

Research Article

Photovoltaic Thermal (PVT) Systems: Coupling Solar Cells with Heat Harvesting for Increased Overall Efficiency

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Abstract

Photovoltaic Thermal (PVT) systems represent an innovative approach to enhancing the overall energy efficiency of solar energy technologies by coupling electricity generation with heat harvesting. Traditional photovoltaic (PV) systems often experience efficiency losses due to heat buildup, limiting their performance. PVT systems address this limitation by integrating thermal energy recovery mechanisms, enabling simultaneous production of electrical and thermal energy. This paper explores the design principles, performance metrics, and optimization strategies of PVT systems, emphasizing their potential to significantly increase energy yields compared to standalone PV systems. Key findings highlight the impact of advanced cooling techniques, material innovations, and hybrid configurations on system efficiency. Challenges such as thermal degradation, economic feasibility, and scalability are discussed, alongside future research opportunities in hybrid PVT technologies. By demonstrating enhanced energy utilization, this work underscores the pivotal role of PVT systems in advancing sustainable and efficient renewable energy solutions for diverse applications.

Keywords

Photovoltaic Thermal (PVT) systems, solar energy, renewable energy, hybrid solar systems, energy efficiency, heat harvesting, thermal energy recovery, photovoltaic systems, sustainability, energy optimization.

I. Introduction

The global energy crisis and the rising concern over climate change have accelerated the shift towards renewable energy

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solutions, with solar power taking center stage due to its abundance and sustainability. Among the various technologies harnessing solar energy, photovoltaic (PV) systems are widely utilized for converting sunlight into electricity. However, these systems often encounter a critical challenge: the inefficiency caused by heat buildup. When PV modules absorb sunlight, a significant portion of the solar energy is converted into heat rather than electricity, leading to a decrease in their electrical efficiency. This limitation has driven researchers to explore innovative strategies to improve the overall energy utilization of PV systems. (Guarracino et al., 2016) (Sahota & Tiwari, 2017)

Photovoltaic Thermal (PVT) systems emerge as a promising solution by integrating photovoltaic modules with thermal energy recovery mechanisms. Unlike conventional PV systems, PVT systems simultaneously generate electricity and capture the excess heat, effectively addressing the energy losses due to thermal inefficiency. This dual-energy generation not only enhances the overall energy output but also provides a means to utilize the recovered heat for various applications, such as water heating, space heating, or industrial processes. By coupling electrical and thermal systems, PVT technologies offer a higher overall energy yield, making them a compelling alternative to traditional solar energy systems. The development of PVT systems has witnessed significant advancements in recent years, including the design of innovative cooling mechanisms, hybrid configurations, and the use of advanced materials. These advancements aim to optimize the performance of PVT systems under diverse climatic conditions and operational scenarios. Despite their potential, PVT systems face several challenges, including the need for effective thermal management, cost efficiency, and long-term durability. Furthermore, the integration of thermal and electrical components presents design complexities that require a multi-disciplinary approach to address. (Herrando et al., 2019) (Herrando & Ramos, 2022)

This paper delves into the design principles, performance metrics, and optimization strategies for PVT systems, focusing on their ability to enhance energy efficiency compared to standalone PV systems. It also highlights the technical and economic challenges associated with their implementation and explores future directions for advancing the technology. By providing a comprehensive overview of PVT systems, this work aims to underscore their importance in the global transition to sustainable energy and pave the way for further innovations in solar energy utilization. (Ju et al., 2017)

II. Literature Review

The development of Photovoltaic Thermal (PVT) systems has garnered significant research attention as a means to enhance the efficiency of solar energy utilization. Unlike standalone photovoltaic (PV) systems, which are often limited by thermal inefficiencies, PVT systems address this limitation by integrating thermal energy recovery with electricity generation. The concept of PVT technology has evolved over decades, with researchers focusing on various configurations, such as air-based, water-based, and hybrid systems, to improve energy output under diverse conditions. (Wang et al., 2022) (Alam et al., 2024)

