Power System Technology
ISSN:1000-3673

Received: 16-11-2025 *Revised: 05-12-2025* *Accepted: 30-12-2025*

Performance and Economic Feasibility of Hybrid Photovoltaic/Thermal/Phase Change Materials and Dusty Panel System: A Comparative Study

Mohamed Bashir Ali Bashir[1*], MD Shouquat Hossain[2], Khondoker Shad[3], Altaf Hussain Rajpar[1]

[1] Department of Mechanical Engineering, College of Engineering, Jouf University, Sakaka, 72388, Saudi Arabia

[2] Faculty of Engineering, Technology and Built Environment, UCSI University, Kuala Lumpur, Malaysia

[3] Department of Mechanical Engineering (BSME) School of Engineering, International University of Business Agriculture and Technology, Dhaka- 1230, Bangladesh

1st mbashir@ju.edu.sa; 2nd shouquat64@gmail.com; 3rd khshad2004@gmail.com; 4th ahrajpar@ju.edu.sa

[1] https://orcid.org/0000-0002-9422-3445; [2] https://orcid.org/0000-0001-8444-2209; [3] https://orcid.org/0009-0009-9701-7776; [4] https://orcid.org/0000-0002-8394-7982

*Corresponding Author: mbashir@ju.edu.sa

***Abstract*—** Using PCMs in photovoltaic/Thermal (PV/T) systems effectively enhances solar system performance by lowering the temperature of photovoltaic (PV) cells, which improves their efficiency and helps manage heat. This study compared two studies on the variations of PV/T/based phase change materials (PCM) integration. The study focuses on a two-sided serpentine flow PV/T/PCM system, reporting a maximum electrical efficiency of 17.52% and a thermal efficiency of 79.93%. The research examines the performance of a similar system under dusty conditions, where the PV/T/PCM with a dusty system achieved an electrical efficiency of 14.83% and a thermal efficiency of 73%. Both analyses indicate a key role for PCM in improving performance, although dust load diminishes it. An economic study found that, despite the initial high setup costs of the PV/T/PCM system, it is financially viable, as it significantly reduces operating costs over time, especially in tropical countries like Malaysia. These findings suggest that the PV/T/PCM system holds promise for sustainable energy generation in regions with high solar intensity, such as Malaysia. The performance under both normal and dusty conditions indicates its potential to be a reliable source of clean energy. Furthermore, the economic feasibility of the system makes it an attractive option for countries looking to lower their carbon footprint and energy costs in the long term. With further research and development, the PV/T/PCM system could become a key player in renewable energy solutions worldwide.

Keywords— dust mitigation, economic viability, electrical and thermal efficiency, phase change materials (PCMs), photovoltaic-thermal (PV/T) systems, thermal absorber.

I. Introduction

Photovoltaic (PV) systems have become one of the most reliable alternative energy sources worldwide, providing immaculate energy [1]. Efficiency and long-term operation challenges must be addressed as these systems are deployed in increasingly diverse environments [2]. One of these challenges is overheating, which results from high working temperatures that

Power System Technology
ISSN:1000-3673

Received: 16-11-2025 Revised: 05-12-2025 Accepted: 30-12-2025

degrade the efficiency of photovoltaic cells. Elevated temperatures can increase internal resistance, reduce the conversion efficiency of solar energy, and consequently lead to energy loss. This issue is amplified in hot and dusty environments, where PV panel efficiency can significantly decline [3]. A viable solution to this problem is using PCMs (phase change materials) in PV/T (photovoltaic/thermal) systems [4]. PCMs can store and release substantial amounts of thermal energy as they undergo a physical change (solid-liquid). This also makes them ideal for heat regulation since they can absorb excess heat when temperatures rise, store it, and then release it when temperatures drop, keeping PV cells within the optimal operating temperature range [5]. Applying PCM to PV/T systems to regulate the operating temperature of PV/T collectors for enhanced energy efficiency while utilizing thermal energy for heating and improving PV systems' performance appears innovative [6]. The novelty of this approach is further reinforced when the PV/T system operates even under dusty conditions [7]. Dust often accumulates directly on PV panels in environments characterized by deserts, semi-arid climates, and tropical climates, hindering solar irradiance from reaching the PV cells, which results in energy loss [8]. Most current research focuses on the theoretical benefits of PCM in PV/T systems, yet limited studies have investigated the impact of dust on the performance of PCM/PV/T systems [9].

