RESEARCH ARTICLE

INTERNATIONAL RESEARCH JOURNAL OF
MULTIDISCIPLINARY TECHNOVATION

Asian Research Association

DOI: 10.54392/irjmt24317

Hybrid Power Generation: Experimental Investigation of PCM and TEG Integration with Photovoltaic Systems

Manjesh Bandrehalli Chandrashekaraiah [a], Beemkumar Nagappan [a], Yuvarajan Devarajan [b, *]

[a] Department of Mechanical Engineering, Faculty of Engineering and Technology, JAIN (Deemed-to-Be University), Bengaluru, Karnataka, India

[b] Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamil Nadu, India

*Corresponding Author Email: dyuvarajan2@gmail.com

DOI: https://doi.org/10.54392/irjmt24317

Received: 02-01-2024; Revised: 30-03-2024; Accepted: 24-04-2024; Published: 16-05-2024

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Abstract: Global warming and escalating energy consumption have presented pressing issues, catalyzing a pivotal shift towards environmental development worldwide. In recent years, the installed capacity of solar photovoltaic (PV) cells, particularly crystalline silicon cells, has experienced a significant surge. Among the myriad studies aimed at enhancing the efficiency of PV cells' power generation, one prominent avenue involves reducing the internal temperature of these cells. The primary objectives of the present study revolved around augmenting power generation and improving photocell efficiency. This was pursued through the strategic blending of nanoparticles with phase change material (PCM), with variations in insertion percentages to modulate the heat absorption capacity of the PV panel. Additionally, the study sought to evaluate the impact of integrating Thermoelectric Generator (TEG) modules and a water-based nano-fluid cooling system beneath the TEG setup. These measures aimed to effectively monitor the conversion of waste heat into electrical energy. Consequently, the proposed orientation of PV panels – involving PCM adjustment via alteration of insertion percentages, coupled with TEG integration and water-based nano-fluid cooling technology – holds significant promise for enhancing efficiency and mitigating solar cell degradation.

Keywords: Photovoltaic Panel, Phase Change Material, Sustainable Practices, Renewable Energy

1. Introduction

The increase in solar photovoltaic (PV) capacity deployed globally over the past ten years proves that PV systems significantly lower carbon emissions and energy usage. [1]. Photovoltaic technology makes utilisation of limitless solar energy possible, which is unmatched. Unfortunately, the most influential single solar cell to date is silicon-based, and according to the accepted test, it has an efficiency of between 20.8 and 25.6%. [2]. The sunlight concentration systems and concentrator photovoltaic (CPV) maintain a very high belief that they are vital contributors to practically enhancing the captured free solar energy. Additionally, the MJSC (multijunction solar cell) can achieve an efficiency of 86.8%. [2]. Although the multijunction solar cell (MJSC) processes some incident solar radiation into electricity, most are turned into heat. If this extra energy is not removed from the system, it will impact photocatalytic activity and cause a 0.45%/°C decrease in output. The intensity and dispersion of solar radiation are 2 crucial factors that have an impact on the efficiency of the solar PV sector. These 2 factors diverge widely geographically.

To increase solar cell performance, this heat has to be harvested. To date, numerous temperature management technologies have been investigated for PV systems. For instance, the idea of using combined PV/T systems was developed and studied. However, it was discovered that the conversion efficiency was inferior to that of two separate systems [3]. Yazdanifard and Ameri [4] A thorough analysis of the energetic performance of PV/T systems was undertaken, and it was discovered that using nano-fluids, concentrators, and optical filters might increase the system's energy efficiency. To run the PV system, they installed hydraulic cooling systems, forced and natural ventilation systems, and forced and natural air ventilation systems. It was found that CPV was the main use for heat pipe systems, and these systems needed to be effective at regulating PV temperatures., but their heat transfer performance was limited, and most significantly, there was no way to reuse heat from PV systems [5]. Combining the energy storage and recovery procedures yields PV modules with PCM systems. Due to their numerous low-temperature applications, competitiveness in the market, lightweight, minimal volumetric expansion during phase change, chemical inertness activity, and low potential for chemical reactivity, organic paraffinic compounds are the most widely utilised PCM in hybrid PVT-PCM systems.

