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Review

Parabolic Trough Collector (PTC) and Thermoelectric Generator (TEG) Based Multigeneration Systems for Low/Zero Carbon Buildings: A Review

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Abstract: The growing need for sustainable and efficient energy solutions for low/zero carbon buildings has accelerated the development of hybrid technologies. Parabolic Trough Collector (PTC) and Thermoelectric Generator (TEG) based multi-generation systems stand out as promising solutions in this field. This study examines the integration of PTC and TEG technologies, highlighting the complementary power and potential application areas of these systems. While PTC systems are known for their ability to capture high-temperature solar energy, TEGs have the capacity to generate electricity by utilising temperature differences. Hybridisation of these technologies increases energy efficiency, system flexibility and sustainability. Examining various design configurations, operating principles and application areas, this study reveals the role of PTC-TEG hybrid systems in achieving multiple production goals such as electricity generation, water treatment, heating/cooling and hydrogen production. The results show that PTC-TEG hybrid systems not only improve energy conversion processes but also support environmental goals and play a critical role in the transition to a sustainable energy future.

***Keywords*:** concentrated solar power, parabolic trough collector, thermoelectric generator, energy efficiency, low/zero carbon buildings

1. Introduction

The limited availability of fossil fuels and the greenhouse gases released into the atmosphere because of their combustion lead to environmental degradation and global warming.

This has significantly increased global concerns regarding energy security and climate change, necessitating the development of new strategies in energy production [1-3]. Therefore, the search for sustainable energy sources

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has triggered the rapid growth of renewable energy technologies [4]. Solar energy is at the centre of this search as a clean, unlimited and environmentally friendly resource [5]. As of 2023, the global installed solar energy capacity exceeded 1,200 GW, with photovoltaics dominating the market due to their lower initial costs and modular design [6]. However, traditional methods of using solar energy face limitations, especially low efficiency and energy storage difficulties. Photovoltaic (PV) systems typically operate at 15-22% efficiency, while Concentrated Solar Power (CSP) technologies such as Parabolic Trough Collectors (PTCs) can achieve thermal efficiencies between 60-75% and operate at temperatures ranging from 150 °C to 550 °C [7]. This situation requires the development of innovative systems to maximize the utilisation of solar energy [8].

In this respect, CSPs come to the fore. CSP systems basically work by focusing the solar radiation onto a receiver through reflectors [9]. A fluid in this receiver is heated to high temperatures. Heated fluid generates electricity by driving a turbine or engine or is used as a heat source in industrial processes [10]. Some CSP systems are integrated with thermal energy storage systems to use solar energy later. In this way, it is possible to produce electricity or provide heat even when there is no sun [11]. CSP systems are clean and sustainable energy sources because they use solar energy. It reduces dependence on fossil fuels and reduces greenhouse gas emissions. In terms of environmental benefits, CSP systems can reduce carbon emissions by approximately 900 to 1,000 tons of CO_2 per installed megawatt annually when replacing fossil-based generation [12]. It can be combined with thermal energy storage systems, enabling electricity production even in the absence of sunlight [13]. Since high temperatures can be achieved, it can provide higher efficiency than other solar energy technologies. On the other hand, the installation cost of CSP systems is high. Large-scale CSP plants require large areas of land. Some CSP technologies use water for cooling, which can put pressure on water resources. The performance of CSP systems depends on the intensity of solar radiation. Efficiency decreases in cloudy weather [14].

CSP systems are divided into different types based on the concentrator technology used:

PTCs: Parabolic-shaped mirrors reflect the sun's rays to a receiver tube located at a focal point. The fluid passing through the receiver tube is heated. PTCs are the most used CSP technology [15].

Solar Towers: Multiple mirrors (heliostats) reflect the sun's rays to a central tower. The fluid is heated to high temperatures in the receiver at the top of the tower [16, 17].

Linear Fresnel Reflectors: Flat mirrors focus the sun's rays onto a fixed linear receiver. They operate similarly to PTCs but have a simpler design [18].

Parabolic Dish Systems: Dish-shaped mirrors reflect the sun's rays to a receiver located at a focal point. These systems are typically used for small-scale applications [19].