This paper takes a step in this direction by examining two recent studies published by Fang et al. in 2025, which discuss performance results for PV/T/PCM systems under different conditions [10]. The first study experimentally investigates the performance of a serpentine flow PV/T/PCM system under controlled radiant conditions. The integration of PCM yields favorable results in thermal and electrical efficiencies [11]. The second study illustrates a practical challenge of the technology when the system operates under dusty conditions, as it evaluates the system's performance with dust accumulation, which impairs the PCM's capacity to maintain system efficiency [12]. Through a thorough comparison of these two studies, this article assesses the performance potential and economic viability of PCM-integrated PV/T systems in clean and dusty environments. PV/T systems consist of PV modules and thermal collectors, generating electricity and thermal energy simultaneously. These hybrid applications aim to reduce PV panel temperatures by removing unused heat from a thermal absorber, which can sometimes be used for other purposes, such as water heating. The integration of PCM in PV/T systems has been the focus of several studies because it can regulate the temperature of the PV panels, preventing overheating and thereby enhancing the system's overall performance [13].

This study adds to the growing body of knowledge on hybrid Photovoltaic/Thermal (PV/T) systems by comparing the performance of systems integrated with Phase Change Materials (PCMs) under controlled and dusty environmental conditions. The novelty of this research lies in its real-world exploration of how dust accumulation affects the efficiency of PCM-enhanced PV/T systems, a factor not extensively addressed in the literature. The findings reveal that while PCM integration significantly improves system efficiency by stabilizing operating temperatures, dust accumulation in arid and tropical regions decreases the system's electrical and thermal performance. The study focuses on a two-sided serpentine flow PV/T/PCM system, reporting a maximum electrical efficiency of 17.52 % and a thermal efficiency of 79.93 %. The research examines the performance of a similar system under dusty conditions, where the PV/T/PCM with a dusty system achieved an electrical efficiency of 14.83 % and a thermal

Power System Technology
ISSN:1000-3673
Received: 16-11-2025 Revised: 05-12-2025 Accepted: 30-12-2025

efficiency of 73 %. Despite these challenges, the economic analysis demonstrates the long-term viability of PV/T/PCM systems, particularly in areas with high solar radiation, suggesting that lower operational and maintenance costs offset their initially higher price. This paper underscores the need for further optimization of these systems, emphasizing the importance of addressing dust-related performance issues to harness their potential fully across diverse environmental conditions.

II. METHODOLOGY

In this experiment, one PV panel in the form of a 250 W polycrystalline photo-voltaic panel (L × W = 1.68 m × 0.99 m) was retrofitted with a parallel serpentine copper tube absorber (14.76 m in length and 1.27 cm in diameter) fixed to the rear side of the PV panel (Fig. 1a to e).

