

INVESTIGATION AND ANALYSIS OF FLUID BASED ABSORPTION FILTERS FOR SOLAR PVT SYSTEM

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A. Title and Abstract

INVESTIGATION AND ANALYSIS OF FLUID BASED ABSORPTION FILTERS FOR SOLAR PVT SYSTEM

Abstract

Beam Split photovoltaic–thermal (PVT) systems offer a promising route to enhance solar energy utilization by simultaneously generating electrical and thermal energy. However, conventional PVT systems suffer from thermal-electrical coupling, where excessive heating of the photovoltaic (PV) surface lowers electrical efficiency. This research addresses the limitation through a fluid-based Spectral Beam-Splitting (SBS) approach employing nanofluid absorption filters to separate the solar spectrum into useful and thermal components. Titanium dioxide (TiO₂) and zinc oxide (ZnO) nanoparticles dispersed in water are investigated for their wavelength-dependent optical selectivity using UV–Vis–NIR spectroscopic analysis. The results have identified TiO₂ nanofluid at 0.04 wt% concentration as the most effective medium for transmitting useful wavelengths for photovoltaic conversion while absorbing thermal radiation for heat recovery.

A compact and portable Beam-Split Photovoltaic-Thermal (BSPVT) system is designed, fabricated, and tested under natural solar conditions to evaluate the real-time performance of these nanofluid filters. The TiO₂-based SBS filter reduced the PV module temperature by 12–15 °C, yielding a 2.5–4 % increase in electrical efficiency and achieving total hybrid efficiencies of around 70–85%. The close agreement between theoretical estimations and experimental results validates the feasibility and scalability of the developed system.

This study demonstrates that fluid-based spectral management using nanofluids is a practical and sustainable solution for improving hybrid solar energy systems. The outcomes bridge the gap between laboratory research and real-world implementation, contributing to the development of next-generation high-efficiency solar collectors integrating nanotechnology with renewable energy conversion.

B. Brief description on state of the art of the research topic

Recent advancements in hybrid photovoltaic–thermal (PVT) technology have focused on improving overall solar energy conversion efficiency by simultaneously harvesting electrical and thermal energy [1]. Traditional PVT systems, however, are constrained by thermal-electrical coupling, where excessive heat accumulation on the PV surface reduces its

electrical output [2][3]. In conventional PV/T systems, heat is extracted through the direct contact between the PV module and the heat-transfer fluid. However, simultaneously maximizing electrical and thermal efficiencies becomes challenging, as maintaining a lower module temperature to preserve electrical performance and prevent overheating inherently restricts the achievable thermal output [4]. To overcome this limitation, Spectral Beam-Splitting (SBS) techniques are developed, wherein the incident solar radiation is optically separated into distinct wavelength bands [5]. As illustrated in Figure 1, the full solar spectrum incident on the Earth's surface (300-2500 nm) consists of UV, visible, and NIR regions [6], [7], of which only a specific portion falls within the responsive range of the silicon PV module. This useful band (highlighted in green) is selectively transmitted to the PV receiver for electricity generation, while the remaining non-useful thermal part of the spectrum is diverted toward a separate thermal receiver. This spectral division enables efficient utilization of both electrical and thermal energy in a beam-split PVT system. This selective routing of spectral components enables simultaneous enhancement of electrical output and efficient thermal energy recovery.