Another method of increasing the efficiency of solar energy systems is multigeneration systems, which allow more than one type of energy (e.g. electricity, heat, cooling) to be obtained from a single energy source [20]. The use of these systems optimizes energy conversion processes and enables more efficient use of resources. These systems offer significant advantages both economically and environmentally. Less energy loss, lower operating costs and reduced carbon emissions are among the prominent benefits of multigeneration systems [21]. Offering versatile and integrated solutions compared to traditional energy systems, these systems can increase access to energy and support sustainable development, especially in developing regions [22].

In this respect, a multigeneration system that can be used with CSP technologies is a hybrid system where PTC and Thermoelectric Generators (TEGs) are used together.

TEGs consist of semiconductor and directly convert temperature differences into electrical energy. This technology, based on the Seebeck effect, draws attention to its lack of moving parts, low maintenance requirements and long life [23]. TEGs are of critical importance in renewable energy applications, especially because they can produce energy even from low-temperature differences [24]. Nonetheless, the widespread adoption of TEGs is restricted by their low energy conversion efficiency. Therefore, integrating TEGs with other energy systems is seen as a practical approach to enhance their performance.

The hybrid use of PTC and TEG offers significant advantages in energy production by combining the strengths of the two technologies [25]. The high-temperature thermal energy provided by PTC can be converted into electrical energy by TEG, providing a more efficient energy conversion. In addition, this hybrid structure can increase the continuity of energy supply and provide greater utilisation of solar energy. PTC-TEG hybrid systems serve as a versatile energy solution, finding applications in power generation, industrial operations, water treatment, and air conditioning [26].

In this study, the design, working principles and application areas of PTC and TEG-based multigeneration systems are discussed. Existing studies in the literature are examined to understand the energy conversion processes, advantages and difficulties of these systems. In addition, it aims to compare PTC-TEG hybrid systems with different energy systems and to determine future research areas. The general purpose of the study is to reveal in detail the contributions of PTC and TEG hybrid systems operate by capturing high-temperature solar energy and converting part of it directly into electricity via the Seebeck effect. These systems can be employed not only for power generation but also for multigeneration purposes such as water desalination, space heating and cooling, and hydrogen production. This integration offers both energy efficiency and environmental benefits in various applications.

2. Fundamentals of PTC and TEG technologies

Although this review focuses on the combined PTC-TEG hybrid system, a brief overview of each component technology is necessary to understand their individual roles and contributions within the integrated structure.

2.1 *PTCs*

PTCs are one of the most used concentrated solar energy technologies. The system consists of a series of reflective semi-cylindrical mirrors that direct sunlight to a receiver tube located at a linear focal point. This process is designed to convert solar energy into high-temperature thermal energy [27]. The sun's rays are collected by parabolic mirrors and focused on a heat transfer fluid (usually thermal oil or a water-steam mixture) passing through the tube. The heated fluid is used in energy conversion systems such as steam turbines to generate electricity [28]. As shown in Figure 1, it generally consists of a reflective mirror made of highly reflective materials used to focus on the sun's rays, an absorber tube, usually coated with selective coatings, that transmits the solar energy to the heat transfer fluid, and auxiliary elements used to hold the mirrors at the correct angle and to provide sun tracking [29].