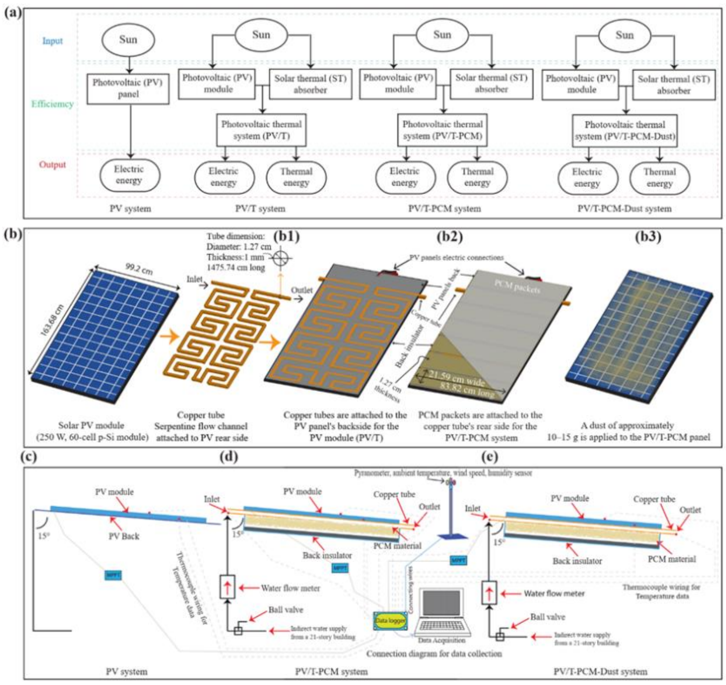

Fig. 1 Illustrated components include (a) experimental apparatus, (b) fabrication methodology, and (c-e) operational principles of PV/T and PV/T–PCM configurations.

The first study analyzed a two-sided serpentine flow double-pass PV/T/PCM system. The PV panel served as a test structure with an embedded PCM layer designed to absorb and store heat. The system was evaluated in a laboratory environment by varying solar radiation, temperature, and water flow. Lauric acid undergoes a phase change, functioning as the PCM due to its high latent heat and thermal stability. We tested the system to develop outlet water temperature, electric power generation, and the PCM's capacity to accumulate and release heat. The effect of flow rate on system performance was studied using the mass flow rate in the 1 LPM–4 LPM range.

Power System Technology
ISSN:1000-3673
Received: 16-11-2025 Revised: 05-12-2025 Accepted: 30-12-2025

1) Experimental setup: Trials of PV/T in the Field

The experimental work was conducted at the Solar Garden of the University of Malaya, Kuala Lumpur, Malaysia. This site was selected because of its typical tropical climate, high temperatures, humidity, and frequent dust deposition. The configuration included four types of solar panels: Solar panel (PV), PV/T, PV/T with PCM, and dust (PV/T/PCM/Dust). All these systems were experimentally studied under artificial and controlled conditions. Sensor instruments measured the PV module temperature, efficiency of the thermal absorber, water flow rates, and solar intensity. Dust was manually deposited to mimic the actual environment, and PCM packets (lauric acid) were embedded into the PV/T system to store excess energy. The experiment also considered the mass flow rate of water circulating in the thermal absorber, a crucial parameter for heat removal and temperature control. Data were acquired during full solar conditions from 10 AM to 4 PM, providing performance values under normal operation circumstances.

2) Contribution of PCMs in the Improvement of the PV/T Systems

Phase change materials (PCMs) play a crucial role in enhancing PV/T systems by storing thermal energy during the day and releasing it at night. These materials absorb and release latent heat during solidification and melting phases, stabilizing the temperature of the PV cells. This thermostatic control is a significant advantage even under extreme sunlight conditions. In the present work, PCMs enhanced the PV/T system, which was evaluated in various test conditions, even in the presence of dust. Experimental results revealed the potential of using PCMs to reduce the temperatures of PV cells, which led to increased electrical and thermal efficiency. The following equations provide the electrical and thermal efficiencies of the PV/T/PCM system:

Electrical Efficiency: The energy conversion efficiency of a solar cell, as described in equation (1), represents the fraction of incoming light converted into usable electricity. For this reason, minimizing energy loss during the conversion of solar energy to electricity is essential for optimizing the efficiency of a solar cell [14]. Achieving this requires the use of high-quality materials, solid design, and regular maintenance of the valve to ensure proper performance. Furthermore, ongoing advances in technology within the solar field increasingly focus on enhancing efficiency and further reducing costs, making solar energy one of the most cost-effective energy sources.