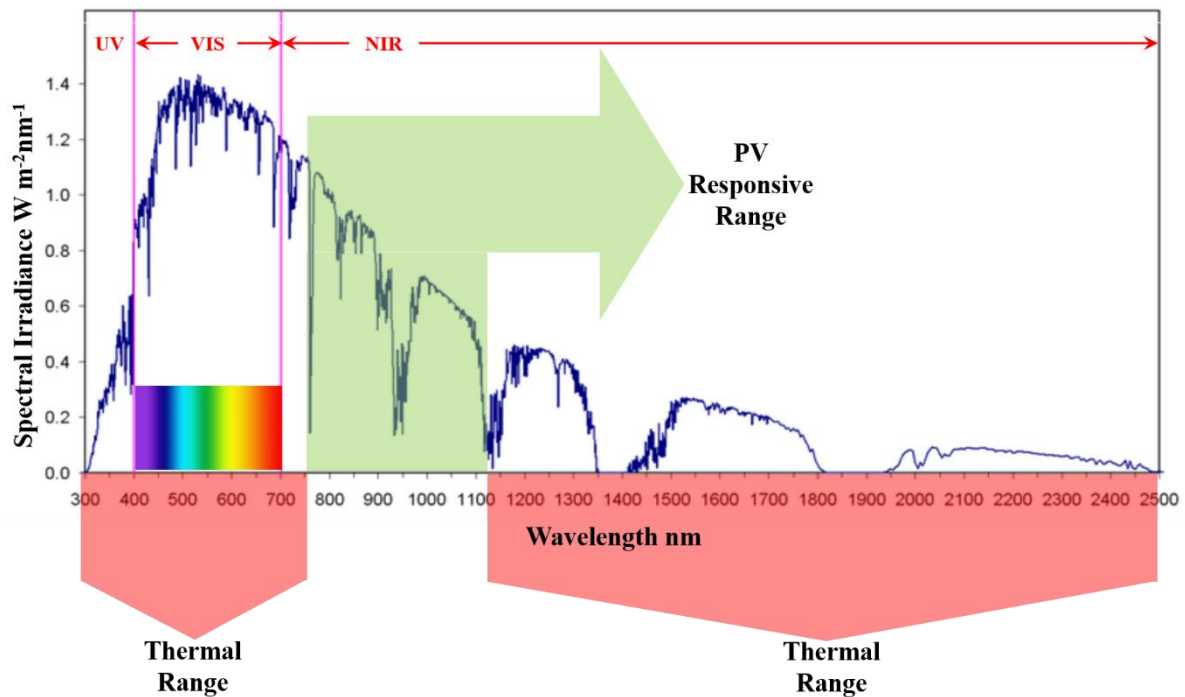


Figure 1 Spectral irradiance distribution of solar radiation showing two components of solar rays; effective photovoltaic (PV) responsive wavelength range and thermal range.

Silicon (Si) solar cells exhibit a responsive range spanning approximately 751 to 1126 nm of the solar spectrum[8]. Within this range, the cell effectively absorbs photons to generate electron-hole pairs, contributing directly to electrical output. Photons with wavelengths shorter

than 751 nm and those beyond 1126 nm contributes only in heating the solar cell. This defined responsive range plays a crucial role in designing spectral beam-splitting filters and selecting suitable fluids for SBS-PVT systems.

The state of the art in this domain involves the integration of nanofluid-based optical filters, which serve as fluidic spectrum splitters (figure 2). These nanofluids, typically composed of oxide, or metallic nanoparticles, exhibit tuneable optical absorption properties depending on particle concentration, and base fluid. Studies by Taylor et al. [8], [9] demonstrated that nanofluids can be engineered to selectively absorb and transmit specific wavelength ranges, effectively tailoring the spectral distribution incident on the PV surface.

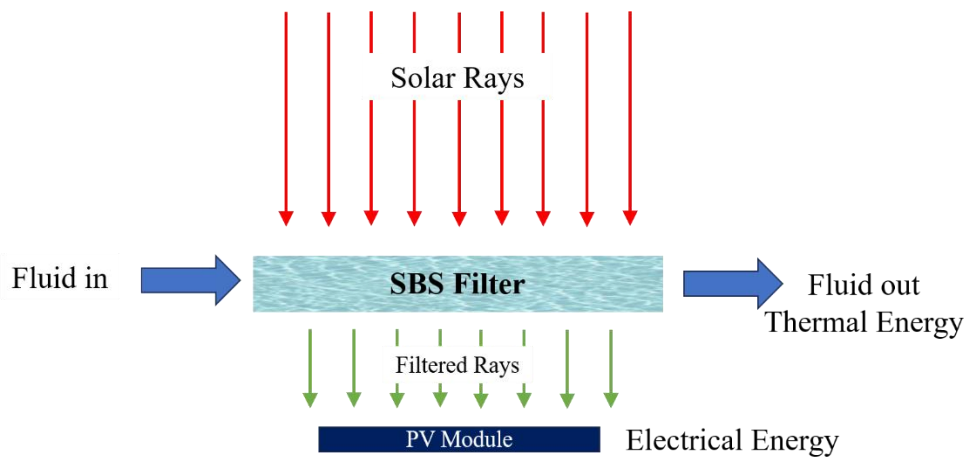


Figure 2 Schematic showing a fluid-based spectral beam splitter above the PV module that filters heating wavelengths while transmitting PV-useful radiation.

Fluid-based spectral beam-splitting (SBS) filters offer a promising pathway for maximizing overall PVT system performance by enabling selective optical control and independent optimization of electrical and thermal outputs. Numerous studies have explored suitable fluids for this purpose[10]. Continued development of low-cost, stable, and tunable nanofluids remains essential for advancing SBS-based PVT technology toward practical commercialization. Researchers such as Joshi and Dhoble [11], [12] and Han et al. [13], [14] have proposed analytical and experimental models showing 10–20% improvements in hybrid efficiency when spectral filters are employed. Despite these advancements, most prior work is limited to laboratory or simulated environments. Only a few authors have attempted to investigate field-scale fluid-based spectral beam-splitting techniques [15], [16], [17], [18], as large-scale implementation remains challenging due to nanofluid stability issues, optical degradation, and material compatibility concerns with solar hardware.

The current research advances the state of the art in solar hybrid energy systems by investigating titanium dioxide (TiO₂) and zinc oxide (ZnO) nanoparticles dispersed in water as the base fluid for use as spectral absorption media in photovoltaic–thermal (PVT) applications. To achieve this, a compact, portable, and experimentally validated PVT system is designed and fabricated to evaluate the performance of these nanofluid filters under natural solar irradiance conditions. The integration of real-time experimental validation with theoretical estimation bridges the gap between laboratory-scale investigations and practical implementation. This approach not only demonstrates the feasibility of fluid-based spectral management but also contributes significantly toward the development of sustainable, high-efficiency solar energy conversion systems.

