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Design and Optimization of Hybrid Thin-Film PV-TE Energy Conversion Systems. Review

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The modern development of renewable energy sources requires the improvement of energy conversion technologies for sustainable power supply. One of the most promising methods of generating electricity is the use of photovoltaic (PV) converters, which directly transform solar radiation into electricity. However, a major drawback of PV modules is their tendency to heat up, which leads to a decrease in output power. This paper presents a review of hybrid PV-TE systems consisting of photovoltaic modules, thermoelectric generators, and an intermediate heat-conducting layer. Such systems not only allow cooling of the photovoltaic cells but also provide additional electricity generation through the Seebeck effect, which converts a temperature gradient into a potential difference. The main design approaches were analyzed, in particular tandem configurations with thermal concentration and systems with spectral splitting. The main challenges for further system optimization were identified and reviewed. Specifically, these include issues of thermal management, the limited efficiency of commercial thermoelectric materials, and the electrical integration of two components with fundamentally different current-voltage characteristics (CVCs).

Keywords: renewable energy, photovoltaic module (PV), thermoelectric generator (TEG), hybrid systems, photovoltaic–thermoelectric systems (PV–TE).

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Content

Introduction

The modern development of renewable energy sources plays a key role in ensuring sustainable energy supply and reducing environmental impact [1]. One of the most promising methods of electricity generation is the use of photovoltaic (PV) converters, which enable the direct conversion of solar radiation into electricity. The most common technology involves silicon-based solar panels with flat photovoltaic cells [2–4].

However, solar panels boperates a single semiconductor material operates effectively only within a limited range of the solar spectrum, thereby reducing their efficiency [5,6]. One way to partially overcome this limitation is through the use of heterostructures consisting of multiple photovoltaic layers with different band gaps. This approach allows for more effective utilization of the solar spectrum. Theoretically, such structures can achieve efficiencies up to 86.8% with an unlimited number of layers [7]. In practice, however, each additional layer increases technological complexity and cost; therefore, modern multijunction solar cells typically consist of 3–4 layers and achieve maximum efficiencies of about 45%.

The operating temperature of photovoltaic modules directly affects their efficiency. An increase in temperature leads to a change in the semiconductor band gap, a reduction in open-circuit voltage, and an increase in recombination losses–all of which reduce the system's output power [8]. Elevated temperatures also accelerate the degradation of materials used in solar panels, shortening their service lifetime [9,10]. Thus, the development of efficient cooling strategies for photovoltaic cells remains one of the key challenges in solar energy research.

A promising approach to address this issue is the use of hybrid photovoltaic–thermoelectric (PV–TE) systems. Such systems not only cool the photovoltaic elements but also generate additional electrical power via the Seebeck effect, which converts a temperature gradient into an electric potential difference [11,12]. Thermoelectric generators (TEGs) can operate effectively at elevated temperatures by utilizing the excess heat produced through the absorption of solar radiation [13,14].

Hybrid PV–TE systems consist of photovoltaic modules, thermoelectric generators, and an intermediate thermally conductive layer that ensures efficient heat transfer between the components [15,16]. The implementation of such designs can enhance the overall efficiency of the system by 5–15%, depending on the operating conditions and materials used [17,18]. Studies have also shown that the incorporation of TE elements into PV systems can extend the service lifetime of photovoltaic modules by stabilizing their operating temperature [19].

In recent years, numerous experimental and theoretical studies of hybrid PV–TE systems have been conducted using various modeling techniques, including finite element analysis (FEM) in software such as COMSOL [20]. These investigations help determine optimal system parameters and evaluate performance under real operating conditions [21,22].

Advances in materials science have also contributed to improving the efficiency of thermoelectric generators. In particular, the use of novel nanostructured materials – such as alloys based on Bi_2Te_3, Sb_2Te_3, and SiGe–has led to higher thermoelectric figures of merit (ZT), making these generators even more efficient [23–26].

Thus, the integration of thermoelectric modules into photovoltaic systems represents a promising direction for improving the efficiency of solar energy conversion. This article discusses modern approaches to enhancing PV–TE systems, their physical operating principles, advantages and disadvantages, as well as the results of experimental and theoretical studies in this field.

I. Comparative analysis of materials and configurations of PV–TE systems

Table 1 presents the comparative characteristics of the main photovoltaic materials used in modern solar cells, including both laboratory and commercial efficiency values. The data indicate that the highest laboratory efficiencies are typical for multijunction III–V structures based on InGaP/InGaAs/Ge, where the efficiency exceeds 40%; however, under industrial conditions these values decrease to 30–35% due to technological and economic limitations [27]. Monocrystalline silicon cells remain the most widespread in the commercial sector owing to their optimal balance of efficiency, stability, and cost, demonstrating efficiencies of 19–22% [2]. Polycrystalline and amorphous silicon are inferior in terms of efficiency, yet they are widely used in low-power and budget systems [4]. Thin-film technologies such as CdTe and CIGS exhibit competitive characteristics, including stability at elevated temperatures and good spectral sensitivity, which makes them promising for integration into hybrid PV-TE systems [2,10]. Perovskite solar cells deserve particular attention, as they have shown a rapid increase in laboratory efficiency to 25–27% within a relatively short

Table 1.