$$\eta_{el} = \frac{P_{\max}}{A_p \times R_s} \times 100\% \quad (1)$$

where $P_{max} = V_{mp} \times I_{mp}$, $A_p = 1.68\ m^2$, R_s = solar irradiance (W/m^2)

Thermal efficiency: The solar panel is a flat plate that is considered a thermal collector system. The thermal efficiency (η_{th}) of the flat-plate solar collector is given by equation (2) as follows. This formula finds the overall collector energy output and the total solar radiation incident. It is one of the key factors determining how well a thermal collector facilitates this transformation. The efficiency of a solar collector is the result of a scientific and empirical

Power System Technology
ISSN:1000-3673

Received: 16-11-2025 Revised: 05-12-2025 Accepted: 30-12-2025

analysis of the heat production principle. Thus, the design depends on the objective and some other conditions.

$$\eta_{th} = \frac{\dot{Q}_{th}}{A_p \times R_s} \times 100\% \tag{2}$$

where $Q_{th} = mC_p (T_{out} - T_{in}) + m_{PCM} \times L_{PCM}$. C_p and m represent water-specific heat (4.18 kJ/kg.K) and mass flow rate (kg/s). T_{out} and T_{in} are outlets, which are inlet water temperatures. m_{PCM} = 8.72 kg.

3) Economic Analysis:

The Annual Worth (A.W.) technique evaluated PV/T–PCM systems against ordinary PV and electric water heaters over 25 years [15], encompassing:

Initial expenditures (PV: MYR 2,000; PV/T–PCM: MYR 5,604.53). Costs for PCM replacement amount to MYR 1,900 every five years.

The second investigation focuses on testing a similar PV/T/PCM system under dusty conditions. The experiment was conducted in an open space in Kuala Lumpur, Malaysia (the average ambient temperature is 25.4°C, and average solar radiation ranges from 4.21 to 5.56 kWh/m²) in outdoor conditions. We simulated the glare using hand-applied dust particles (clay, ash, and limestone powder), mimicking their natural appearance. We compared the electric and thermal efficiencies of the dust-applied system to those of the clean one. A cost analysis of the PV/T/PCM systems was also proposed to estimate their nature, including initial expenses, maintenance, and long-term savings. The environmental temperature, wind velocity, relative humidity, and solar radiation were continuously recorded.

III. Results

A) Electrical and Thermal Effectiveness:

Fig. 2 shows that the photovoltaic/thermal-PCM system performed electrically better than the PV and the photovoltaic/thermal systems with dusty systems across all flow rates. The PV/T/PCM system achieved a maximum electrical efficiency of 17.52% and a thermal efficiency of 79.93%. The integration of PCM effectively lowered the temperature of the PV modules, resulting in increased electrical output and improved thermal performance. The maximum outlet water temperature reached 43.93 °C at 1:30 p.m. with a flow rate of 1 LPM.

The PV/T/PCM/Dust was tested in a dusty environment. The system recorded a maximum electrical efficiency of 14.83% and a thermal efficiency of 73% (Fig. 3). When dust accumulates on the PV panels, the amount of sunlight absorbed decreases, reducing electrical and thermal performance. The maximum outlet water temperature of the dusty system was 40.34 °C at 12:30, with the same flow rate.

Power System Technology
ISSN:1000-3673
Received: 16-11-2025 *Revised: 05-12-2025* *Accepted: 30-12-2025*