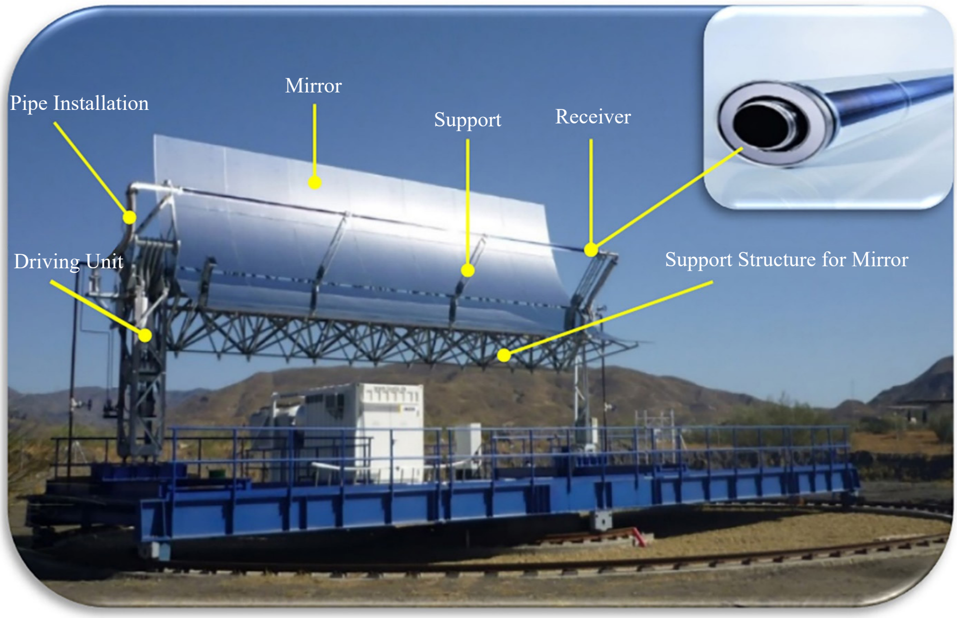

Figure 1. Structure of PTC [29]

PTCs enable high-temperature energy production, offer wide-scale applications, and are technologically mature and suitable for commercial use. The most important disadvantages are the high initial installation costs and the decrease in energy production capacity at night or on cloudy days [30].

2.2 *TEGs*

TEGs are a technology that converts temperature differences into electrical energy and work based on the Seebeck effect. This effect means that an electrical potential is created when there is a temperature gradient [31]. As shown in Figure 2, a TEG system uses the temperature difference between two different semiconductor materials [32].

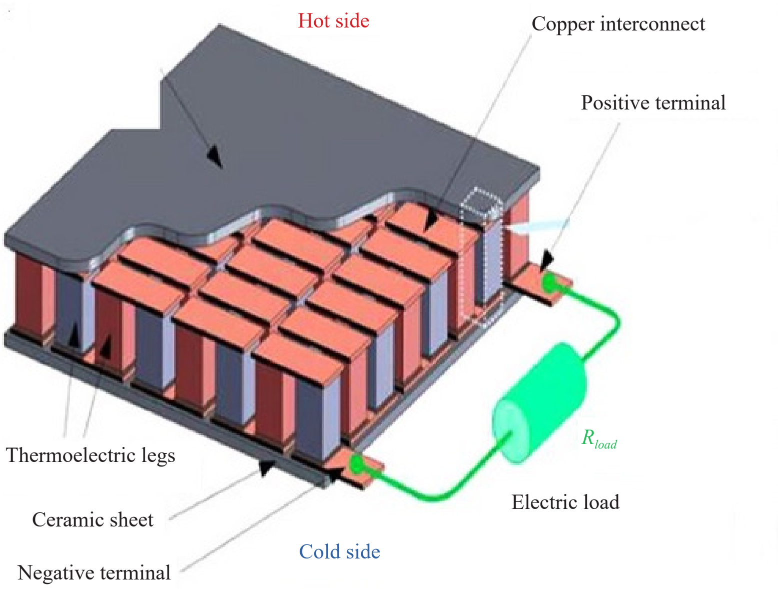

Figure 2. Structure of TEG [32]

This difference causes electrons to move, and this movement creates an electric current. The key benefit of TEGs is that they operate without any moving parts. Thanks to these features, they are durable and silent. They also have low maintenance costs and a long life [31]. Thanks to their compact design, they can be integrated into various applications. However, their energy conversion efficiency is low. While PTC provides high-temperature thermal energy generation, TEG can directly convert this temperature difference into electrical energy [33].

PTC and TEG systems exhibit distinct characteristics, making them suitable for different energy applications. A critical limitation of TEGs is the material properties used for thermoelectric conversion. The dimensionless figure of merit (ZT), which dictates the efficiency of thermoelectric materials, remains relatively low in commercially available compounds, typically ranging from 0.7 to 1.1. This restricts overall conversion efficiency despite favourable thermal gradients [23]. To provide a clear understanding of their comparative advantages and limitations, Table 1 summarizes the key features of these technologies.

The comparison highlights aspects such as energy source, efficiency, operational temperature range, applications, system complexity, cost, maintenance requirements, environmental impact, energy storage capabilities, and scalability. This overview facilitates the identification of opportunities for integrating these systems into hybrid configurations, where their complementary strengths can be utilised to enhance overall energy generation efficiency and sustainability. Therefore, when these two technologies are combined in a hybrid system, both energy conversion efficiencies can be increased, and energy production processes can be made more flexible. In particular, in cases where PTC cannot produce energy continuously, the efficiency of TEG increases, and the overall efficiency of the system increases.