C. Definition of the Problem

The photovoltaic (PV) modules convert only a limited portion of the incident solar spectrum primarily within the responsive wavelength range into useful electrical energy [9]. The remaining components of the solar wavelength range are absorbed as heat, leading to a significant temperature rise in the PV module. This temperature increase adversely affects the electrical performance, reducing the open-circuit voltage 2.3 mV/°C and power output, typically by 0.4-0.5% per °C rise in cell temperature[19], [20], [21]

Conventional Photovoltaic Thermal (PVT) systems as illustrated in figure 3 attempt to address this heating issue by circulating a fluid to cool the PV surface through direct contact while simultaneously recovering thermal energy. However, these systems face a fundamental limitation:

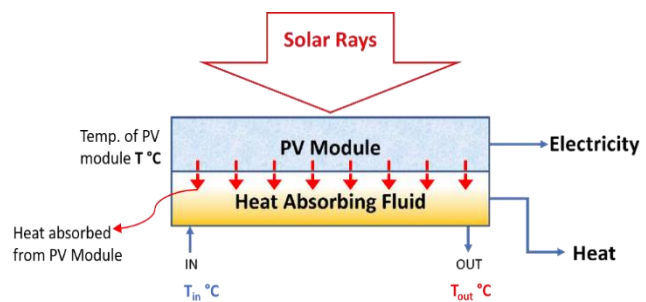


Figure 3 A Conventional PVT System

“The electrical and thermal efficiencies cannot be maximized simultaneously in conventional PVT systems because the thermal output is restricted to lower temperatures to maintain PV efficiency and prevent overheating.”

At lower fluid temperatures, although electrical performance improves, the recovered thermal energy is of low grade and limited practical utility. Conversely, when attempting to extract high-temperature heat, the cooling effectiveness decreases, leading to PV overheating

and loss of electrical efficiency. This inherent thermo-optical conflict restricts the overall energy potential of conventional PVT systems.

D. Objective and Scope of Work

Objectives

1. To identify suitable fluid for Spectral Beam Splitting (SBS) filter for solar PVT system.
 - a. Identify potential nano particle and base fluid for spectral beam splitting filter.
 - b. To perform spectroscopic analysis of nanofluids to identify optimal concentrations for spectral selectivity.
2. Development of Beam Split Photovoltaic-Thermal (BSPVT) system for experiment in natural and real operating environment.
 - a. To develop a filter housing to circulate an optically selective nanofluid over the PV panel for effective spectrum separation and heat absorption.
 - b. To design and fabricate a portable, adjustable, and cost-effective experimental setup for evaluating the PVT system with fluid-based absorption filters.
3. Performance analysis of the system developed and feasibility for sustainable commercial operation.
 - a. To carry out theoretical performance estimation of the BSPVT system.
 - b. To experimentally investigate the system under different configurations.
 - c. To assess the feasibility and potential of fluid-based spectral beam-splitting for hybrid solar energy utilization.

Scope of the Work

The present research aims to enhance the overall efficiency of solar Photovoltaic Thermal (PVT) systems through the development and analysis of a fluid-based spectral beam-splitting (SBS) approach. The study covers a complete cycle of literature review, material selection, theoretical modelling, experimental validation, and performance analysis, focusing on the use of TiO_2 and ZnO nanofluids in water as optical filtering media.

The scope of the work includes:

- Conducting a comprehensive literature survey to identify research gaps in existing PVT and SBS systems, emphasizing the need for a cost-effective, experimentally validated, and field-operable hybrid setup.

- Selection and preparation of suitable nanofluids based on optical and thermal properties, followed by spectroscopic characterization to determine optimal nanoparticle concentration for maximum spectral selectivity.
- Design and fabrication of a compact, modular, portable, and adjustable BSPVT system integrated with a nanofluid filter and a silicon PV module for testing under natural solar conditions.
- Theoretical estimation of solar radiation parameters and experimental evaluation of system performance in terms of electrical, thermal, and hybrid efficiencies.
- Feasibility assessment of the developed system for sustainable solar energy utilization, establishing the foundation for future large-scale or commercial implementation.

The present study's outcomes will provide valuable insights for future work involving advanced nanofluids and integrated thermal storage systems.