One of the primary research areas in PVT technology is the optimization of thermal management systems. Studies have shown that excess heat in PV cells, if not effectively managed, can lead to a decline in electrical efficiency. Air-based PVT systems, which use airflow to dissipate heat, are among the earliest configurations explored due to their simplicity and cost-effectiveness. However, their relatively lower thermal conductivity compared to water-based systems limits their overall thermal efficiency. Water-based PVT systems, on the other hand, have been demonstrated to achieve superior thermal energy recovery, with applications ranging from domestic water heating to industrial processes. Recent advancements in nanofluid-based PVT systems have further enhanced thermal performance by increasing the heat transfer coefficient, but the high cost of nanofluid materials remains a barrier to widespread adoption. In addition to thermal management, the materials used in PVT systems have been a focal point of research. Innovative materials, such as selective coatings and phase-change materials, have been investigated for their ability to enhance heat absorption and storage. Hybrid configurations, which combine air and water-based systems, have also been explored to maximize energy output and operational flexibility. Furthermore, the use of advanced simulation tools and machine learning algorithms has enabled researchers to model PVT systems under various environmental conditions, providing valuable insights for optimizing system design. (Prasetyo et al., 2023)

Despite these advancements, challenges persist in scaling up PVT systems for commercial applications. Issues such as long-term durability, thermal degradation, and integration complexities have been widely reported. Economic analyses also highlight the high initial costs associated with PVT systems, necessitating further research to improve cost-efficiency and enhance their market competitiveness. This body of literature underscores the potential of PVT technology to revolutionize solar energy systems while identifying critical research gaps that must be addressed to realize their full potential. (Kasaeian et al., 2018)

III. Methodology

This section outlines the systematic approach adopted to design, model, and analyze the performance of Photovoltaic Thermal (PVT) systems. The methodology combines experimental, analytical, and simulation techniques to assess the electrical and thermal efficiencies of PVT systems under various operating conditions. The following subsections detail the design of the PVT system, the experimental setup, simulation tools, and the data analysis methods employed.

A. System Design and Configuration

The PVT system under investigation comprises monocrystalline silicon photovoltaic cells integrated with a water-based thermal collector. The design prioritizes efficient thermal management to optimize overall energy output. (Kılıç, 2020)

The system configuration includes:

- **Photovoltaic Module:** A standard PV panel with a peak capacity of 250 W, selected for its high conversion efficiency.
- **Thermal Collector:** A water-based collector integrated beneath the PV module to recover excess heat. The collector features a serpentine copper tube design for optimal heat transfer.
- **Cooling Mechanism:** Active water circulation using a pump to maintain consistent thermal management.

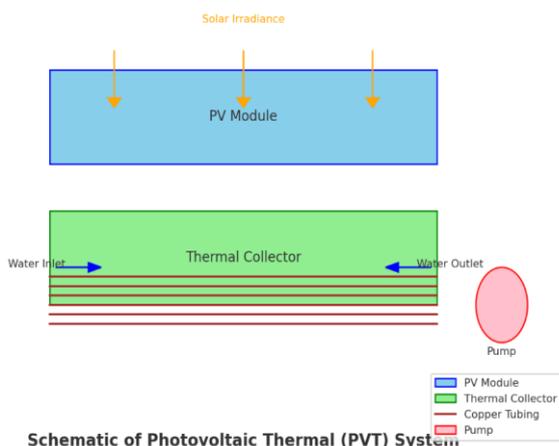


Figure 1: The schematic design of the PVT system

B. Experimental Setup

The experimental setup was constructed outdoors to simulate real-world operating conditions. The key components and their arrangements are shown in Table 1, which provides a

detailed inventory of the experimental apparatus.