Photovoltaic materials and their efficiencies with references

Material	Typical laboratory efficiency	Commercial efficiency	Reference
Monocrystalline silicon (c-Si)	26–27%	19–22%	NREL Efficiency Chart [27]
Polycrystalline silicon	22–24%	16–19%	Razykov et al., Solar Energy (2011) [2]
Amorphous silicon (a-Si)	10–12%	6–9%	Parida et al., Renewable Energy Rev. (2011) [4]
CdTe thin films solar cells	22–23%	17–19%	Fedenko et al. (2025) [10]
CIGS ($Cu(In,Ga)Se_2$)	23–24%	15–19%	Razykov et al. (2011) [2]
GaAs (III–V)	29–30%	≈25%	Nelson, *Physics of Solar Cells* (2003) [5]
MultijunctionIII–V (InGaP/InGaAs/Ge)	40–47%	30–35%	NREL Efficiency Chart [27]
Perovskites	25–27%	~20%	Green, *Third Generation Photovoltaics* (2006) [6]

time; however, their widespread deployment is constrained by issues of durability and degradation [6].

Table 2 summarizes the main thermoelectric materials that are used or considered for the development of thermoelectric generators in hybrid systems, along with typical values of the thermoelectric figure of merit ZT and the approximate efficiency of thermal-to-electric energy conversion. The most common materials in the low-temperature range remain Bi_2Te_3-based alloys and Bi_2Te_3–Sb_2Te_3 solid solutions, which, at ZT ≈ 1, provide efficiencies of 4–7% and are well-matched to the operating temperature ranges of photovoltaic modules [28]. Materials based on PbTe and SiGe are more effective in medium- and high-temperature applications; however, their use in conventional PV-TE systems is limited due to temperature mismatches [25,29]. Promising candidates include SnSe and nanostructured Bi_2Te_3, which–owing to reduced thermal conductivity and optimized electronic properties–exhibit enhanced ZT values reaching 2 or more, potentially enabling thermoelectric conversion efficiencies of 8–10% [22,26]. Nevertheless, such materials require complex synthesis technologies and currently remain the subject of intensive scientific research.

Table 3 presents a comparative analysis of the efficiency of hybrid photovoltaic–thermoelectric systems depending on configuration, the type of thermoelectric material, and cooling conditions. The results show that conventional tandem PV–TE systems with passive cooling provide a moderate increase in overall efficiency of about 3–7% due to the utilization of thermal losses from the photovoltaic cell [18,30]. The use of active air or liquid cooling on the cold side of the TEG makes it possible to maintain a higher temperature gradient, increasing the system efficiency gain to 8–12% [17,19]. The greatest potential is demonstrated by systems employing spectral

Table 2.

Thermoelectric materials, ZT values, and conversion efficiencies with references

Material TE	Typical ZT	Approximate efficiency	Reference
Bi_2Te_3 (n/p)	0.9–1.2	4–6%	Goldsmid, *Introduction to Thermoelectricity* (2010) [28]
Bi_2Te_3–Sb_2Te_3 alloys	1.1–1.4	5–7%	Tritt, Vining – Nat. Mater. (2009) [24]
PbTe	1.0–1.5	6–8%	Snyder & Toberer, Nat. Mater. (2008) [25]
SiGe alloy	0.5–1.0	3–5%	DiSalvo, Science (1999) [29]
SnSe (p-type)	1.5–2.6	8–10%	Dresselhaus et al., Adv. Mater. (2007) [26]
Organic / polymer thermoelectric materials	0.1–0.3	<1%	Zhu et al. (2019) [31]
Nanostructured Bi_2Te_3	1.5–2.0	7–9%	Kraemer et al., Nat. Mater. (2011) [22]

Table 3.

Efficiency of hybrid PV/TE systems as a function of configuration and operating conditions

PV/TE system configurations	Type of TE material	Cooling conditions	Increase in overall system efficiency	Reference
Tandem conventional PV–TE system	Bi_2Te_3	Passive (radiator)	+3–7%	Meng, Li (2014) [18]
PV–TE system with air cooling on the cold side	Bi_2Te_3	Active air cooling	+5–10%	Omer & Infield (2000) [19]
PV–TE system with water or liquid cooling	Bi_2Te_3	Active liquid cooling	+8–12%	Garud & Lee (2022) [17]
PV–TE system with thermal concentration (copper plate / increased TE area)	Bi_2Te_3–Sb_2Te_3	Passive cooling	+6–10%	Zhang & Xuan (2019) [32]
PV–TE system with spectral splitting (separation of IR and visible light)	PbTe або Bi_2Te_3	Passive + optical filter	+10–15%	Ju et al. (2012) [33]
PV–TE system with reflective component and light focusing	Bi_2Te_3	Passive	+12–18%	Yang et al. (2023) [34]
PV–TE system under solar concentrators (CPV–TE)	III–V + Bi_2Te_3 або SnSe	High - temperature	до +20%	Faddouli et al. (2024) [26]
PV–TE system with high ZT (nanostructured Bi_2Te_3 or SnSe)	SnSe, Bi_2Te_3 nano	active/passive	15–22% (modeling)	Kraemer et al. (2011) [22]

splitting, thermal concentration, and optical focusing, where the total efficiency gain can exceed 15%, and in some modelling, studies may reach 20% or more [32,33]. However, such approaches require complex optical and thermal infrastructures, which limits their practical implementation and highlights the need for an optimal compromise between efficiency, complexity, and economic feasibility in hybrid PV–TE systems.