E. Original Contribution of the Research

- Developed and experimentally validated a compact, portable Beam-Split Photovoltaic-Thermal (BSPVT) system capable of testing fluid-based spectral filters under real outdoor solar conditions, bridging the gap between laboratory modelling and practical implementation.
- Identified and optimized TiO₂ and ZnO nanofluids (water-based) through spectroscopic analysis for their wavelength-dependent optical behaviour, establishing TiO₂ at 0.04% concentration as the most effective for spectral beam-splitting applications.
- Designed and fabricated a lightweight fluid filter module, providing high transmissivity in the PV responsive range.
- Demonstrated that integrating a TiO₂ nanofluid filter with a crystalline-Si PV panel results in a temperature reduction of 12–15 °C, a 2.5–4% gain in electrical efficiency, and total hybrid (thermal + electrical) efficiencies up to 70–85%.
- Provided the first systematic outdoor performance evaluation of a nanofluid-based spectral filter PVT system with variable flow rates, validating its feasibility, scalability, and cost-effectiveness for sustainable solar energy utilization.

- Contributed to the advancement of fluid-based spectral beam-splitting technology by integrating optical characterization, theoretical estimation, and real-time experimental validation into a unified framework.

F. Methodology of Research, Results / Comparisons

• Research Methodology

The research methodology integrates theoretical estimation, nanofluid preparation and characterization, experimental testing, and performance evaluation of a fluid-based spectral beam-splitting (SBS) system designed for hybrid Photovoltaic-Thermal (PVT) operation. The approach ensures a systematic transition from conceptual modelling to practical validation under real solar conditions.

1. Theoretical Estimation

Theoretical models are used to estimate the solar radiation components incident on a tilted surface using correlations developed by Gopinathan [22], The optimum tilt angle, and collector geometry are determined by using correlations given by Gueymard [23], and Kacira et al. [24] to simulate maximum solar gain.

The electrical thermal and overall efficiency of the system is predicted by using following relations[11]:

Electrical efficiency (η_e) of the PV module is predicted using the temperature correction relation:

$$\eta_e = \eta_{stc} [1 + \gamma (T_{pv} - T_{stc})] \quad \dots\dots\dots \text{Eq 1}$$

Thermal efficiency (η_t) was computed as:

$$\eta_t = \frac{\dot{m} C_p (T_{out} - T_{in})}{AG} \quad \dots\dots\dots \text{Eq 2}$$

The total hybrid efficiency (η_h) of the system was then obtained as:

$$\eta_h = \eta_e + \eta_t \quad \dots\dots\dots \text{Eq 3}$$

These estimations provided the baseline for evaluating experimental performance.

2. Nanofluid Preparation and Characterization

- Nanofluids: Titanium dioxide (TiO_2) and zinc oxide (ZnO) nanoparticles are dispersed in water at concentrations ranging from 0.01 to 0.05 wt% using ultrasonication for uniform dispersion.
- Spectroscopic Analysis: UV–Vis–NIR spectrophotometry is performed over 300–2500 nm to evaluate transmittance and absorption[4].
 - TiO_2 nanofluid showed strong absorption in the near-infrared region (700–2500 nm) while maintaining high transmittance in the visible band.
 - ZnO exhibited moderate selectivity with higher scattering losses at higher concentrations.
- The optimum concentration is identified as 0.04 wt% TiO_2 , offering ideal spectral separation for hybrid operation.

3. Experimental Setup and Procedure

A Beam-Split Photovoltaic Thermal (BSPVT) system is designed and fabricated using a PMMA-based spectral filter housing mounted directly over a 10 W silicon (Si) PV module. A schematic diagram of the experimental setup is illustrated in figure 4. The working nanofluid was circulated across the PV surface using a

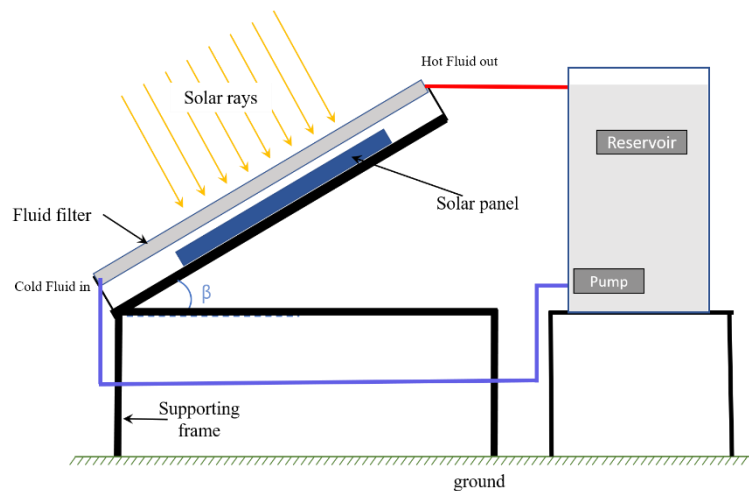


Figure 4 Schematic diagram of the experimental setup.

submersible pump connected through PU hoses, with a flow control valve incorporated to regulate the fluid flow rate. To monitor the thermal and electrical behaviour of the system, comprehensive instrumentation was deployed: A K-type thermocouple is fixed at the back surface of the PV module to measure the module temperature, while P-type thermocouples are positioned at the inlet and outlet of the filter housing to record fluid temperatures. A pyranometer is used to measure incident solar irradiance (G), and a PV analyser is employed to assess the electrical performance of the module. The instrumentation layout is illustrated in

the schematic diagram (figure 5), while figure 6 shows the photograph of the actual fabricated system.