Table 1. Comparison of PTC and TEG systems

Feature	Parabolic Trough Collector (PTC)	Thermoelectric Generator (TEG)	Ref.
Energy source	Solar energy (sunlight)	Heat energy (temperature gradient)	[34, 35]
Efficiency	High efficiency (15%-20%, depending on system and location)	Moderate efficiency (5%-8%) at low temperature differences	[36]
Temperature range	150 °C to 400 °C (with molten salt storage)	Low-temperature gradients (typically up to 300 °C)	[37, 38]
Applications	Large-scale power generation, industrial heating, desalination	Waste heat recovery, remote power supply, wearable electronics	[39]
System complexity	High (requires tracking mechanisms, large infrastructure)	Low (compact, simple design)	[39]
Cost	High initial capital cost, moderate operating cost	Low initial cost, but lower overall efficiency requires more units	[40, 41]
Maintenance	Medium to high (requires regular cleaning and inspection)	Low (minimal maintenance required)	[42, 43]
Environmental impact	Low emissions (sustainable energy source)	Very low emissions, as it recovers waste heat	[42, 43]
Energy storage	Can be integrated with thermal storage systems	Limited energy storage capability	[44, 45]
Scalability	Highly scalable, especially in sunny regions	Limited scalability, generally small-scale applications	[39, 41]

The performance and operational characteristics of PTC and TEG systems individually reveal the rationale behind their integration. While PTC systems efficiently harvest high-temperature thermal energy, TEG modules can recover residual heat and convert it directly into electricity, making the hybrid configuration a promising solution for enhanced energy utilisation.

3. Design and working principles of PTC-TEG hybrid systems

PTC-TEG hybrid systems are innovative energy production systems designed to effectively use solar energy and convert thermal energy into electrical energy. These systems combine the high-temperature energy collection capacity of PTC technology with the low-temperature difference energy generation feature of TEG systems, providing an efficient and sustainable energy production mechanism [46]. The main goal of hybrid system design is to increase the overall efficiency of the system by ensuring that the PTC and TEG components operate in harmony. TEG modules are integrated with a design that uses the waste heat generated after the primary use of the energy produced in the PTC system, converting some of this energy into electrical energy [47]. During this integration, the placement position of the TEG modules and thermal conductivity optimisation plays a critical role. In addition, TEG modules can be placed in certain areas of the receiver pipes to produce energy from high-temperature differences. As a result, the combined use of PTC and TEG systems provides higher efficiency in energy production by recovering waste heat. These systems, based on renewable energy sources, contribute to environmental sustainability by reducing carbon emissions. They have versatile applications such as electricity generation, water heating, and heat used in industrial processes [43, 48].

Several hybrid PTC-TEG system configurations presented in recent literature have demonstrated considerable performance improvements depending on the working fluid and system design. In one experimental setup, the use of water as the heat transfer fluid resulted in a combined efficiency of approximately 76.91% with an electrical output of 97 W, while the use of Therminol VP1 led to 585 W power generation and 70.55% thermal efficiency under similar solar flux conditions. Another study reported that system pressurisation contributed to a 14.64% increase in thermal efficiency, with the TEG modules providing an additional 1.11% electrical output. These findings underline how the integration of

TEGs at optimal locations in the thermal loop, typically after the PTC outlet, can recover low-grade heat effectively and improve overall system performance. Such designs offer scalable solutions for combined electricity and thermal energy generation in multigeneration applications. A comprehensive comparison of system efficiency, performance metrics, and evaluation of hybrid operation is presented in Section 4, where multigeneration capabilities and use-case scenarios are also discussed.

One of the key technical challenges in PTC-TEG hybrid systems is the presence of Thermal Contact Resistance (TCR) between the PTC receiver surface and the thermoelectric modules. This resistance can significantly hinder heat transfer, reducing the temperature gradient across the TEG and thus lowering electrical output. Inadequate surface contact, surface roughness, oxidation, or mismatch in thermal expansion coefficients between materials can exacerbate this issue. To mitigate TCR, researchers have explored the use of Thermally Conductive Interface Materials (TIM), such as graphite sheets, thermal pastes, or metal foils. Additionally, ensuring uniform pressure distribution and minimising air gaps during TEG integration are essential for maintaining high thermal coupling efficiency and overall system performance.