Furthermore, some waste heat recovery systems/techniques can convert the waste heat, which the PCM absorbs; one of the solutions is Thermoelectric generators (TEG). This is further used to generate electricity by tapping the excess heat that PCM absorbs. This combination increases power generation, and fewer solar cells will be used, lowering costs. Environmentally friendly, nontoxic, and inexpensive systems include PCMs and TEGs [6].

The energy crisis and the effects of climate change have made technologies for CO_2 capture, sustainable fuels, and the use of sustainable resources, particularly solar power, more important than ever. Solar thermal collelactors or series of PV cells can harvest solar energy [7]. The most common method for capturing solar energy and supplying remote places with electricity is through photovoltaic panels [8]. Photovoltaics converts the UV and visible portions of the sun spectrum into electricity while the remaining portions become heat energy. This energy raises the temperature of the solar panels, which reduces their effectiveness [9]. In a study by Huen *et al.,* it was shown that combining the conversion efficiency of the hybrid system might be greatly enhanced by PV and TEG modules, which convert heat into power [10]. Opaque PV-integrated TEG. They evaluated the effect of the air duct and thermoelectric cooler (TEC) module packing on the hybrid system's performance [11]. Likewise, ANSYS Fluent software was used to model a hybrid system comprising an array of PV cells and a TE device. It was shown that hybrid systems provide more power than single PV cells do [12].

2. Literature Review

Dimri *et al.,* investigated the thermal model and an ANN were used in a different study to observe the performance of 3 different PV modules: opaque, semi-transparent, and those with an Al base and TEG. The PV-TEG water collector with an Al base displayed the greatest overall electrical energy gain among the units. Rodrigo *et al.* [13] For the CPV-TE modules' thermal management, Zhang J. et al. used passive cooling. Comparing the hybrid system's efficiency to the photovoltaic alone module, it increased by 2.8%. They also demonstrated that the thermoelectric physical properties unaffected the system's cost and efficiency. In an experiment in the PV-TEG system, the TEG modules' ceramic plates were eliminated to minimize the heat resistance, which improved the performance of the photovoltaic-thermoelectric hybrid system. Additionally, the PV-TEC system uses a V-shaped groove to maintain each. Contrasting a CPV cell with its nearby PV cells boosts solar irradiation [14]. 2019 Theoretically and empirically, a novel hybrid PVT/TEG air collector was investigated., according to Nazri *et al.* By increasing the air mass flow rate, heat exergy decreased, and PV exergy increased [15]. Additionally, data shows that energy deterioration expanded when solar radiation and concentration ratio increased [16]. Abdo et al. suggested a brand-new design for a CPV-TEG that included a microchannel heat sink [17]. It was revealed that this one had a much higher incidence of thermal energy gain compared to a conventional unit.

LekbirA.*et.al.* and colleagues suggested an innovative PV/T-TEG hybrid system based on nanoparticles (Nano-fluids) to enhance the performance of a hybrid PV module and TEG module [18]. The nano-fluid raised the temperature gradient by lowering the temperature of the TEG's cold side. It was shown that CPV/T-TEG with nanoparticles produced electrical energy greater by 10.01%, 47.69%, and 49.49% when compared to using nanoparticles, CPV, and CPV/TEG systems to CPV/T, respectively. So1tani *et al.* [19] examined a hybrid PV/TEG system's performance throughout a test project. They evaluated four distinct working fluids' cooling capacities versus natural cooling: atmospheric air, water, Silicon dioxide/water, and Iron oxide black/water nano-fluids. It was discovered that nano-fluids might cool the system more effectively than water. By increasing the difference in temperature between the TE plates, phase change materials (PCM) can boost the output and performance of the combined CPV/T-TEG systems. Cui.*et.al* [20] presented a hybrid PV/PCM/TEG module that concentrates energy. They underlined that the PCM increased the PV panel's temperature variations, which enhanced the system's overall efficiency. In a related investigation, the heat released by a PV panel was preserved by utilising PCM. The TEG modules are then employed to generate the power by transmitting the residual heat there. To end, aluminium fins were employed to extract the leftover heat energy that the TEG could not use. The suggested electrical efficiency of hybrid and single PV systems was reported to be 13.44% and 13.42%, respectively [21]. The performances of the CPV/TEG and CPV/TEG/PCM schemes were numerically compared, according to Motiei P. *et al.* [22]. The simulation outcomes showed that increasing PCM thickness could boost effectiveness. Additionally, 4.60 °C, 0.319%, and 0.059% were the reported figures for the PV temperature drop, PV efficiency, and TEG efficiency. Yin *et al.* [23] developed PCMs by adding copper foam and expanded graphite to a CPV/TEG hybrid unit. They concluded that decreasing the PCM's heat resistance might not substantially affect Solar cell performance, which will boost the productivity of TEGs. Second, comparable research used computational and experimental analysis to establish the PCM's properties that produced the photovoltaic-thermoelectric system's most ideal output. The device had 50 millimetres thick PCM layer with a K = 5 W/m K and a melting point of 40–45 °C.

