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REVIEW ARTICLE

A critical review on energy harvesting approaches by using thermoelectric generator in solar photovoltaic system

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Abstract

Electricity generated from sunlight has been proven to be one of the most practical solutions for meeting the world's energy needs. To be competitive with conventional energy resources, the solar cell, a semiconductor device that directly converts solar radiation into electrical power, requires ongoing improvements in conversion efficiency and economic viability. This paper reviews the fundamentals of thermoelectric generators, including the operating principle. The main aim of the paper was to present an energy-harvesting approach that uses a thermoelectric generator, to prove the application of this hybrid technology, and to summarize the findings. Thermoelectric generators provide a means of cogenerating heating, cooling, and electricity from either waste heat or the primary heat flux of solar energy systems, thereby enhancing system efficiency and functionality. The combination of photovoltaic systems and thermoelectric generators, which together provide heating and cooling while generating electricity, has been discussed in the literature. This paper evaluates the methods and effects of thermoelectric devices on the functionality of photovoltaic systems through a review of the published literature. This study provided a comprehensive analysis of recent work in this field, including solar photovoltaic systems, solar energy applications, and potential solar configurations for industrial use.

Keywords: Renewable energy, photovoltaic system, solar desalination, thermoelectric generator, hybrid PV/TEG, waste heat recovery

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1. Introduction

In the global energy context, energy demand continues to increase, and meeting this demand will primarily depend on fossil fuels such as oil, natural gas, and coal. To replace fossil fuels, renewable energy sources must be used to the maximum extent in daily life. As the global population increases, there is an urgent need for nonconventional energy sources. D. Das et.al [1] had mainly concentrate on environmentally sustainable development to reduce the impact on fossils fuel. In addition to generating electricity, solar photovoltaic systems provide clean energy. Solar energy is widely regarded as the most prominent renewable energy source due to its virtually unlimited availability and suitability for a broad spectrum of applications, ranging from small-scale domestic use to large-scale industrial power generation.

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Habchi et.al [2] mainly focus on experimental analysis solar photovoltaic thermal system with parallel pipe integration. Any organization that fully implements a solar PV system will receive CDM benefits. The main benefit of CDM is the reduction of carbon emissions into the environment, while some researchers focus on solar air-heating and air-drying systems for various industrial and agricultural applications. Solar energy is not limited to electricity production; it also serves critical functions in solar cooking and solar desalination, addressing essential needs for food and water. S. A. Kedar et.al [3-4] had mainly studied hybrid solar desalination system had been providing good quality of drinking water while solar cooking provides good quality of food for human community. From an overall perspective of solar applications, solar photovoltaic systems are mainly applied to thermoelectric generators. Specifically, solar energy is used in two ways: (a) solar thermal systems and (b) solar photovoltaic systems. Most research on thermoelectric generators has focused on analytical modelling, experimental validation, and numerical simulations to perfect their performance across a wide range of thermal applications. Z. Said et.al [5] had mainly studied the thermal performance phase change material (PCM) mainly used in nanotechnology or nanofluids for the thermoelectric generator. To improve thermal performance, PCM must be integrated into a solar PV system to raise the temperature of the PV module. Thermoelectric generators primarily utilize heat from solar PV or solar desalination systems. Further research primarily explores using solar thermoelectric generators to generate electricity, while some researchers focus on employing six thermoelectric generators to increase the output voltage and current. Y. Yakut et.al [6] had developed experimental setup with voltage 7.52 V with intensity of solar radiation 66 W/m2 the output power obtained 5.3 W while M. He et.al [7] mainly focus on Peltier and Seeback effect along with the application on thermoelectric generator. In most solar PV systems, the Peltier effect contributes more than the Seebeck effect to keeping overall thermal performance. A. Alinia et al. [8] mainly focus on hybrid PV/TEG system, they argued that combined experimental results to get better electrical output in the photovoltaic system.

We reviewed various articles on solar PV and generator systems. Although most researchers focus on overall thermal performance, research on integrating thermoelectric generators with solar PV systems is needed, as it will be useful for various solar energy applications. The primary novelty of this research lies in the author's critical review of thermoelectric generators for solar photovoltaic applications and the examination of these generators' overall impact on thermoelectric devices. Figure 1 shows a schematic diagram of a photovoltaic–thermoelectric system for power generation [36]. Zhang W. et.al [9] had mainly studied the various characteristics of Photovoltaic thermoelectric radiant windows whereas G. Mittal et.al [10] had mainly studied on photovoltaic-thermoelectric generator (PV-TEG) hybrid system, which integrates a solar PV module with a thermoelectric generator, represents a promising technological approach for augmenting total energy harvest from solar irradiation. A primary challenge in such systems, however, is increased PV cell temperature, which not only reduces the electrical efficiency of the photovoltaic part but also introduces thermal instability, affecting the coupled performance and reliability of the entire hybrid unit.