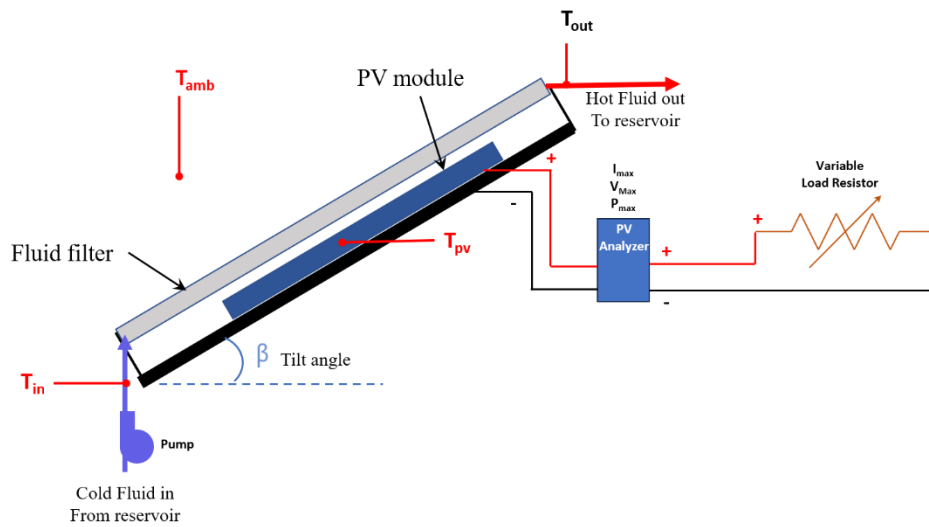


Figure 5 Instrumentation schematic of the BSPVT experimental setup showing fluid circulation, temperature measurement points, tilt angle adjustment, and PV electrical performance monitoring.

Tests are performed under natural sunlight for flow rates between 52–70 LPH, comparing three configurations:

1. PV without filter
2. PV with empty filter
3. PV with TiO₂ 0.04% nanofluid filter

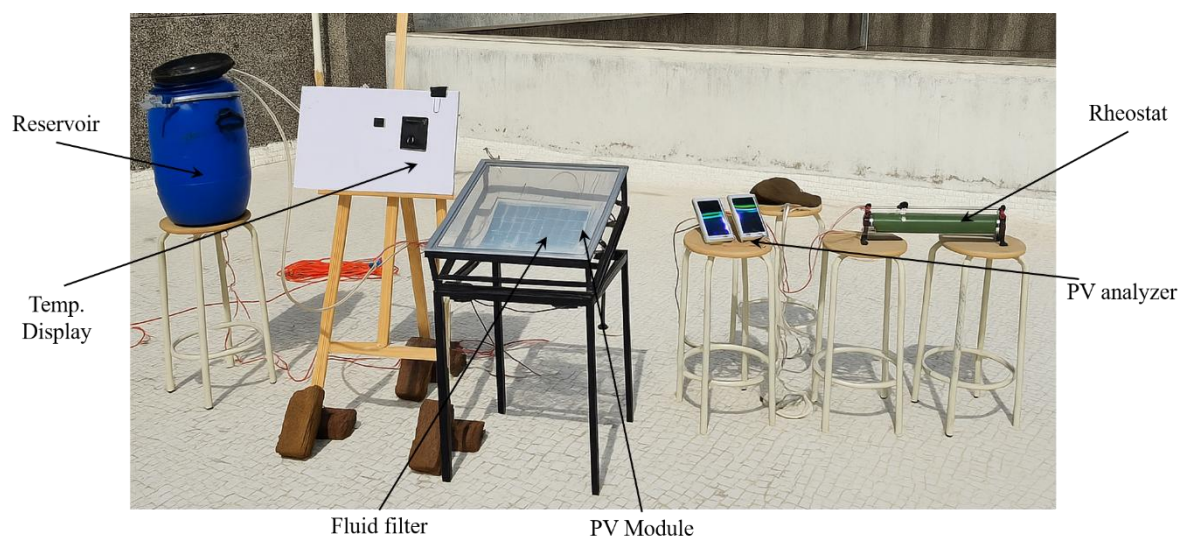


Figure 6 Photograph of the experimental setup.

- **Results and Comparison**

1. Spectral and Thermal Performance

- The spectroscopic data confirmed that TiO₂ nanofluid selectively absorbs heating range while transmitting most of the responsive range of Si solar cell (751 – 1126 nm) to the PV cell.
- The filter with TiO₂ nanofluid significantly reduced thermal loading on the PV module, maintaining lower operating temperatures during peak irradiance hours.