II. Principle of operation and key characteristics of system components

The efficiency of a hybrid photovoltaic – thermoelectric (PV-TE) system is a complex function determined by the characteristics of its individual components. A deep understanding of the physical principles underlying their operation, as well as their strengths and weaknesses, is essential for the analysis, modeling, and optimization of the hybrid system [35].

The core of any solar module is the photovoltaic converter – a semiconductor device that operates based on the internal photoelectric effect within a p-n junction structure (Fig. 1). The process of energy conversion begins when a photon of solar radiation with energy exceeding the semiconductor band gap (Eg) is absorbed by the material. This absorption leads to the generation of a pair of free charge carriers – an electron and a hole. The internal electric field of the p-n junction, which exists in the depletion region, spatially separates these charge carriers before they can recombine: electrons are driven toward the n-region, while holes move toward the p-region. This directed motion creates a photogenerated current (Iph) and a potential difference in the element's output. Depending on the technology, solar cells can be of several types: from the most common and economically viable crystalline silicon (c-Si) to thin-film types, for example, based on amorphous silicon (a-Si), as well as highly efficient multi-junction (MJ) heterostructure devices composed of several semiconductor layers with different band gap energies (e.g., InGaP/InGaAs/Ge). The latter allow for more complete utilization of the solar spectrum, achieving efficiencies of up to about 35% [27].

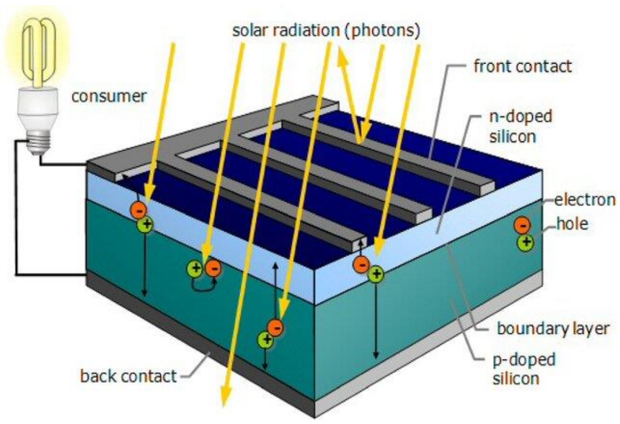

Fig. 1. Principle of operation of a photovoltaic cell [39].

The output power of the photovoltaic cell is calculated from its current–voltage (I–V) characteristics:

$$P_{PV} = \max\,(J_{PV}V_{PV}) \tag{1}$$

where J_{PV} is photovoltaic current, V_{PV} – photovoltaic voltage.

The photovoltaic efficiency is expressed as:

$$\eta_{PV} = \frac{P_{PV}}{A_G G} \tag{2}$$

where A_G – illuminated area, G – solar radiation intensity.

A fundamental problem of all PV elements is the significant energy loss caused by thermalization. Photons with energies lower than Eg pass through the material without absorption, while the energy of photons that greatly exceeds Eg is only partially used for the generation of charge carrier pairs; the excess energy is rapidly dissipated as thermal vibrations of the crystal lattice (phonons). As a result, a substantial portion of the absorbed radiation is not converted into electricity but instead degrades into heat (Qh), heating the working surface.

An increase in temperature is a key negative factor that reduces performance: it leads to changes in the band gap width, increases the intrinsic leakage current –causing a decrease in open-circuit voltage (Voc)–and accelerates carrier recombination, which lowers the overall output power. This issue turns heat from an undesirable byproduct into a valuable resource for the second component of the hybrid system – the thermoelectric generator (TEG).

TEG is a solid-state device that directly converts thermal energy into electrical energy through the Seebeck effect [28]. Its module consists of a large number of n-type and p-type semiconductor "legs" connected electrically in series by metallic electrodes. When a temperature gradient (Th > Tc) is established across the module, charge carriers (electrons in the n-type and holes in the p-type) begin to diffuse more intensively from the hot side to the cold side. The accumulation of charges on the cold side creates a potential difference, generating a Seebeck current (Iseebeck) in the external circuit (Fig. 2).