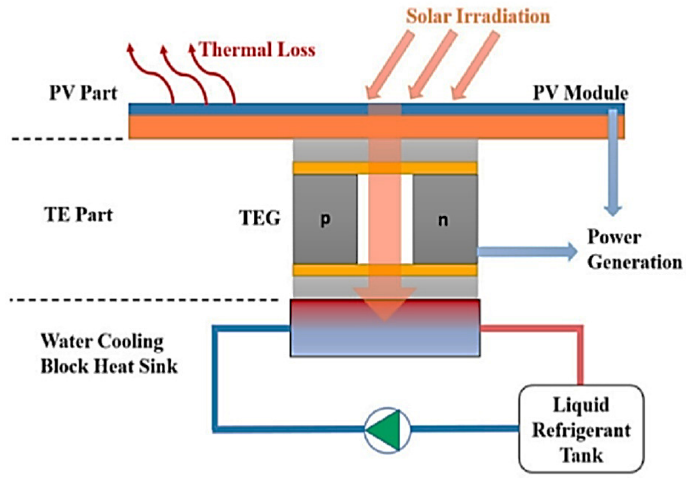

Figure 1. Schematic diagram of Photovoltaic and Thermoelectric system

2. Thermoelectric generator (TEG)

A thermoelectric generator is primarily an electromotive device that relies on the Seebeck effect. Implementing a thermoelectric generator in the fixed part of the system improves the thermal performance of solar systems. Yet the poor performance of the thermoelectric generator has been a major obstacle to experimental aims. They may improve the performance of free heat-source energy systems, particularly photovoltaic systems used for power generation. D. Beretta et al. [11] had mainly studied thermoelectric in the thermoelectric generator whereas A. R. M. Siddique et.al [12] had mainly reviewed of the state of the science on wearable thermoelectric power generators (TEGs)and their existing challenges, he argued that there is great need for thermoelectric generator for solar thermal applications. W. Liu et al. [13] analyzed thermoelectric interface materials for a thermoelectric power generation module.

Research on thermoelectric generators over recent decades has been largely dedicated to advancing the performance of thermoelectric materials. Efforts have focused on two main fronts: exploring novel material compositions with improved thermoelectric properties and developing engineering techniques to perfect their thermal efficiency. This study focuses on the development of a thermoelectric generator suitable for industrial applications. In terms of development, no research has been conducted on thermoelectric systems with modern features. A. M. Hameed et. al [14] had mainly focus on experimental investigation on solar air heater system, he argued that porous medium higher thermal efficiency by 10% with flow rate of 14 % whereas S. A. Kedar et.al [14] had mainly reviewed various techniques for the thermal performance improvement of solar air heaters, their studies shows solar air plays as an important role for industrial as well as residential community. S. A. Kedar et.al [16 -17] head studied experimental performance on compound parabolic concentrator in solar desalination system, he argued that the hybrid configuration, which incorporated Mylar material into the system design, yielded a significantly lower output of approximately 3.5 liters of fresh water per day. S. A. Kedar et.al [18-19] had mainly studied effect of reflecting material to the performance of the solar desalination system. The experiment was conducted in Pune, western India. He also studied a single-stage ETC-CPC combination in a solar desalination system. He argued that the single-effect boiling method is one of the more effective solutions for providing potable water to the rural community. The findings indicated that a standalone ETC configuration intended for a household-scale system achieved a freshwater production rate of 27-28 liters per day. Figure 2 shows the schematic of the hybrid solar desalination system using ETC and CPC [16]. Whereas figure 3 presents the complete schematic of the solar air-heating system [15]. S. A. Kedar et. al [41] had studied a critical review of solar air heating system and he argued that solar air heating system plays a vital role in thermoelectric generator system.

In the studies on the solar air heater and solar desalination system, no thermoelectric generator was employed. If the author coupled the entire system to a thermoelectric generator, the thermal performance of the solar air heater and the solar desalination system would improve.