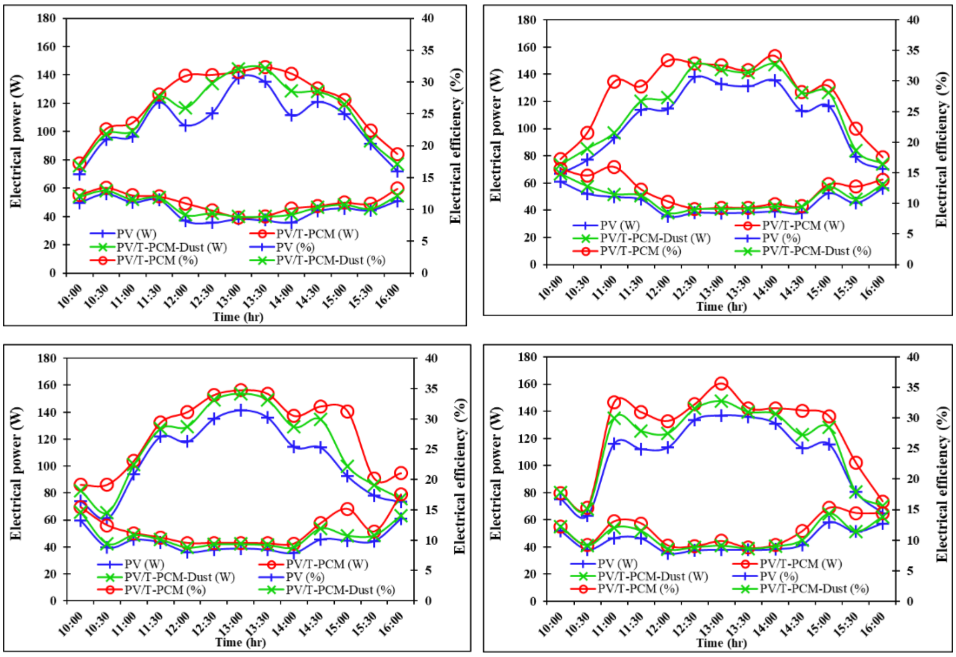

Fig. 2 Electrical efficiency vs. flow rate (photovoltaic/thermal-PCM Vs dusty module).

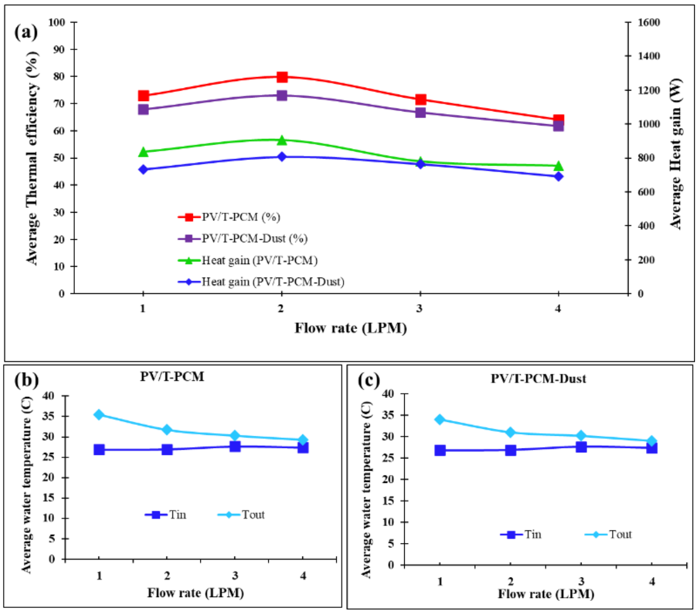

Fig. 3 PV/T/PCM and PV/T/PCM/Dust modules thermal performance; (a) thermal efficiency; (b) PV/T/PCM; and (c) PV/T/PCM/Dust inlet and outlet with mass flow rate.

Influence of Dust on Performance: The second study also demonstrated that the dust layer significantly impacts the performance of PV/T/PCM systems. The observed difference in the maximum outlet water temperature between clean and dusty systems was 10.43 °C at 1 LPM, providing direct evidence of reduced thermal performance. These dust particles obstruct sunlight absorption, preventing the system from achieving maximum thermal and electrical efficiency.

Power System Technology
ISSN:1000-3673

Received: 16-11-2025 Revised: 05-12-2025 Accepted: 30-12-2025

IV. DISCUSSION

Both sets of results demonstrate the potential of PCM use to enhance PV/T operation from an energy perspective, particularly regarding thermal energy management and overheating mitigation. However, the second research highlights significant issues caused by dust accumulation on the PV panels, especially in water-stressed areas, where dust deposition on the surface of the devices is prevalent.