2. Electrical and Thermal Efficiency

Key Observations:

- TiO₂ nanofluid filter achieved a PV temperature reduction of 12-15°C compared to the bare module.
- The corresponding electrical efficiency improvement is found to be about 2.5-4%, with the overall hybrid efficiency reaching 70-85%
- Electrical efficiency alone remains low (~10-11%) and declines with rising PV temperature during the day. However, when combined with thermal recovery through the fluid filter, overall efficiency increases 4-8 times higher.
- Experimental investigation of the fluid and hybrid system is performed in natural sunlight for optimising the feasibility of the system. Moderate flow rate gives higher performances (58 LPH).

Table 1 Performance comparison of various SBS-PVT configurations showing average PV temperature, electrical efficiency, thermal efficiency, and total overall efficiency under different flow rates and TiO₂ nanofluid conditions.

Configuration	Avg. PV Temp. (°C)	Electrical Efficiency (%)	Thermal Efficiency (%)	Total Overall Efficiency (%)
Bare PV Module	61 - 64	5.09 - 10.06	--	5.09 - 10.06
Empty Filter	60 - 63	5.31 - 10.66	--	5.31 - 10.66
TiO₂ (0.04%) 52 LPH	40-50	8.58 - 11.35	26.7 - 51.7	35.45 - 59.09
TiO₂ (0.04%) 58 LPH	41 - 51	7.31 - 11.00	36.1 - 66.8	44.81 - 74.35
TiO₂ (0.04%) 70 LPH	43 - 53	6.28 - 9.83	44.39 – 79.24	50.74 - 85.52

3. Comparative Assessment

Compared to conventional PVT systems, the developed BSPVT system demonstrated:

- Higher electrical efficiency due to effective optical filtering.
- Improved thermal energy recovery with better fluid heat absorption.
- Compact and portable design, allowing flexible field testing.
- Low fabrication cost and minimal maintenance requirements, making it viable for decentralized solar energy solutions.

G. Achievements with Respect to Objectives

Objective 1:

To identify suitable fluid for Spectral Beam Splitting (SBS) filter for solar PVT system.

- a. Identify potential nano particle and base fluid for spectral beam splitting filter.
- b. To perform spectroscopic analysis of nanofluids to identify optimal concentrations for spectral selectivity.

Achievements:

- Conducted an extensive literature survey to shortlist TiO_2 and ZnO nanoparticles as potential candidates due to their superior optical selectivity, stability, and thermal properties.
- Selected water as the base fluid for its high transparency in the visible region, non-toxicity, and good thermal capacity.
- Successfully prepared nanofluids with varying concentrations (0.01-0.05 wt%) using ultrasonication techniques to ensure uniform dispersion.
- Performed UV-Vis-NIR spectroscopic characterization (300-2500 nm) and established that TiO_2 nanofluid at 0.04 wt% provides optimum optical selectivity transmitting Si responsive range (useful for PV) while absorbing near-infrared wavelengths (useful for thermal gain).
- Validated that ZnO nanofluid exhibits moderate optical filtering capability with higher scattering losses at higher concentrations.

Objective 2:

Development of Beam Split Photovoltaic-Thermal (BSPVT) system for experiment in natural and real operating environment.

- a. To develop a filter housing to circulate an optically selective nanofluid over the PV panel for effective spectrum separation and heat absorption.
- b. To design and fabricate a portable, adjustable, and cost-effective experimental setup for evaluating the PVT system with fluid-based absorption filters.

Achievements:

- Designed and fabricated a compact and portable BSPVT setup integrating a 10 W silicon PV module with a PMMA-based fluid filter chamber.
- Developed a fluid circulation system using a submersible pump, flow control valve, and PU hoses to maintain controlled flow rates between 50–70 LPH.
- Integrated thermocouples, a pyranometer, and a PV analyser for real-time measurement of solar irradiance, temperature & $P_{\max}$.
- Ensured system flexibility by incorporating adjustable tilt and flow control, enabling experiments under natural sunlight to replicate real operating conditions.
- Achieved a stable and leak-proof design suitable for extended outdoor testing of nanofluids.

Objective 3:

Performance analysis of the system developed and feasibility for sustainable commercial operation.

- a. To carry out theoretical performance estimation of the BSPVT system.
- b. To experimentally investigate the system under different configurations.
- c. To assess the feasibility and potential of fluid-based spectral beam-splitting for hybrid solar energy utilization.

Achievements:

- Developed theoretical models for solar radiation estimation and performance prediction using Gopinathan, Gueymard, and Sukhatme correlations, providing baseline efficiency estimates for validation.

- Conducted comparative experimental studies under three configurations i.e. bare PV, empty filter, and nanofluid filters to evaluate system performance.
- Found that the TiO₂ nanofluid filter (0.04 wt%) achieved a PV temperature reduction of 12-15°C, resulting in an electrical efficiency improvement of 2.5-4% compared to the bare PV module.
- Recorded total hybrid efficiency in the range of 70-85%, confirming the dual benefit of electrical enhancement and thermal energy recovery.
- Demonstrated that the fluid-based SBS approach is technically feasible, cost-effective, and scalable, marking a significant step toward commercial hybrid solar energy systems for sustainable applications.