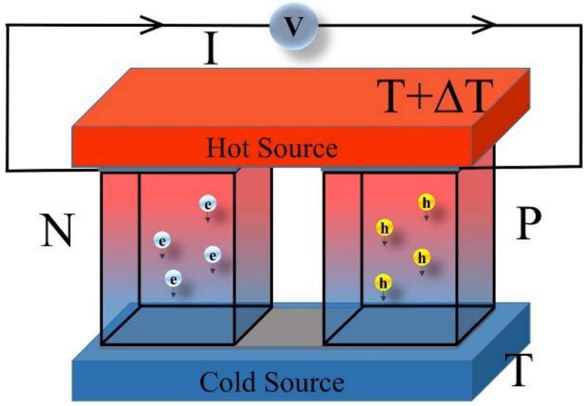

Fig. 2. Thermoelectric module [34].

The efficiency of the thermoelectric generator is defined as the ratio of the generated electrical power to the amount of heat passing through the hot junction. (Q_h):

$$\eta_{TEG} = \frac{P_{TEG}}{Q_h}. \tag{3}$$

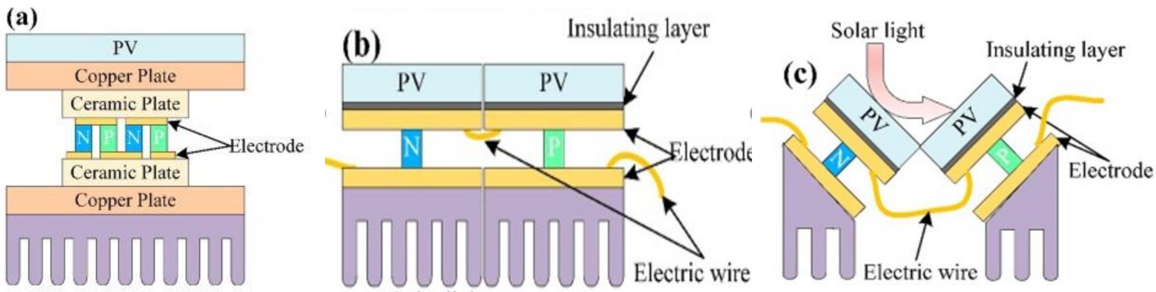

Fig. 3. Schemes of (a) a conventional PV-TE system, (b) a PV-TE system without ceramic plates, and (c) a PV-TE system with a V-shaped groove [32].

The maximum efficiency of a TEG depends on the average operating temperature ($T_{avg} = \frac{T_h+T_c}{2}$) and dimensionless thermoelectric figure of merit

$$ZT = \frac{S^2\sigma T}{\kappa}, \quad (4)$$

where σ – conductivity, κ– thermal conductivity. The formula for maximum efficiency is as follows:

$$\eta_{TEG,max} = \frac{T_h-T_c}{T_h} \cdot \frac{\sqrt{1+ZT_{avg}}-1}{\sqrt{1+ZT_{avg}}+\frac{T_c}{T_h}} \quad (5)$$

The efficiency of this process for a specific material is described by the dimensionless thermoelectric figure of merit (ZT), which depends on the Seebeck coefficient (S), the electrical resistivity (ρ), and the thermal conductivity (κ). For high efficiency, a material should possess a high Seebeck coefficient to generate greater voltage, low electrical resistivity to minimize Joule losses, and – critically–low thermal conductivity to maintain the maximum temperature gradient between the hot and cold sides.The most common materials used for TEGs are chalcogenide alloys based on bismuth telluride (Bi_2Te_3) and antimony telluride (Sb_2Te_3) [28]. In a hybrid system, the TEG performs a dual function: it generates additional power (PTE) from the waste heat of the photovoltaic element while simultaneously cooling it. This cooling occurs not only through passive heat dissipation but also due to the Peltier effect – the phenomenon inverse to the Seebeck effect – which involves heat absorption at the hot junction of the TEG when current passes through it [29]. Thus, both components of the system operate in symbiosis: the TEG enhances the performance of the PV element by stabilizing its temperature and simultaneously converts the unused thermal energy into additional electricity, thereby increasing the overall solar energy conversion efficiency. The overall efficiency of the PV-TE system (ηtotal) is determined as the sum of the efficiency of the PV element (ηPV) and the additional efficiency provided by the TEG. If the TEG utilizes the heat that has passed through the PV element, part of the energy that could have been converted by the PV cell is already used. A more accurate formulation accounts for the fact that the TEG converts only a portion of the energy not transformed by the PV element. One of the common models is:

$$\eta_{\text{заг}} = \eta_{PV} + \eta_{TEG} \cdot (1 - \eta_{PV} - \alpha_{opt}), \quad (6)$$

where α_{opt} – optical loss fraction (reflection, partial absorption), and $(1 - \eta_{PV} - \alpha_{opt})$ represents the thermal energy available for the TEG.

Another simplified model often used is:

$$\eta_{\text{заг}} = \eta_{PV} + \eta_{TEG} \cdot \beta \quad (7)$$

Where β –is the fraction of heat from the PV that reaches the TEG.