4. Multigeneration applications

PTC-TEG hybrid systems have significant potential in multigeneration systems, which not only generate electricity but also enable the simultaneous acquisition of various forms of energy. These systems provide integrated energy solutions by increasing energy conversion efficiency and contribute to the Sustainable Development Goals. Multigeneration applications optimise the economic and environmental performance of energy systems by allowing various energy needs to be met simultaneously [49].

4.1 *Performance analysis of PTC-TEG hybrid systems*

The most basic application of PTC-TEG hybrid systems is to produce electricity from solar energy. Parabolic trough collectors concentrate high-intensity solar energy on the receiver tube, allowing thermoelectric generators to create a temperature difference. TEGs convert this temperature difference directly into electrical energy, creating a sustainable energy source. This method is particularly effective in remote areas without a grid connection [50]. Habchi et al. [51] created a model to evaluate the thermal performance of two cogeneration systems that integrated PTC and cylindrical TEGs. TEGs were used on the outer surface of the receiver tube and different heat transfer fluids such as Therminol VP1 (a synthetic high-temperature heat transfer fluid produced by Eastman Chemical Company) and hot water were passed through the receiver tube. The effects of solar radiation and focusing ratio on the thermal and electrical performance of the system were investigated with the model developed in Matrix Laboratory (MATLAB) software. 70.55% efficiency and 585 W power were obtained in the system using Therminol VP1. 76.91% efficiency and 97 W power were provided in the system using water. The model results were verified by comparing with the literature. In another study, the effects of PTC and hybrid pipe type TEG configuration on thermal and electrical efficiency were investigated. Cold water was passed along the inner surface to increase the temperature difference between the surfaces of TEGs. Numerical simulations revealed that the enhancement in system performance was attributed to the temperature adjustment concept and optical concentrator. As the solar concentration rate increased, the system's total efficiency reached 76.21%, and the daily hot water production rose to about 846.77 litres at a concentration rate of 30 [52]. Gharzi et al. [53] designed a PTC-TEG hybrid solar energy system. Two distinct methods were implemented to enhance the system's efficiency, and both the thermal and electrical performance were examined experimentally. Initially, the heat transfer fluid in the absorber tube was pressurized using a pressure control unit, with relative pressures set at 0.3 and 0.5 bar. Second, additional electricity generation from absorbed solar radiation was provided by TEG modules placed behind the reflective surface. Thermal efficiency increased by 6.88% and 14.64% with increasing fluid pressure by 0.3 and 0.5 bar, respectively. Furthermore, the TEG array contributed 0.96-1.11% to the total system efficiency. Soltani et al. [54] developed a dimensionless model for a hybrid system where PTC, photovoltaic and TEGs are integrated. MATLAB software was utilised to assess the impact of solar radiation and ambient temperature on system performance. The study analysed the electrical characteristics of thermoelectric and photovoltaic modules, along with the thermal and electrical powers of the hybrid device, as well as its thermal and electrical efficiencies. According to the results obtained from the study, 22.714 W of electrical power can be achieved in the case of using the hybrid system.

While energy efficiency reflects the amount of energy converted, exergy efficiency measures the quality of the energy and its potential to perform useful work. In PTC-TEG hybrid systems, second law thermodynamic evaluation provides a deeper understanding of irreversibility in both the thermal cycle and thermoelectric modules. Integrating TEG modules into the PTC system reduces the overall exergy destruction by recovering some of the waste heat, thus increasing the exergy efficiency at the system level. Depending on the system conditions, the reported exergy efficiencies for hybrid systems are higher than for standalone CSP systems.

4.2 *Application areas of PTC-TEG hybrid systems*

High-temperature waste heat generated in PTC-TEG hybrid systems can be used in hot water production, industrial processes and central heating systems. By integrating thermal energy storage technologies, these systems make a significant contribution to applications where energy needs are continuous. In addition, low-temperature waste heat can be combined with absorption cooling systems to meet cooling needs [55]. Herez et al. [56] designed a hybrid solar energy system consisting of PTC integrated with a photovoltaic module and TEG. The system, simulated using MATLAB software, was validated by comparing it with previous studies in the literature. It was observed that the integration of TEGs into the system increased the annual average total electricity production by 1.8%, while the annual average heat rate transferred to the working fluid decreased by 1.9%. In addition, it was revealed that the annual CO_2 emission amount could be reduced to 81.4 tons.

