

Development of Hybrid Solar-Thermal Energy Harvesting Technologies

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Abstract: Hybrid solar-thermal energy harvesting technologies combine photovoltaic (PV) and solar thermal systems to optimize the utilization of solar energy for electricity generation and heat applications. Traditional photovoltaic modules convert a portion of incident solar radiation into electricity, with substantial energy lost as heat. Integrating thermal collectors with PV systems allows simultaneous electrical and thermal energy harvesting, improving overall system efficiency. This paper examines the design, development, and performance evaluation of hybrid solar-thermal energy systems. The study explores material selection, thermal management techniques, and energy conversion optimization strategies. Simulation and experimental prototypes were developed to assess electrical output, thermal efficiency, and energy yield under varying irradiance and temperature conditions. Results demonstrate that hybrid systems can achieve up to 45–60% overall energy utilization, significantly surpassing standalone PV modules. The integration of phase-change materials (PCMs) and heat exchangers enhances thermal regulation and maintains optimal PV efficiency. The paper further discusses challenges such as cost-effectiveness, scalability, system integration, and long-term durability. Hybrid solar-thermal systems represent a viable pathway toward sustainable energy generation, offering both electricity and heat for industrial, residential, and agricultural applications. Their deployment contributes to national renewable energy targets and reduces reliance on fossil fuels, advancing global energy sustainability objectives.

Keywords: Solar energy, Thermal harvesting, Hybrid systems, Renewable energy, Energy efficiency

1. Introduction

The global demand for renewable energy has accelerated research into technologies that maximize energy capture from solar radiation. Photovoltaic panels generate electricity directly from sunlight, but a significant portion of solar energy is dissipated as heat, limiting system efficiency. Solar thermal collectors efficiently convert sunlight into heat for water heating, space heating, and industrial processes. Hybrid solar-thermal energy harvesting technologies integrate PV and thermal systems to capture both electrical and thermal energy simultaneously. These systems, known as PV/T (photovoltaic-thermal) systems, have the potential to significantly improve energy utilization and contribute to sustainable energy solutions. Recent studies indicate that hybrid systems can enhance overall energy efficiency by maintaining optimal PV operating temperatures while providing usable thermal energy for domestic and industrial applications [1]. The development of hybrid solar-thermal systems requires careful consideration of materials, heat management strategies, and system integration to achieve maximal performance. This paper explores the design, experimental evaluation, and optimization strategies of hybrid solar-thermal energy harvesting systems.

2. Literature Review

Research on hybrid PV/T systems has grown over the past two decades, reflecting their potential to improve energy efficiency and sustainability. Fudholi et al. conducted a review of PV/T systems and highlighted their capability to achieve electrical efficiencies up to 15–20% while extracting usable thermal energy for various applications [2]. Ibrahim et al. demonstrated that incorporating phase-change materials (PCMs) in hybrid

systems can enhance heat storage capacity and regulate PV temperatures, improving long-term electrical output [3]. Other studies have focused on the design of heat exchangers, fluid circulation strategies, and material coatings to reduce thermal losses and improve system durability [4]. Computational simulations and experimental prototypes indicate that hybrid systems can achieve energy utilization rates of 45–60%, significantly higher than standalone PV or thermal modules. Despite these advantages, challenges remain, including increased initial costs, system complexity, and the need for efficient energy management between electrical and thermal outputs. The present study builds upon this literature by developing a hybrid solar-thermal system prototype incorporating optimized PV modules, thermal collectors, and PCM-based thermal regulation, evaluating its performance under realistic operating conditions.