Figure 2. Schematic diagram of hybrid solar desalination system (ETC + CPC)

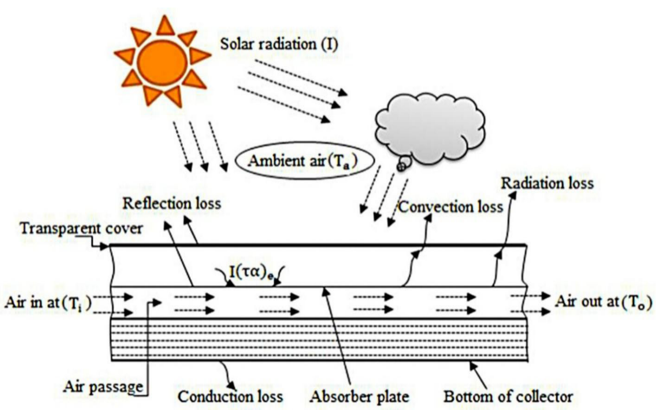

Figure 3. Schematic diagram of solar air heating system

N. Kim et.al [20] mainly focuses on mathematical systems to be considered for transfer of heat with the help of heat exchangers of the two surfaces in thermoelectric modules. This phenomenon can be attributed to the strong dependence of thermal conductivity on the average operating temperature of the working fluid or medium. Since thermal conductivity governs heat transfer within the system, temperature-induced variations directly affect the system's thermal performance and efficiency. O. H. Ando Junior et.al [21] had concentrated on comparative analysis for electrical design and performance evaluation of thermoelectric generator. B. Orr et.al [22] had mainly reviewed waste heat recovery system using thermoelectric generators and heat pipes also another author mainly focusses on heat pipes with different solar PV systems. All experiments were conducted across different climatic conditions in India. In summary, the results show that thermoelectric generators play a significant role in solar applications, particularly in photovoltaic systems.

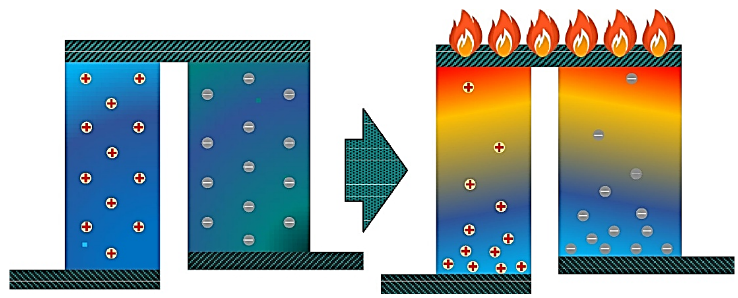

Figure 4. Seebeck effect in a thermoelectric uncouple

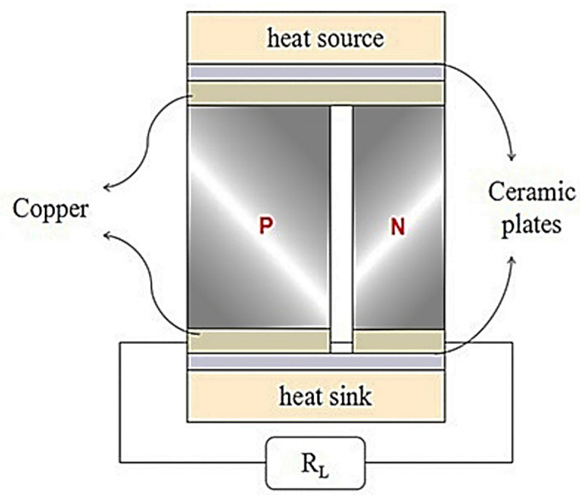

Figure 5. A single pair of thermocouples

Figure 4 illustrates the Seebeck effect in a thermoelectric unicouple, while Figure 5 depicts a thermocouple pair forming P and N junctions and copper and ceramic plates [23].

3. Materials for thermoelectric generators in solar applications

The thermal performance of a thermoelectric generator primarily depends on the materials used, the hot and cold junction temperatures, and the materials' shape and size. Improving the identification of better materials for the thermoelectric generator will contribute to the overall thermal performance of the hybrid system.

Materials research for thermoelectric generators is greatly needed. Y. K. Lee et.al [24] had mainly focus on Sn Se Polycrystalline for thermoelectric material, which will be useful for improve the thermal performance characteristics. H. L. Shi et.al [25] had been conducted studies on carbon allotrope for hybrid combination along with the fiber that are flexible and portable. Beyond technical performance, the cost of materials is a key factor influencing the feasibility and economic viability of the entire system design. However, the study reveals a significant research gap in thermoelectric generator development to enhance thermoelectric applications in various solar systems [37].