H. Conclusion

The present research successfully demonstrates the feasibility and effectiveness of a fluid-based spectral beam-splitting (SBS) approach for improving the overall performance of Photovoltaic-Thermal (PVT) systems. By addressing the fundamental limitation of conventional PVT configurations where electrical and thermal efficiencies cannot be maximized simultaneously, this study introduces an innovative method to optically separate useful and non-useful portions of the solar spectrum using nanofluid-based absorption filters.

A comprehensive literature survey established the need for a cost-effective and experimentally validated system capable of operating under natural solar conditions. Based on theoretical and optical evaluations, titanium dioxide (TiO₂) and zinc oxide (ZnO) nanoparticles were selected and dispersed in water to prepare stable nanofluids for spectral filtering. Spectroscopic analyses confirmed that TiO₂ nanofluid at 0.04 wt% concentration exhibits superior spectral selectivity, efficiently transmitting visible wavelengths for photovoltaic conversion while absorbing infrared radiation for thermal energy recovery.

A compact, portable Beam-Split Photovoltaic–Thermal (BSPVT) system was designed, fabricated, and experimentally tested to validate the concept. The system successfully reduced the PV module surface temperature by 12-15°C, resulting in a 2.5-4% increase in electrical efficiency, while simultaneously achieving total hybrid efficiencies in the range of 70–85%. Theoretical estimations of solar radiation and energy conversion closely correlated with the experimental results, confirming the robustness of the analytical models and experimental methodology adopted.

Overall, the research bridges the gap between theoretical modelling and practical implementation of spectral beam-splitting in hybrid solar systems. It provides a scalable, low-cost, and sustainable solution for maximizing solar energy utilization by integrating nanofluid-based optical management with existing PV technology. The outcomes of this study serve as a foundation for the development of next-generation high-efficiency hybrid solar collectors and open new avenues for integrating nanotechnology into renewable energy systems.

Nomenclature

<i>BSPVT</i>	Beam Split Photovoltaic-Thermal
<i>Si</i>	Silicon
<i>nm</i>	nanometer
<i>NIR</i>	Near Infrared
<i>PV</i>	Photovoltaic
<i>PVT</i>	Photovoltaic-Thermal
<i>SBS</i>	Spectral Beam Splitting
<i>UV</i>	Ultraviolet
<i>Vis</i>	Visible
η_e	Electrical Efficiency
η_t	Thermal Efficiency
η_h	Hybrid/overall efficiency

I. List of Publications

1. Jiwanapurkar, P.R., Bhargav, H.A. and Ramani, B. (2023) ‘Fluid based solar spectral beam splitters for hybrid photovoltaic thermal systems: a review’, *Int. J. Renewable Energy Technology*, Vol. 14, No. 3, pp.241–258. <https://doi.org/10.1504/IJRET.2023.132982>
(UGC Care Listed Journal)
2. Jiwanapurkar, P. R and Bhargav, H. A (2025). Spectroscopic Analysis of Water-Based TiO₂ and ZnO Nanofluid for Fluid-Based Beam Split Photovoltaic-thermal System. *Journal of Solar Energy Research*, 10(Emerging Trends in Photothermal Conversion for Solar Energy Harvesting), 45-55. [10.22059/jser.2025.379717.1445](https://doi.org/10.22059/jser.2025.379717.1445)
(SCOPUS Indexed Journal)

References:

- [1] S. S. Joshi and A. S. Dhoble, "Photovoltaic -Thermal systems (PVT): Technology review and future trends," *Renewable and Sustainable Energy Reviews*, vol. 92, pp. 848–882, Sep. 2018, doi: 10.1016/J.RSER.2018.04.067.
- [2] T. P. Otanicar, P. E. Phelan, and J. S. Golden, "Optical properties of liquids for direct absorption solar thermal energy systems," *Solar Energy*, vol. 83, no. 7, pp. 969–977, 2009, doi: <https://doi.org/10.1016/j.solener.2008.12.009>.
- [3] Tobnaghi Davud, "The Effect of Temperature on Electrical Parameters of Solar Cells," *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, vol. 2, no. 12, pp. 6404–6407, 2013, [Online]. Available: https://www.ijareeie.com/upload/2013/december/2F_The Effect.pdf
- [4] P. Jiwanapurkar and H. Bhargav, "Spectroscopic Analysis of Water-Based TiO₂ and ZnO Nanofluid for Fluid-Based Beam Split Photovoltaic-thermal System," *Journal of Solar Energy Research*, vol. 10, pp. 45–55, Mar. 2025, doi: 10.22059/jser.2025.379717.1445.
- [5] Jackson ED, "Areas for improvement of the semiconductor solar energy converter," in *Transactions of the Conference on the Use of Solar Energy*, Tucson: Univ. of Arizona Press, 1955, pp. 122–126.
- [6] Solanki C S, *Solar Photovoltaics Fundamentals, Technologies and Applications*, 3rd Edition. New Delhi: PHI Learning, 2013.
- [7] S. P. and N. J. K. Sukhatme, *Solar energy : principles of thermal collection and storage*. Tata McGraw-Hill Education (India) Private Limited, 2015.
- [8] R. A. Taylor *et al.*, "Feasibility of nanofluid-based optical filters," *Appl Opt*, vol. 52, no. 7, pp. 1413–1422, 2013, doi: 10.1364/AO.52.001413.
- [9] R. A. Taylor, T. Otanicar, and G. Rosengarten, "Nanofluid-based optical filter optimization for PV/T systems," *Light Sci Appl*, vol. 1, no. 10, pp. e34–e34, 2012, doi: 10.1038/lsa.2012.34.
- [10] P. R. Jiwanapurkar, H. A. Bhargav, and B. Ramani, "Fluid based solar spectral beam splitters for hybrid photovoltaic thermal systems: a review," 2023.
- [11] S. S. Joshi and A. S. Dhoble, "Analytical approach for performance estimation of BSPVT system with liquid spectrum filters," *Energy*, vol. 157, pp. 778–791, 2018, doi: 10.1016/j.energy.2018.05.204.
- [12] S. S. Joshi and A. S. Dhoble, "Use of Silicone Oil and Coconut Oil as Liquid Spectrum Filters for BSPVT: With Emphasis on Degradation of Liquids by Sunlight," *Journal of Solar Energy Engineering, Transactions of the ASME*, vol. 140, no. 1, pp. 1–9, 2018, doi: 10.1115/1.4038052.
- [13] X. Han, X. Chen, Q. Wang, S. M. Alelyani, and J. Qu, "Investigation of CoSO₄-based Ag nanofluids as spectral beam splitters for hybrid PV/T applications," *Solar Energy*, vol. 177, no. November 2018, pp. 387–394, 2019, doi: 10.1016/j.solener.2018.11.037.

- [14] X. Han, D. Xue, J. Zheng, S. M. Alelyani, and X. Chen, "Spectral characterization of spectrally selective liquid absorption filters and exploring their effects on concentrator solar cells," *Renew Energy*, vol. 131, pp. 938–945, 2019, doi: 10.1016/j.renene.2018.07.125.
- [15] H. Huang *et al.*, "Photovoltaic–thermal solar energy collectors based on optical tubes," *Solar Energy*, vol. 85, no. 3, pp. 450–454, 2011, doi: <https://doi.org/10.1016/j.solener.2010.12.011>.
- [16] S. Vijayaraghavan, S. Ganapathisubbu, and C. Santosh Kumar, "Performance analysis of a spectrally selective concentrating direct absorption collector," *Solar Energy*, vol. 97, pp. 418–425, 2013, doi: 10.1016/j.solener.2013.08.008.
- [17] F. Crisostomo, N. Hjerrild, S. Mesgari, Q. Li, and R. A. Taylor, "A hybrid PV/T collector using spectrally selective absorbing nanofluids," *Appl Energy*, vol. 193, pp. 1–14, 2017, doi: 10.1016/j.apenergy.2017.02.028.
- [18] S. S. Joshi, A. S. Dhoble, T. Sathe, and C. Mangrulkar, "Performance Analysis of Photovoltaic Thermal System Using Silicone Oil Spectrum Filter," *Applied Solar Energy (English translation of Geliotekhnika)*, vol. 54, no. 1, pp. 4–9, 2018, doi: 10.3103/S0003701X18010061.
- [19] J. J. Wysocki and P. Rappaport, "Effect of Temperature on Photovoltaic Solar Energy Conversion," *J Appl Phys*, vol. 31, no. 3, pp. 571–578, Mar. 1960, doi: 10.1063/1.1735630.
- [20] P. Singh, S. N. Singh, M. Lal, and M. Husain, "Temperature dependence of I–V characteristics and performance parameters of silicon solar cell," *Solar Energy Materials and Solar Cells*, vol. 92, no. 12, pp. 1611–1616, Dec. 2008, doi: 10.1016/J.SOLMAT.2008.07.010.
- [21] S. M. . Sze and K. Kwok. Ng, *Physics of semiconductor devices*. Wiley-Interscience, 2007.
- [22] K. K. Gopinathan, "A general formula for computing the coefficients of the correlation connecting global solar radiation to sunshine duration," *Solar Energy*, vol. 41, no. 6, pp. 499–502, Jan. 1988, doi: 10.1016/0038-092X(88)90052-7.
- [23] M. Collares-Pereira and A. Rabl, "The average distribution of solar radiation-correlations between diffuse and hemispherical and between daily and hourly insolation values," *Solar Energy*, vol. 22, no. 2, pp. 155–164, Jan. 1979, doi: 10.1016/0038-092X(79)90100-2.
- [24] M. Kacira, M. Simsek, Y. Babur, and S. Demirkol, "Determining optimum tilt angles and orientations of photovoltaic panels in Sanliurfa, Turkey," *Renew Energy*, vol. 29, no. 8, pp. 1265–1275, Jul. 2004, doi: 10.1016/J.RENENE.2003.12.014.