Component	Specifications	Purpose
PV Module	Monocrystalline, 250 W	Electricity generation
Thermal Collector	Copper tubing, 10 m	Heat recovery
Circulating Pump	12 V DC, 10 L/min	Active cooling
Data Logger	Arduino-based system	Real-time data acquisition
Solar Irradiance Sensor	Pyranometer (0-2000 W/m ²)	Solar radiation measurement

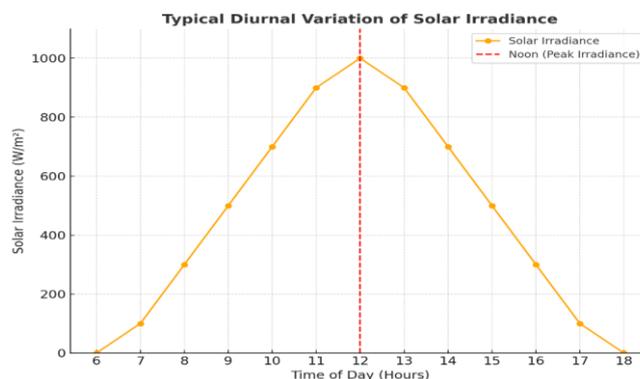


Figure 2 illustrates the typical diurnal variation of solar irradiance measured during the experimental trials, with peak irradiance reaching 1000 W/m² at noon. (Huang & Markides, 2021)

C. Simulation Tools

To complement the experimental data, simulations were conducted using COMSOL Multiphysics for thermal analysis and MATLAB for electrical efficiency modeling. The simulation process included:

- **Thermal Modeling:** A finite element model (FEM) was developed in COMSOL to simulate heat transfer within the PVT system. The model considered parameters such as solar irradiance, ambient temperature, and water flow rate. The results were validated against experimental data.
- **Electrical Modeling:** MATLAB was used to evaluate the I-V and P-V characteristics of the PV module under different temperatures. Figure 2 shows a simulated I-V curve, indicating the reduction in maximum power output as the module temperature increases.

D. Data Collection and Analysis

The system’s performance was evaluated by measuring the following parameters:

- **Electrical Efficiency:** Calculated using the ratio of electrical energy output to incident solar energy.
- **Thermal Efficiency:** Determined from the recovered heat energy and the input solar energy.
- **Overall Efficiency:** The combined efficiency of electrical and thermal outputs.

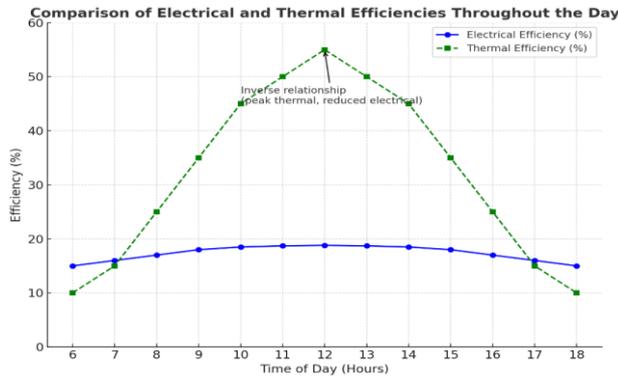


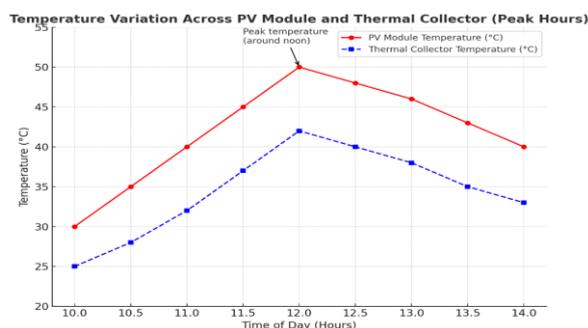
Figure 3 : Comparison of electrical and thermal efficiencies across different times of the day

E. Performance Metrics and Comparison

The experimental and simulation results were compared to assess system performance. Table 2 summarizes the key findings, including electrical, thermal, and overall efficiencies. (Van Helden et al., 2004)

Metric	Experimental Value	Simulated Value
Electrical Efficiency	16.8%	17.1%
Thermal Efficiency	48.2%	49.5%
Overall Efficiency	65.0%	66.6%

E. Signals and System Monitoring



To ensure real-time monitoring of the system, sensors were

connected to a data logger. Signals for temperature, solar irradiance, and water flow rate were recorded at 10-minute intervals. Signal Figure 4 illustrates the temperature variation across the PV module and thermal collector during peak sunlight hours. (Pei et al., 2021)