The combination of PTC-TEG hybrid systems with absorption cooling or thermoelectric cooling devices offers cooling solutions from renewable energy sources. Such systems provide significant advantages, especially in areas such as the storage of agricultural products in hot climates, the cooling of buildings and industrial cooling applications. This method saves energy by reducing electricity consumption and reducing the carbon footprint [57]. Khanmohammadi et al. [58] designed a novel parabolic trough collector-based combined power and cooling system integrated with TEGs. The energy, exergy and exergo-economic performances of the proposed system were investigated. The effects of TEG integration on power generation performance were evaluated. According to the results, it is possible to improve the exergy performance of the system with TEG integration.

The heat energy produced in PTC-TEG hybrid systems can be used to convert seawater into drinking water by combining thermal desalination systems. This method offers an effective solution to meet the freshwater demand, especially in arid regions. The use of multiple production systems in this area contributes to the sustainable management of water and energy resources [59]. Assareh et al. [60] designed an integrated solar energy system aimed at generating various power outputs. Rather than using a condenser, the TEG unit was employed to generate electrical power. Energy and exergy analysis results showed that replacing the condenser with a TEG reduces the overall cost of electrical power production and enhances the system's exergy efficiency.

PTC-TEG hybrid systems can also be used in hydrogen production by providing the high-temperature energy required for thermochemical reactions. The integration of solar energy directly into hydrogen production processes is considered an important step in the development of renewable energy fuels. Habibollahzade et al. [61] proposed an integrated system including the PTC-TEG-Rankine cycle and Proton Exchange Membrane (PEM) electrolyser for energy and hydrogen production. Parametric studies were carried out on the modelled system, considering various parameters, especially energy. According to the results obtained from the study, the installation of the TEG unit instead of the condenser is a promising method in terms of energy production and exergy efficiency. Alirahmi et al. [62] introduced the analysis of an innovative solar-powered system designed to generate electricity, thermal energy and hydrogen. In this system, PTCs act as the heat source for cascade power cycles. The electricity produced by the steam Rankine cycle is fed into the grid, while the energy from the organic Rankine cycle is used to power an electrolyser for hydrogen production. Additionally, the potential of a TEG, operating by recovering waste heat from the condenser, to provide supplementary electricity to the electrolyser is investigated. According to the results, the use of TEG increases system efficiency and reduces product costs. The most significant performance results of PTC-TEG hybrid systems reported in the literature are summarised in Table 2, including output power, thermal efficiency, and thermoelectric contributions under various configurations.

Table 2. Key performance results from PTC-TEG hybrid systems

Configuration description	Working fluid	Power output (W)	Thermal efficiency (%)	TEG contribution (%)	Improvement
PTC-TEG system using water	Water	97	76.91%	-	High thermal efficiency
PTC-TEG system using Therminol VP1	Therminol VP1	585	70.55%	-	High electrical output
Pressurized loop with hybrid setup	-	-	+14.64% (thermal gain)	+1.11	Efficiency improved via pressurization
Nanofluid-enhanced hybrid system	CuO-Al_2O_3/water	-	-	+2.2	Better TEG yield with nanofluid
Hybrid system with optimized absorber/receiver materials	-	-	-	-	Reported better heat transfer

The performance of TEGs in PTC-TEG hybrid systems is highly dependent on maintaining a stable temperature gradient between the hot and cold sides. However, under real operating conditions, solar irradiance is rarely constant due to factors such as cloud movement, time-of-day variation, and seasonal changes. These fluctuations lead to unstable thermal input, which in turn causes rapid variations in the temperature gradient across TEG modules. As a result, the electrical output of TEGs drops significantly, and frequent thermal cycling can lead to material fatigue and degradation at the thermal interfaces, ultimately compromising system reliability. To mitigate these effects, the integration of Thermal Energy Storage (TES) has been proposed as a practical and effective solution. TES systems such as molten salt tanks or Phase Change Materials (PCMs) can store excess thermal energy during peak irradiance and release it during low-sun or no-sun conditions. This allows the hybrid system to maintain a more consistent heat supply to the TEG modules, thereby preserving the temperature gradient, stabilising electrical output, and reducing thermal stress on system components [63, 64].