III. Designs and configurations of hybrid PV-TE systems

The design of an efficient hybrid PV–TE system requires careful consideration and optimization of optical, thermal, and electrical aspects. Depending on the method of solar spectrum utilization, the quality of thermal contact between components, and the overall architecture, existing systems can be classified according to several main approaches, each aimed at addressing specific challenges and improving overall efficiency [37]. The most common approach is the tandem configuration, in which the photovoltaic cell is placed directly on top of the thermoelectric generator. In this architecture, the PV cell absorbs the visible and ultraviolet portions of the solar spectrum to generate electricity, while the unutilized solar energy converted into heat is transferred to the hot side of the TEG for additional power generation.

3.1. Classic design with a thermal concetrator

The typical hybrid system, shown in Fig. 3(a), is a multi-layer structure [32]. The design consists of a PV panel that absorbs solar radiation, a ceramic plate that acts as an electrical insulator, the hot side, the cold side of the TEG, and a heat sink (radiator) for dissipating heat into the ambient environment.

A classical thermoelectric (TE) module consists of a ceramic plate, electrodes, and thermoelectric "legs." The area of the thermoelectric element is smaller than that of the photovoltaic (PV) element due to the use of the thermal concentration method. The solar energy absorbed by the PV element is partially converted into electrical energy and partially into thermal energy, which is subsequently utilized by the TE module. A copper plate is used to ensure uniform temperature distribution across the PV element.

The application of this method reduces the system cost by minimizing the size of the thermoelectric module.

The main objective of the integrated design proposed in this paper is to simplify the PV-TE structure to improve heat transfer. As shown in Fig. 3(a), the classical PV-TE system requires a copper plate with high thermal conductivity to provide heat concentration. However, since the metallic electrodes of the thermoelectric legs also possess high thermal conductivity, they can serve as thermal concentrators.

Because the metallic electrodes of the thermoelectric legs have high thermal conductivity, a new design was proposed in which the TE area was increased and both the copper and ceramic plates were removed (Fig. 3(b)). Electrical connections between the n-type and p-type legs in the TE module were implemented using electrical wires.

An important factor in PV-TE systems is the utilization of reflected solar radiation. However, in the design shown in Fig. 3(b), photons reflected from the PV element are scattered into the surrounding environment, which significantly decreases system efficiency. If, however, an angle is formed between two adjacent PV elements, photons reflected by one element can be absorbed by another [32].

Based on this principle, the PV-TE system employs a V-shaped groove structure that enhances the absorption of solar radiation, as illustrated in Fig. 3(c). To further explain the effectiveness of the V-shaped structure, the study presents an equation describing the process of multiple absorption of reflected light.

$$a_m = a_f + a_f(1 - a_f) \qquad (8)$$

where a_m – V-groove absorption efficiency, a a_f – efficiency absorption flat surface. From this equation, it can be seen that a V-type groove can enhance solar light absorption.

3.2. Systems with a spectral splitting

In general, there are two main types of hybrid PV-TEG systems based on spectral separation. The first type does not include a reflector, and the photovoltaic (PV) modules and thermoelectric generators (TEGs) are arranged parallel to each other, as shown in Fig. 4 [38]. The PV modules mainly absorb ultraviolet and visible light, while infrared radiation is transmitted to heat the upper side of the TEG, thus creating a temperature difference between its hot and cold sides. The second type incorporates a reflective component, as shown in Fig. 5 [38]. In this hybrid configuration, the PV modules and the TEG are positioned perpendicularly, and solar radiation is directed by a reflector according to a cutoff wavelength [34]: radiation with wavelengths longer than the cutoff is reflected toward the TEG, while shorter wavelengths are directed to the PV module.

Figure 4 illustrates a typical structure of a combined hybrid PV-TEG module, where PV panels and TEGs are interconnected either in parallel or in series [39]. When the PV and thermoelectric elements are connected in series, power losses are minimized because such a configuration requires fewer power electronic switches. To establish the necessary temperature difference, the PV panel is placed on one surface of the TEG, while a heat sink is positioned on the opposite side. TEG not only collects waste heat and reduces the temperature of the PV modules but also effectively improves the overall utilization efficiency of the solar spectrum.

The configuration shown in Fig. 4 is relatively simple and does not require a complex optical design. Higher efficiency in such a system can be achieved under diffuse light conditions and low-intensity solar radiation. The second configuration includes a reflective component; therefore, effective light focusing requires a sufficient amount of direct sunlight (Fig. 5). Consequently, the first type is widely used in the design and research of Maximum Power Point Tracking (MPPT) for hybrid systems [40], and most MPPT methods mentioned in this paper are based on this configuration.