4. Applications for renewable system

4.1. Thermoelectric power generator and PV system with phase change material

Gurbuz et.al [27] mainly focus on enhancing thermal efficiency in PV / TEG hybrid system for increasing producing power. They conducted an experimental investigation of natural and forced-air cooling using a nanofluid, which was primarily intended for electricity generation. He argued that their experimental results (52.19%) show superior performance, while another author primarily investigated a phase-change material system in which fluid was circulated through copper tubes to assess the effect on thermal performance. M. Naderi et.al [28] A hybrid combination thermoelectric generator with solar PV system. The heat sink reduces the overall temperature. Figure 6 shows a schematic representation of the hybrid PV-TEG module [26].

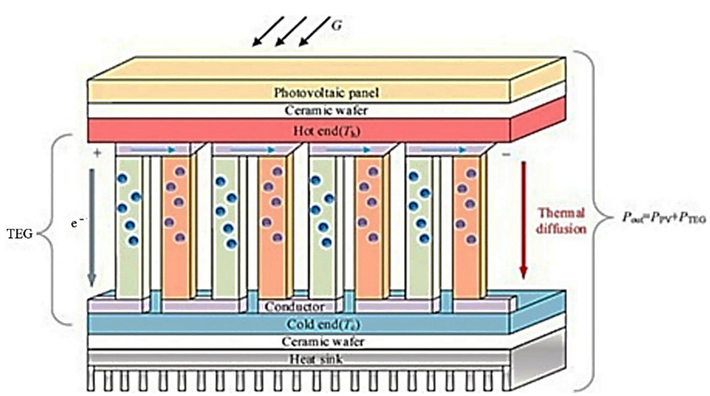

Figure 6. Hybrid combination of PV-TEG module

4.2. Thermoelectric generator in solar water heating system

Across the entire system, the increase in water temperature was primarily achieved by the thermoelectric heating system. Solar water heating systems include electrical energy generation, primarily via thermoelectric generators. He primarily argued that the system consumed 161W of electrical power. The setup was implemented primarily to induce thermal degradation of the solar PV module. The main findings show that system hybridization improves thermal performance. A. Faddouli et al. [29] had mainly conducted comparative enhancement of a normal solar water heater as well as smart thermal / thermoelectric hybrid systems, their results mainly show that through thermoelectric generators in solar water heating systems gives higher temperature performance than ordinary systems. T. H. Kil et al. [30] primarily studied a highly efficient concentrating photovoltaic/thermoelectric hybrid generator; their study showed that the hybrid system produced better results for electricity generation.

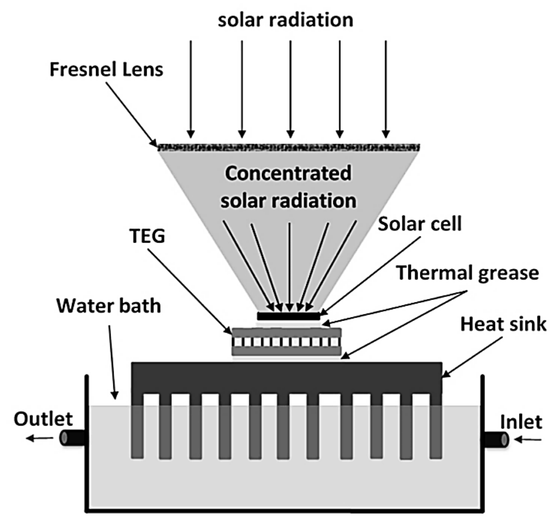

Figure 7. Thermoelectric generator with solar water heating system

Incorporating thermoelectric heating into the storage tank of a solar water heater can significantly increase the water temperature. The thermoelectric module contributes to the thermal energy input, thereby enhancing the system's overall output. A typical integration of a thermoelectric generator into a solar water-heating system is shown in Figure 7 [40].

5. Result and discussion

Most researchers use thermoelectric generators in solar systems. Hybridization with a solar PV system yields improved results and has potential applications due to its novel approach. A review of many research articles shows that thermoelectric generators are not used in most solar thermal applications. Excess solar PV output powers a thermoelectric generator.