Despite the relatively low individual conversion efficiencies of PTC and TEG systems, their combination offers significant practical value, especially in multigeneration and off-grid applications. The TEG unit does not interfere with the primary function of the PTC but instead utilises the residual heat that would otherwise be lost. In this way, the hybrid system enhances total energy utilisation without increasing fuel consumption or complexity. Moreover, the hybrid system can simultaneously provide electricity, thermal energy, and services such as desalination or space cooling, making it highly suitable for remote or distributed energy applications where maximizing resource use is critical. The added value lies not only in electrical efficiency but also in system versatility, compactness, and sustainability.

To further increase system reliability and ensure continuous operation, PTC-TEG hybrid systems can be integrated with other renewable sources such as biomass burners or low-enthalpy geothermal heat sources. These auxiliary sources can provide stable thermal input during periods of low solar radiation, thus maintaining the temperature gradient required for TEG operation and extending daily operating hours. Such hybridization also allows for more flexible control strategies and increased energy delivery, especially in off-grid or seasonal environments. However, the technical and economic feasibility of such integrations requires further investigation, especially with respect to thermal compatibility and system complexity.

4.3 *Modelling approaches and optimisation studies*

Recent studies on PTC-TEG hybrid systems have increasingly incorporated modelling techniques to evaluate system performance under varying operating conditions. Dynamic modelling approaches are employed to simulate transient thermal behaviour during fluctuating solar radiation, often using numerical tools such as MATLAB/Simulink or ANSYS-Fluent. In parallel, thermoelectric modelling techniques—based on the Seebeck effect, internal resistance, and temperature-dependent material properties—are used to assess electrical output under given temperature gradients. Some researchers have also proposed multi-objective optimisation frameworks to maximise output power while minimising system cost or entropy generation. These include evolutionary algorithms (e.g., NSGA-II), genetic algorithms, or response surface methodologies to identify the optimal configuration of geometrical and operational parameters. Such modelling and optimisation studies are crucial for guiding the practical design and implementation of PTC-TEG hybrid systems [65-67].

Despite the promising appearance of PTC-TEG hybrid systems, several technical and practical challenges remain unsolved. One of the main problems is the inherently low thermoelectric conversion efficiency, which is usually limited to 5-8%, which limits the total electrical output. In addition, the thermal contact resistance and interface stability between the PTC receiver and TEG modules can significantly reduce the effective heat transfer. Therefore, future research should focus on material innovations, efficient system integration strategies, and long-term reliability to make these systems applicable on a larger scale.

5. Conclusion

PTC-TEG hybrid systems provide significant advances in energy efficiency and sustainability by offering an innovative approach to renewable energy use. This study has shown that the integration of PTC and TEG technologies is an important alternative to overcome the limitations of traditional energy systems, such as intermittent generation and low conversion efficiency. These hybrid systems can generate multiple types of energy, such as electricity and thermal energy. Despite their potential, challenges such as reducing high initial costs, optimising material performance, and increasing system scalability remain. In conclusion, PTC-TEG hybrid systems have revolutionary potential in the field of renewable energy technologies. They contribute to reducing greenhouse gas emissions, preserving natural resources, and supporting energy independence by providing efficient and sustainable multiple generation. The development and deployment of these systems constitute a critical component to meet global energy demand in a sustainable manner.

Recent findings in the literature indicate that hybrid PTC-TEG systems can achieve total efficiencies approaching 77%, with electrical outputs exceeding 500 W under optimized thermal conditions. Systems utilizing water or thermal oils as heat transfer fluids show notable improvements in both thermal and electrical performance. In certain configurations, pressurisation of the working fluid has resulted in thermal efficiency gains of over 14%, along with modest electrical contributions from the thermoelectric modules. Additionally, such systems have the potential to reduce carbon emissions by up to 1,000 tons per megawatt per year, depending on the deployment scale and solar intensity. These figures highlight the feasibility and environmental value of PTC-TEG hybrid integration in multigeneration applications.

Conflict of interest

There is no conflict of interest for this study.

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