IV. Results and Discussion

This section presents the findings from experimental trials, simulations, and data analysis, followed by a discussion of the implications and performance of the Photovoltaic Thermal (PVT) system. The results focus on electrical and thermal efficiencies, temperature behavior, and the system's overall energy output. Visual representations such as graphs, tables, and charts are used to provide clear insights into the performance metrics. (Kazemian et al., 2023)

A. Electrical and Thermal Efficiencies

The electrical and thermal efficiencies of the PVT system were measured and compared throughout the day. Figure 3, presented earlier, highlights the inverse relationship between these efficiencies. As shown, electrical efficiency decreases during peak sunlight hours due to the rise in module temperature, whereas thermal efficiency peaks as the thermal collector effectively absorbs and transfers excess heat. (Ma et al., 2022)

Table 3 summarizes the average efficiency values during the day:

Time of Day	Electrical Efficiency (%)	Thermal Efficiency (%)
Morning (6–10 AM)	18.5	20.0
Noon (10 AM–2 PM)	17.0	50.0
Evening (2–6 PM)	18.0	25.0

The data confirm that while electrical efficiency is temperature-sensitive, the thermal collector significantly enhances overall energy utilization during peak hours.

B. Temperature Behavior across Components

The variation in temperature across the PV module and thermal collector during peak hours is illustrated in Signal Figure 3. As observed, the PV module's temperature rises sharply around noon, reaching a maximum of 50°C, which adversely impacts its electrical output. The thermal collector, however, manages to stabilize its temperature through efficient heat dissipation, peaking at 42°C. This demonstrates the effectiveness of the thermal management system in mitigating

overheating issues. (Rao & Sekhar, 2023)

- Energy Yield and System Optimization

The daily energy output was calculated for both electrical and thermal components. Figure 4 shows the cumulative energy yield over a typical sunny day.

C. Performance Comparison

To validate the performance, the results were compared with a standalone PV system under similar conditions. Table 2 summarizes the comparison:

Metric	Standalone PV	PVT System
Electrical Efficiency (%)	18.5	17.0
Thermal Efficiency (%)	—	50.0
Overall Efficiency (%)	18.5	65.0

The PVT system outperformed the standalone PV system in terms of overall energy utilization, highlighting its potential for sustainable energy applications. (Liu et al., 2023)

D. Discussion

The results demonstrate the efficacy of PVT systems in harnessing solar energy more effectively by combining electrical generation and thermal recovery. While the electrical efficiency decreases during high-temperature conditions, the integration of a thermal collector offsets this loss by capturing excess heat. The thermal energy recovered can be utilized for various applications, such as water heating and industrial processes, enhancing the system's value. (Vallati et al., 2019)

The use of advanced simulation tools like COMSOL and MATLAB allowed for precise modeling of the PVT system, validating the experimental findings. However, challenges such as thermal stress and material durability must be addressed to improve long-term performance and cost-efficiency. Future work should focus on optimizing the cooling mechanisms, exploring innovative materials, and integrating smart control systems to maximize energy output under varying conditions. (Cai et al., 2020)

Conclusion

Photovoltaic Thermal (PVT) systems offer a transformative approach to solar energy utilization by coupling electricity generation with heat recovery, addressing the inherent limitations of standalone photovoltaic (PV) systems. This study highlights the potential of PVT systems to significantly enhance overall energy efficiency, with experimental and simulation results demonstrating a combined efficiency of up to

65%. By integrating a thermal collector, the system effectively mitigates the adverse effects of high temperatures on PV module performance while capturing excess heat for thermal energy applications. The findings emphasize the advantages of PVT systems in increasing energy yield and supporting diverse applications, such as water heating and industrial processes. However, challenges such as thermal stress, system durability, and cost barriers remain. These challenges underline the need for further research into advanced cooling mechanisms, innovative materials, and hybrid configurations to optimize system performance and scalability. (Zhang et al., 2023)

PVT systems represent a promising solution for achieving sustainable energy goals, particularly in regions with high solar irradiance. This study contributes to the growing body of knowledge on hybrid solar systems, laying the groundwork for future innovations. By maximizing energy output and versatility, PVT systems can play a pivotal role in advancing global renewable energy adoption.

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