precedence to the power generation of the PV cells and modify the electrical load on the TEG to optimize the overall power yield. Conversely, in scenarios where a substantial temperature differential exists, the algorithm can redirect its attention to maximizing the power generation from the TEG.

Concerning thermal integration, heat exchangers and thermal conductors are meticulously engineered and situated to effectively convey the waste heat generated by the PV cells to the TEG. This is accomplished through the employment of materials possessing high thermal conductivity and refined heat transfer configurations. Microchannel heat exchangers could be employed to augment the heat transfer rate between the two components. By this means, the TEG can capitalize on the otherwise squandered heat to produce supplementary electrical power, thereby augmenting the overall energy conversion efficiency of the integrated system.

With respect to mechanical design, a compact and modular methodology is adopted to diminish the physical size and weight of the system. Components are thoughtfully arranged and integrated to curtail the installation space requirements. Lightweight yet resilient materials are chosen for fabricating the system enclosure and supporting structures. This not only renders the system more apt for installation in spatially restricted environments but also mitigates the costs related to transportation and installation.

Furthermore, the integrated design takes into account the simplicity of maintenance. Modular components are devised to be readily accessible and replaceable, minimizing the downtime necessary for repairs. Diagnostic sensors are strategically positioned throughout the system to continuously oversee the performance and condition of each component. This enables anticipatory maintenance, where potential problems can be detected and resolved before they precipitate system breakdowns. Consequently, the overall installation and maintenance costs of the integrated TEG-PV system are markedly reduced, making it a more economically feasible alternative for a broad spectrum of applications.

In summary, the combined design and optimization of TEG and PV systems present a prospective solution for augmenting energy generation efficiency, downsizing the system, and cutting costs, thereby smoothing the path for the more extensive application of these technologies across diverse fields.

4. Conclusion

Driven by today's strong demand for renewable energy, photovoltaic (PV), a key clean energy technology, has been widely used worldwide and continues to receive high attention. The emergence of TEG in the field of photovoltaic modules has opened up new avenues for the efficient utilization of energy. In this paper, the development of TEG in four main types of PV is presented in complete detail, documenting the thermoelectric performance of different kinds of coupled systems.

(1) The combination of TEG and PV shows many significant advantages. It has the ability to comprehensively utilize the waste heat that the photovoltaic module generates throughout the electricity generation procedure, and this effective use of waste heat not only realizes the maximization of energy output, but also provides a new way of thinking for the diversified use of energy. In comparison with the common PV system, the energy efficiency of the PV-TEG coupling system is significantly enhanced. However, the complexity and variability of the actual application situation can easily lead to uneven distribution of temperature, and it is necessary to adjust the operation strategy of the system. Additionally, the addition of PCM can realize continuous power generation to achieve the predetermined results. It should be noted that the development of thin-film batteries in combination with TEG can make self-powering of portable electronics a reality. Finally, we also investigate the effect of the TEG arrangement on the system, and only a suitable arrangement can improve the efficiency of the system.

(2) When TEG and SSPV are coupled, they can effectively lower the temperature of PV components and enhance the system's thermoelectric performance, thus achieving a high energy utilization rate. Essentially, the spectral energy that PV cannot absorb is transferred to TEG. And the system's efficiency is boosted by utilizing various spectral beam splitters, tracking systems, and cooling fluids. SSPV-TEG is a solution to the problem of inefficiency caused by the mismatch between the thermoelectric properties of PV and TEG in the direct coupling form, which is worthy of in-depth study.

(3) The coupling of TEG and CPV is the main method to promote the general utilization of PV technology. The efficiency of the system increases when the concentration of sunlight rises, but when the concentration is high enough, it cuts down the efficiency of the system. This is due to the fact that the decrease in PV cell efficiency caused by high temperatures is greater than the increase in power from TEG. The general PV-TEG system is less efficient

than the CPV-TEG coupled system. The reason for this is that the temperature gradient of the TEG in the CPV-TEG system is higher than that of the PV-TEG system.

(4) The coupling of TEG with PV/T reflects the diversity of PV/T systems and greatly enriches the structural forms of PV/T-TEG coupled systems. Different structural forms include air, liquid, heat pipe, phase change material The combination of these components with TEG is various, which in general can improve the power generation efficiency of PV and maintain stable performance output under various environmental conditions. Even when the efficiency of the PV fluctuates due to external factors, the TEG can continue to provide a certain amount of power supply, which greatly enhances the reliability and stability of the system.

(5) In terms of development opportunities, policy support will boost the combination of TEG and PV. Governments may offer subsidies, tax incentives, and set regulatory targets. The growth in market demand is also beneficial, especially as the need for clean energy rises across residential, commercial, industrial, and transportation sectors. Technological advances, such as new materials and manufacturing techniques, improve system performance. Enhancements in energy storage address intermittency issues. The system is well-suited for decentralized energy systems, particularly in remote and disaster-stricken areas. International cooperation accelerates innovation, while competition drives cost reduction. It stands at the forefront of the renewable energy revolution, promising to meet energy needs and address environmental concerns.

In summary, the application of TEG in photovoltaic modules has great development potential. Through continuous technological innovation and application expansion, it is expected to make an important contribution to the realization of sustainable energy development. In future research and practice, it is necessary to strengthen interdisciplinary cooperation, integrate the resources of all parties, and jointly overcome technical difficulties to promote the integration of TEG and PV, so as to lay a solid foundation for the construction of a clean and low-carbon energy future.

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Conflicts of interests

The authors declare no conflict of interest.

Authors' contribution

Conceptualization and design: Tao Li; methodology: Tao Li; investigation: Xinyu Peng; formal analysis: Shiyang Zhou; data curation: Shiyang Zhou; writing and original draft preparation: Tao Li and Xinyu Peng; writing—review and editing, Tao Li and Xinyu Peng; supervision, Tao Li; project administration, Shiyang Zhou; funding acquisition, Tao Li. All authors have read and agreed to the published version of the manuscript.

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