In real-world conditions, solar photovoltaic (PV) systems experience power losses due to partial shading (PSC), which occurs because of obstacles such as trees,

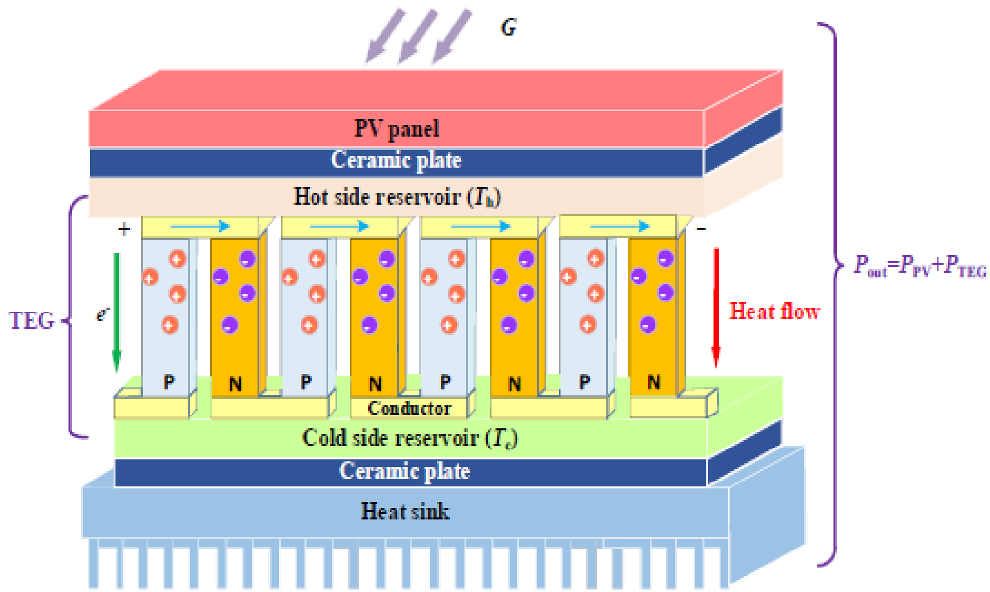

Fig. 4. Structure of a typical hybrid module [38].

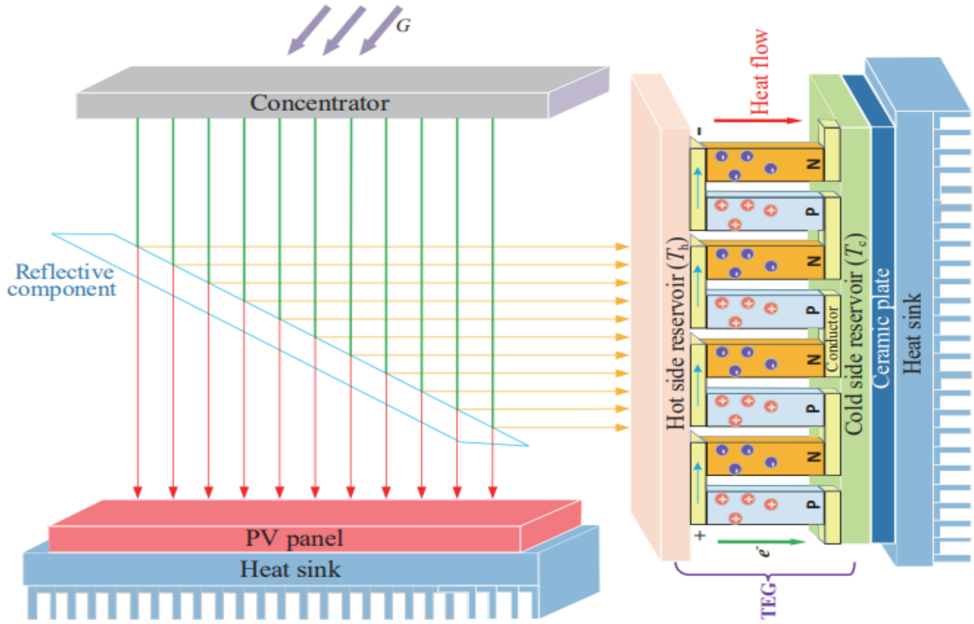

Fig. 5. Photo-thermoelectric device with a reflecting component [38].

clouds, or buildings. Under such shading, the shaded PV panels begin to behave as energy consumers rather than generators. They function as diodes under reverse bias, leading to a significant voltage drop, excessive energy dissipation, and heat generation. This phenomenon is known as the "hot spot effect." Severe hot spots can irreversibly damage entire solar modules [33].

3.3. Methods of Cooling the Cold Side of a TEG

As shown in Fig. 6, an amorphous silicon–based photovoltaic (PV) cell was used in the PV-TE system [38]. In this study, the PV cell was manufactured by Qiangsheng Solar Ltd. and had an area of 30 × 30 mm². The lower side of the PV cell possesses good insulating properties, allowing it to be directly attached to the thermoelectric (TE) electrode using thermally conductive adhesive.

For the fabrication of the TE module, an n-type (Bi_2Te_3) thermoelectric ingot supplied by Wangu Electronic Technology Ltd. was used. Thermoelectric legs were formed from an ingot using the Wire Electrical Discharge Machining method. The TE electrodes were made of copper, and their connections with the TE legs were established using Cu-211 electrically conductive adhesive (Erbond).

Additionally, four nickel sheets were attached to the TE electrodes using the same Cu-211 conductive adhesive. These nickel sheets served as connectors between the TE electrodes and the electrical testing system. To improve heat transfer, the PV cell was fixed onto the top electrode of the TE module using thermally conductive adhesive.