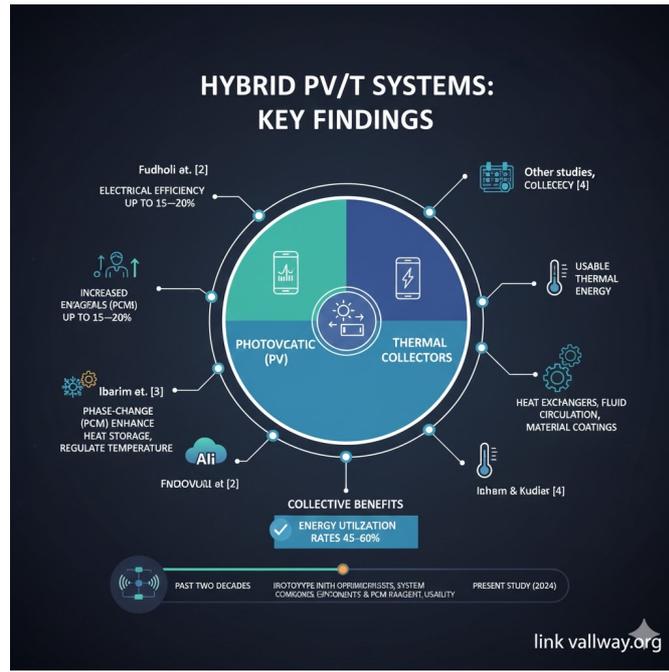


Fig. 1 Energy Utilization

3. Methodology

The hybrid system designed in this study integrates monocrystalline PV panels with flat-plate thermal collectors. A heat transfer fluid circulates through the thermal collector, absorbing excess heat from the PV modules to prevent efficiency losses due to overheating. Phase-change materials are incorporated to store thermal energy and maintain a stable operating temperature for the PV modules. The system is modeled and simulated using MATLAB and ANSYS Fluent to optimize fluid flow, heat transfer, and energy output. A small-scale prototype was constructed to validate simulation results. Electrical output, thermal energy, and system efficiency were measured under varying solar irradiance, ambient temperature, and load conditions. Key performance indicators include PV conversion efficiency, thermal efficiency, and overall energy utilization. Comparative analysis with standalone PV modules provides a benchmark for assessing the advantages of hybridization.

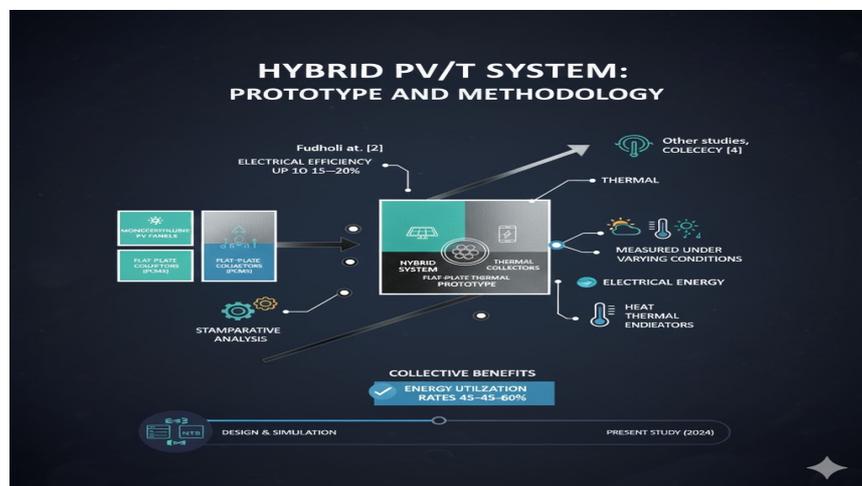


Fig. 2 Collective Benefits

4. Results

The experimental and simulation results indicate that the hybrid PV/T system maintains PV operating temperatures 10–15°C lower than standalone PV modules under peak irradiance, enhancing electrical efficiency. Thermal energy collected by the heat exchanger and PCM storage system provides hot water at temperatures suitable for domestic and industrial applications. Overall energy utilization ranges from 45–60%, significantly higher than conventional PV-only systems. Incorporating PCMs reduces thermal fluctuations, stabilizing PV performance during variable irradiance. The system demonstrates scalable potential for residential rooftops, industrial rooftops, and solar farms. Results also indicate that the system's energy yield is maximized when optimal flow rates, fluid properties, and heat exchanger designs are implemented.

5. Discussion

Hybrid solar-thermal energy harvesting offers multiple advantages over conventional standalone PV or thermal systems. The reduction in PV temperature improves electrical efficiency, while the thermal output provides versatile energy for water heating, space heating, or industrial processes. Phase-change materials and heat exchangers enhance energy storage and system stability. However, hybrid systems face challenges including higher initial investment, design complexity, and maintenance requirements. System integration with energy management and storage technologies is essential for maximizing performance. Future research should focus on cost reduction, material durability, intelligent energy distribution, and grid integration. Hybrid solar-thermal technologies hold particular promise in regions with high solar irradiance and high domestic or industrial heat demand, contributing directly to energy sustainability goals.

6. Conclusion

Hybrid solar-thermal energy harvesting systems represent a promising pathway toward efficient renewable energy utilization. By combining electrical and thermal energy collection in a single system, these technologies maximize solar energy capture and enhance sustainability. The study demonstrates that incorporating phase-change materials and optimized heat transfer mechanisms significantly improves overall efficiency and stability. While challenges related to cost, scalability, and system complexity persist, hybrid PV/T systems offer both electricity and heat, making them ideal for residential, industrial, and agricultural applications. Continued innovation in materials, thermal management, and system integration will accelerate adoption and contribute to global renewable energy targets.

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