A PV/TEG hybrid system would have a significant capacity to provide renewable energy, according to the publications examined by Madhavadas et al. The use of a suitable heat sink could enhance the system's performance. Some researchers have suggested using PCMs and nano-fluids to do this. Additionally, the presence of fins improves heat transfer. A careful examination of various review studies allows us to conclude that using expanded surfaces, also known as fins, has the highest heat transmission rate. [24]. As a result, including this rectangular fin would proportionally increase the output of the [PV -PCM-TEG - Fins] arrangement.

Overall, the novel combination of these techniques - nanoparticle-enhanced PCM, TEG modules, water-based nano-fluid cooling, and optimized PV panel orientation - offers promising outcomes for improving the efficiency and longevity of solar energy systems, thereby contributing to the sustainable development of renewable energy technologies. In this research, we aim to explore the optimal blending of nanoparticles with phase change material (PCM) by varying the insertion percentage. This variation directly impacts the heat absorption capacity of photovoltaic (PV) panels. We will investigate how increasing the percentage of power generation can be achieved by integrating nanoparticle-blended PCM beneath the panels to facilitate quicker heat flow. Additionally, we will monitor the conversion of waste heat into energy and assess the effects of incorporating Thermoelectric Generator (TEG) modules and a water-based nano-fluid cooling system below the TEG setup. Our goal is to develop a numerical model that can effectively evaluate the performance of a monocrystalline PV panel when combined with PCM, TEG, insertion rates, and water-based nano-fluid cooling technology.

3. Experimental Work

The photovoltaic panel absorbs solar irradiation; some of the energy is immediately transformed into electricity by the monocrystalline silicon cell, and the remaining portion is lost to the environment by radiation and convection. The PV panels will have a phase change material connected with different percentages of nanoparticles mixed in. The extended surfaces, which are welded at the bottom of the PV panel, will dissipate the excess heat to the PCM, which absorbs and stores it as latent heat and, in turn, dissipates it to the heat dissipated from TEG attached to the back of the PCM, raising the temperature of the hot sides of the TEGs. By adjusting the percentage of insertion, TEG, and water-based nano-fluid cooling technology, water-based cooling agents are employed in this study as the heat sinks, attached to the cold sides of TEGs, to analyse the performance of monocrystalline PV panels integrated with PCM. Paraffin wax has many possible uses as a phase change material (PCM) in solar thermal systems. It offers more than only its fundamental features, including thermal stability, compatibility, heat transfer capabilities, customizability, scalability, and environmental sustainability. The use of solar energy holds great potential for enhancing the efficiency, dependability, and sustainability of solar energy generation and utilisation on a global scale. Table 1 shows the Significant properties of PCM. Therminol-66 is a very effective heat transfer fluid well-suited for solar thermal systems. It works with phase change materials (PCMs) such as paraffin wax to enhance energy storage, heat transfer, and the system's overall efficiency. This substance's outstanding thermal stability, effective heat transfer qualities, compatibility with materials, environmental safety, and long-term dependability make it the preferable option for solar energy applications that prioritise high performance and sustainability. Table 2 represents the Significant properties of heat transfer fluid.