The study analyzes the influence of two cooling methods: water cooling and air cooling. As shown in Fig. 6(a), in the air-cooling system, a fan is used to provide airflow through the lower part of the TE module. In the water-cooling system, a mixture of ice and water is used for TE cooling, and an aluminum radiator is placed between the PV-TE system and the cooling liquid (Fig. 6(b)).

To measure the efficiency of the PV-TE system, a solar simulator (94023A) and an I–V test station (PVIV-1A) developed by Newport Corporation are used (Fig. 6(c)). During the experiment, the voltage

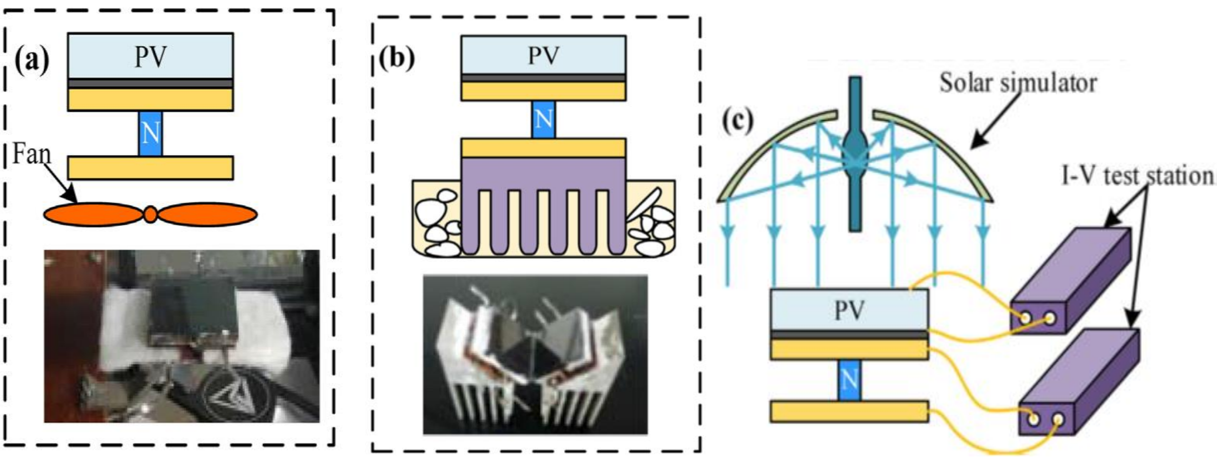

Fig. 6. Schematic diagram of (a) a PV-TE system with an air-cooling system, (b) a PV-TE system with a V-type groove, and (c) the entire testing system [38].

measurement accuracy is ±0.02%, and the current measurement accuracy is ±0.23% [41].

To simplify the experiment, the open-circuit voltage of the TE module is used to calculate the output power. It should be noted that this method can also eliminate the error caused by the electrical contact resistance of the conductive adhesive. When using welding technology to connect the TE legs to the electrodes, a mold must be fabricated. Although the cost of the mold can be neglected in mass production, it is too expensive for producing test samples in the laboratory. Therefore, conductive adhesive is used to connect the TE legs and the TE electrodes. However, the conductive adhesive introduces significant electrical contact resistance. To avoid the error caused by this resistance, the output power is calculated only from the open-circuit voltage of the TE module [41].

$$P_{TE} = \frac{A_{TE} V_{TE}^2}{4\rho H_{TE}} \qquad (9)$$

where ρ electrical resistivity of the TE material, V_{TE} – open-circuit voltage of the TE module, A_{TE} and H_{TE} – area and height of the TE leg.

IV. Thermal Management Issues

The efficiency of a thermoelectric generator (TEG) is directly determined by the temperature gradient (ΔT) between its hot and cold sides; therefore, controlling heat flows is one of the key challenges in hybrid PV/TEG systems. In a tandem structure consisting of a photovoltaic (PV) cell, an intermediate adhesive or insulating layer, a thermoelectric module, and a heat sink, each additional layer introduces a certain thermal resistance. As a result, part of the heat is retained within the PV cell, causing its to overheat, while the heat flux reaching the hot side of the TEG is reduced. Consequently, the efficiency of both system components decreases [42].

The issue is further complicated by the imperfections of cooling systems. Passive heat sinks are technologically simple and inexpensive; however, their efficiency is often insufficient to dissipate large heat fluxes under high solar irradiance and elevated ambient temperatures. In contrast, active cooling systems (using fans or liquid pumps) provide significantly better heat removal but have a major drawback – additional electrical power consumption. This reduces the overall energy gain of the system while also complicating its design, increasing both cost and failure risk.

4.1. Limitations of Materials and Interfaces

The durability and performance of a hybrid system largely depend on the choice of materials and the quality of interfacial contacts. Among the main challenges is the limited efficiency of current thermoelectric materials. Despite decades of research, the figure of merit (ZT) of commercial compounds, such as Bi_2Te_3, remains around 1, which restricts the maximum thermoelectric conversion efficiency to only a few percent. This raises questions regarding the economic feasibility of employing TEGs in combination with photovoltaic modules in large-scale solar installations [43].