Thermoelectric generators are mainly incorporated into waste-heat systems and various solar systems, where researchers have argued that excess heat can be used not only for heating applications but also for electricity generation. Some case studies show higher thermal efficiency, which mainly helps the overall solar PV system. Some articles primarily investigated the application of hybrid solar desalination systems. The author examines a hybrid system (ETC + CPC), while other researchers primarily study solar–natural gas power plants that use the Rankine cycle. A key finding of the study was that the integration of a thermoelectric generator allowed the simultaneous production of electricity and distilled water. The authors contended that this configuration improves the overall thermal performance and offers considerable scope for enhancing exergy efficiency, thereby highlighting the thermodynamic advantages of the hybrid design.

Atalay et.al [31] had mainly focused on exergoeconomic and exergo-environmental analyses of a large-scale solar dryer with PCM energy storage medium, he argued that PCM is important energy storage medium in large scale solar dryer. Whereas G. Palanikumar et.al [32] had experimentally studied box type Solar Cooker and nanoparticles mixed bar plate coating with effect of thermal image cooking pot. M. N. AlMallahi et.al [33] mainly analyzed of solar-powered adsorption desalination systems he argued that there is great future in the solar powered adsorption desalination system whereas M. Al-Addous et al. [34] mainly reviewed different innovations in solar-powered desalination in the Middle East and North Africa (MENA) whereas R. Khenfer et al. mainly studied experimental investigation of water-based hybrid energy system [35]. S. Shanmugan et.al [37] had studied solar cells absorption viewpoint of Mie theory: Experimental analysis of TiO_2 doping V/Ce whereas M. A. Javadi et.al [38] had analyses of combined cooling and power plants with parabolic solar collector whereas A. Alhamayani [39] had studied performance analysis and machine learning algorithms of parabolic trough solar collectors using Al_2O_3-MWCNT as a hybrid nanofluid.

Finally, several researchers studied the need for thermoelectric techniques for solar desalination and energy production and examined various optimization methods. With further research, solar thermoelectric technology will become less costly, cleaner, and more environmentally sustainable, contributing to a better future.

6. Conclusion

In response to the escalating global demand for sustainable energy solutions, solar energy has appeared at the forefront of renewable technologies due to its immense potential and reduced environmental impact. This paper offers a systematic and comprehensive review of recent advancements in the integration of thermoelectric modules (TEMs) with diverse solar energy systems—an approach conceived to transcend the inherent efficiency constraints of standalone photovoltaic (PV) panels. The principal novelty of this research domain lies in the dual functionality of TEMs, which exploit the Peltier effect for active heating and cooling and, when ran as thermoelectric generators (TEGs), the Seebeck effect for waste-heat recovery. To ease a coherent and structured examination of this interdisciplinary field, the study categorizes the extant literature into four primary application areas.

- Solar Photovoltaic Systems: Where TEMs are primarily employed for active panel cooling to mitigate efficiency losses from elevated temperatures, or as TEGs to convert residual heat into added electrical output.
- Solar Water Heating Systems: Focusing on the integration of TEGs to harness thermal energy for co-generation of electricity and heat.
- Solar Desalination Units: Examining the use of TEMs to enhance condensation rates or improve the thermal management of desalination processes.
- Other Novel Solar Configurations: Encompassing hybrid systems

7. Future scope

- This review examines hybrid systems that integrate various solar energy applications.
- Current review is limited to solar PV but extends to the thermal solar system for wide scope in industrial / residential application.
- Design, cost and implementation point of view there is wide scope in thermoelectric system for better future.
- For the material point of view there is scope in fiber material for thermoelectric generator to enhance the thermal efficiency of the entire system.

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Conflict of competing interests

All authors certify that they have no affiliations with or involvement in any organization or entity that has any financial or non-financial interests in the subject matter or materials discussed in this manuscript. Conflict of interest the authors declare that they have no conflict of interest for the publication of paper.

Author contributions statement

Shridhar Kedar - Writing – original draft, supervision, Neeta Mandhare - Formal review analysis, Harish Shinde - Conceptualization, Methodology, Nilesh Kolhalkar – Conceptualization, Ganesh Vijay More – Methodology, Deepak Watvisave - Writing – review & editing, Sumedh Ingle – Supervision, Madhavi Patil - Writing editing, Vishal Deore - Writing review

Declaration of interests

Please include a statement declaring whether the authors have any competing financial or personal interests related to this work.

Data availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Declaration of generative AI and AI-assisted technologies in the writing process

No generative AI or AI-assisted technologies were used in the preparation of this manuscript.

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