Table 1. Significant properties of PCM

Category	**Paraffin Wax**
Melting Temperature (˚C)	62
Thermal Conductivity (W/mK)	2.53
Latent Heat of Fusion (KJ/kg)	212
Specific Heat Capacity (KJ/Kg.K)	0.52
Density (Kg/m³)	1400

Table 2. Significant properties of heat transfer fluid

HTF	**Therminol - 66**
Oil Density (Kg/m³)	1010
Specific Heat Capacity (J/Kg˚C)	1495
Oil Thermal Conductivity(W/m˚C)	0.12
Kinematic Viscosity (m^2/s)	29.64 x 10^{-6}
Range of use (˚C)	0 – 345

4. Results & Discussion

This section discusses the solar panel temperature concerning power generation with and without PCM. In addition, Solar Panel Temperature with PCM with Hybrid Power generation and the Power Generation with Temperature for PV, PV+PCM, and PV+PCM+TEG are compared.

4.1 Solar Panel Temperature Vs Power Generation with PCM and TEG

Figure 3 displays the variation in temperature of Solar PV Panels with PCM and TEG to generate a Hybrid Power Generation.

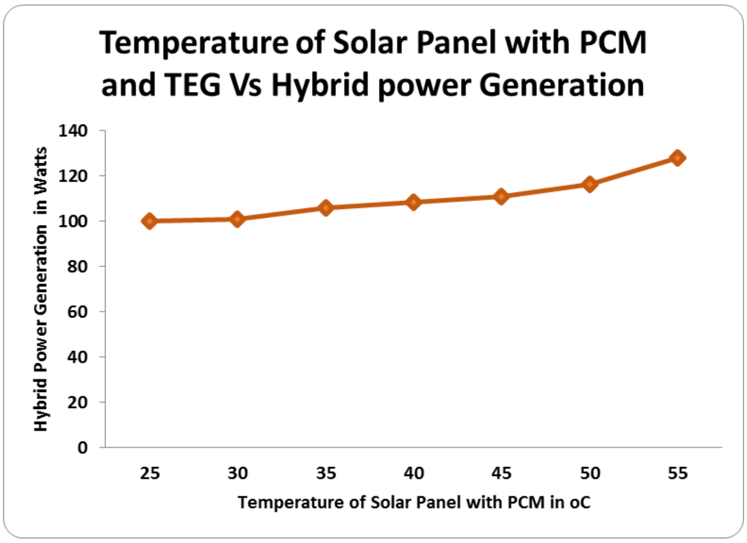

Figure 1. Solar Panel Temperature with PCM Vs Hybrid Power Generation

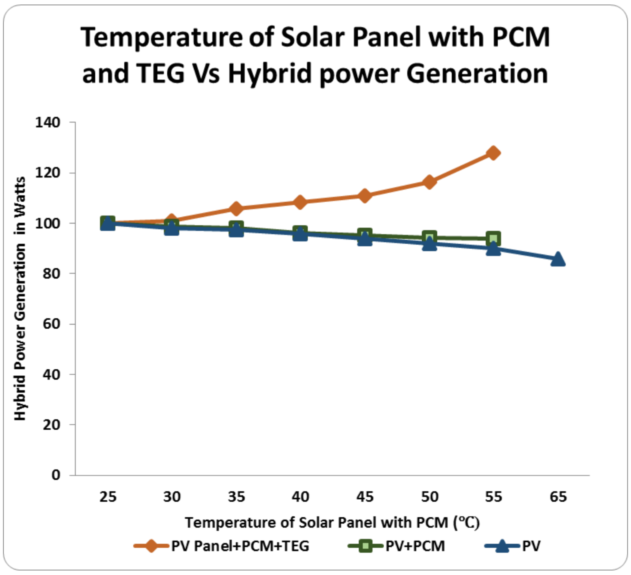

Figure 2. Power Generation Vs Temperature (PV, PV+PCM, PV+PCM+TEG)

By adding TEG beneath the PCM Chamber, for the same temperature as the PV Panel, there was an increase of 18% in power generation. From Figure 3, the Solar Panel temperature with PCM with Hybrid Power generation showed positive results. There is a drastic improvement in power generation with an increase in temperature. Power generation of 104 and 131 Watts were achieved at 25 and 55 ℃ respectievely. These positive results are due to the incorporation of TEG. TEG improved the power generation with temperature [18]. The results obtained align with various studies [17-20].