Another critical issue is thermomechanical degradation. Since PV cells, thermoelectric modules, and heat-dissipating components (e.g., radiators) are made of materials with different coefficients of thermal expansion (such as silicon, ceramics, copper, and aluminum), regular heating–cooling cycles between day and night induce significant mechanical stresses at the layer interfaces. Over time, this leads to microcracks, delamination, and degradation of joints.

Additionally, challenges related to thermal interface materials (TIMs) should be noted. These materials are used to reduce the thermal resistance between layers. Conventional thermal pastes and adhesives tend to dry out and degrade under elevated temperatures and cyclic thermal loading, which significantly worsens heat transfer. Therefore, the stability and durability of thermal interfaces are critical factors for ensuring the reliable operation of hybrid systems.

4.2. Issues of Electrical Optimization and Cost

A significant challenge for PV/TEG complexes lies in the electrical integration of two components with fundamentally different current–voltage characteristics and maximum power points (MPP). Photovoltaic cells exhibit performance dependence on illumination intensity, whereas the efficiency of a TEG is primarily determined by the thermal gradient. As a result, in simple series or parallel configurations, one of the components always operates outside its optimal regime. To ensure efficient operation, specialized controllers with two independent MPPT algorithms are required, which considerably complicates the system architecture and increases its cost.

Another limiting factor is the high cost of thermoelectric modules, which at the current stage of technological development make their use in photovoltaic installations economically constrained. The additional energy gain often fails to offset the increased initial equipment cost, thereby reducing the investment attractiveness of hybrid solutions.

Various strategies to overcome these limitations have been discussed in scientific literature. These include the search for and development of new thermoelectric materials with enhanced ZT values (for example, based on nanostructured compounds or topological insulators), the implementation of highly efficient heat dissipation systems such as heat pipes and microchannel cooling structures, as well as the design of thermally stable, high-conductivity thermal interfaces. Attention is also devoted to the development of intelligent energy management algorithms capable of simultaneously optimizing the operation of both PV and TEG subsystems, thereby minimizing losses and improving the overall efficiency of the hybrid system.

Conclusions

The conducted analysis shows that hybrid photovoltaic–thermoelectric (PV–TE) systems are capable of partially addressing one of the key challenges in solar energy – the inefficient utilization of the thermal component of solar radiation. A significant portion of the energy that is not converted into electricity by the photovoltaic cell inevitably becomes heat, which degrades the operational performance of the module. The integration of a thermoelectric generator allows this adverse factor to be transformed into an additional source of electrical energy while simultaneously stabilizing the temperature regime of the photovoltaic cell. Material analysis indicates that thin-film photovoltaic technologies are the most rational choice for such systems, as they exhibit lower temperature sensitivity, and the use of well-established Bi_2Te_3-based thermoelectric materials ensures a predictable and reproducible efficiency gain.

At the same time, it has been established that the efficiency of a PV–TE system is determined not so much by the individual parameters of the PV or TE module, but by the quality of their thermal and electrical integration. Even moderate reductions in thermal resistances between layers and improvements in heat removal from the cold side of the thermoelectric generator can significantly influence the total system output. More complex configurations, particularly those employing spectral splitting or radiation concentration, offer the potential for higher efficiencies, but require substantially greater resources for implementation. In this context, hybrid PV–TE systems should be considered as a promising solution for autonomous and specialized applications, whereas further progress in the field is directly linked to the development of more efficient thermoelectric materials, stable thermal interfaces, and adaptive energy management schemes.

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Проєктування та оптимізація гібридних тонкоплівкових PV-TE систем перетворення енергії

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Сучасний розвиток відновлюваних джерел енергії вимагає вдосконалення технологій перетворення енергії для сталого енергозабезпечення. Одним із найбільш перспективних методів отримання електроенергії є використання фотоелектричних (PV) перетворювачів, що дозволяють безпосередньо перетворювати сонячне випромінювання в електрику. Проте одним з їх недоліків є те, що вони нагріваються, в результаті чого зменшується потужність. У даній статті проведений огляд гібридних PV-TE систем, що складаються з фотоелектричних модулів, термоелектричних генераторів і проміжного теплопровідного шару. Такі системи дозволяють не тільки охолоджувати фотоелектричні елементи, але й додатково генерувати електроенергію за рахунок ефекту Зеєбека, який перетворює температурний градієнт у різницю потенціалів. Проаналізовано основні конструктивні підходи, зокрема тандемні конфігурації з тепловою концентрацією та системи зі спектральним розділенням. Виявлено та розглянуто основні виклики для подальшої оптимізації системи. Зокрема, це проблеми термічного управління, обмежена ефективність комерційних термоелектричних матеріалів, електрична інтеграція двох компонентів із принципово різними ВАХ.

Ключові слова: відновлювальна енергетика, фотоелектричний модуль (PV), термоелектричний генератор (TEG), гібридні системи, фото-термоелектричні (PV-TE) системи.