4.2 Solar Panel Temperature Vs Hybrid Power Generation with PCM and TEG

Figure 2 represents the comparative graph of power generation vs temperature recorded in solar PV panels, solar PV panels with PCM, and solar PV panels with PCM and TEG. It is observed that around 23% of temperature reduction of PV module while using PCM, and It has also been observed that by using TEG under the PCM duct, 40% of the heat has been utilised by TEG to convert into electricity [19]. The PV cells should be maintained at a lower temperature for better efficiency. The PV cells should be maintained at a lower temperature for better efficiency. The system can replace a certain amount of primary energy consumption and achieve sustainable development energy saving and emission reduction using solar energy [20]. When the phase change material is added, the efficiency of the solar panel increases to 6%, and by adding thermoelectric generators, the power output increases to almost 18%. The study has shown prominent levels of potential in the concept of integrating PV/PCM/TEG power systems [21]. The results align with various studies' results [18-21].

5. Conclusion

Incorporating Phase Change Material (PCM) and Thermoelectric Generator (TEG) modules serves the purpose of transferring excess heat from PCM to TEG via PCM, effectively converting heat loss into electricity. At the culmination of this research endeavor, we successfully constructed an experimental setup featuring a Mono crystalline Photovoltaic (PV) panel with an integrated attachment of Nanomaterial-inserted PCM housed within a chamber, along with Thermoelectric Generator modules and a water-based nano-fluid cooling duct. This comprehensive experimental arrangement facilitated the analysis of the increment in power generation percentage within both the solar PV panels and the TEG setup, thereby realizing a Hybrid Power Generation system.

The empirical findings unveiled crucial insights, emphasizing the significance of maintaining PV cells at lower temperatures to optimize efficiency. Furthermore, the developed system showcased its potential to supplant the consumption of primary energy to foster sustainable development, energy conservation, and emission reduction through solar energy utilization. Specifically, the incorporation of phase change material led to a notable increase in solar panel efficiency by up to 6%. Additionally, the integration of thermoelectric generators resulted in a remarkable surge in power output, reaching nearly 18%.

This study underscores the considerable promise inherent in the paradigm of integrating PV/PCM/TEG power systems, heralding a significant advancement towards the realization of efficient and sustainable energy solutions.

6. Scope of Future Studies

The study's prospective research trajectory encompasses several pivotal domains of emphasis. To begin with, further investigation is required to optimise the phase change material (PCM) and nanoparticle merging in photovoltaic (PV) panels to maximise efficiency gains. Furthermore, it is imperative to enhance the integration of water-based nano-fluid cooling technology beneath the Thermoelectric Generator (TEG) modules within the TEG configuration. Furthermore, research should encompass practical implementation considerations such as environmental impact and economic feasibility, as well as scalability. Ongoing surveillance and evaluation of the system's performance across diverse scenarios will be imperative in order to authenticate its dependability and efficacy as time progresses. In general, forthcoming investigations seek to improve the sustainability, dependability, and efficacy of solar energy systems via the development and refinement of integrated technologies.

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Authors Contribution Statement

Manjesh Bandrehalli Chandrashekaraiah – Methodology, Investigation, Formal analysis, Validation, Writing – original draft, Writing – review & editing. Beemkumar Nagappan –, Formal analysis, Validation, Writing – original draft, Writing – review & editing. Yuvarajan Devarajan– Conceptualization, Methodology, Investigation, Formal analysis, Validation, Writing – original draft, Writing – review & editing. All the authors read and approved the final version of the manuscript.

Funding

This research was conducted without the aid of any financial grants.

Competing Interests

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

Has this article screened for similarity?

Yes

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