Thermal performance and PCM effectiveness: PCM significantly reduced the temperature of PV systems and increased power output in all cases studied. The first work indicated that incorporating PCM into such systems could lead to a notable decrease in PV panel temperature and, consequently, an increase in electricity output. However, the second study revealed that PCM cannot operate effectively due to dust from the feed water obstructing its function. Dust can likely cover the sunlight exposure, decreasing light penetration to the PV cells, which reduces the thermal energy available for PCM absorption and, in turn, lowers the system's thermal efficiency.

1) *Environmental Considerations:*

The findings of the second investigation emphasize the value of considering environmental factors, such as dust and humidity, in the design of PV/T systems. Additional measures to mitigate dust impacts may be necessary in dusty regions, such as installing cleaning systems or using anti-dust-coated PV panels. PCM Integration and Dust Effects on Efficiency: The experimental measurements have indicated significant improvements in system performance due to incorporating PCMs into the PV/T design.

Electrical and thermal efficiency: The maximum electrical efficiency is 17.52%, while thermal efficiency reaches 79.93% in the PV/T/PCM system (Table 1). These results are very competitive with older types of PV systems, where electrical efficiency was relatively low and thermal energy was barely recovered.

Dust accumulation affected the performance of the PV/T/PCM/Dust system, resulting in an electrical efficiency of 14.83% and a thermal efficiency of 73%. However, despite the impact of dust, the PCM can still help mitigate performance losses by lowering the temperature in the PV cells.

Temperature Control: The primary role of the PCM in this system is to regulate the temperatures of the PV cells by capturing excess heat. In addition, the PV/T/PCM system can lower the panel temperature by 10.43 °C compared to the reference PV system, as shown in this study. The decrease in temperature, improved cell efficiency, and reduced thermal stress on the system enhanced the panel's performance, preventing a reduction in the PV panel's lifetime.

The Effect of Dust: Dust accumulation on PV cells reduces energy output. The PV/T/PCM/Dust system's performance decreased significantly because dust blocked sunlight. However, the PCM could still absorb and control heat to a certain extent. This study's findings highlight the necessity of developing robust PV/T systems to overcome environmental factors such as dust.

Power System Technology
ISSN:1000-3673
Received: 16-11-2025 Revised: 05-12-2025 Accepted: 30-12-2025

Thermal Absorber Design: The simultaneous serpentine thermal absorber configuration effectively enhanced heat transfer in the PV/T system. Due to its serpentine shape, it can expand by increasing the thermal energy absorbed by the PV panel, which increases the system's overall efficiency. This was improved with PCM as a medium energy storage in the middle of the day.

TABLE 1

MAXIMUM ELECTRICAL AND THERMAL EFFICIENCIES OF THE PV/T/PCM AND PV/T/PCM/DUST SYSTEMS.

System Type	Electrical Efficiency (%)	Thermal Efficiency (%)
PV/T/PCM	17.52	79.93
PV/T/PCM/Dust	14.83	73.00

2) Economic Analysis

The second part of that article reported on the economic analysis of PV/T/PCM systems, focusing on the initial investment shown in Table 2, system maintenance, and life-cycle cost savings.

Initial Investment:

- The cost per unit of the PV/T system is MYR 1650.77 (US$ 387.33).
- The cost of one unit of the PV/T/PCM system is MYR 1753.76 (US$ 411.50).
- The electrical water heater is priced at MYR 686.16 (US$ 160.56).

Maintenance Costs: The PV/T/PCM system has a higher installation cost than the conventional one, but its high efficiency and reduced overheating lead to lower maintenance frequency.

TABLE 2

INITIAL AND MAINTENANCE COSTS OF PV/T SYSTEMS.

System Type	Initial Cost (MYR)	Maintenance Cost (MYR/year)
PV/T	1650.77	200
PV/T/PCM	1753.76	150
Electrical Heater	686.16	50

Long-Term Savings: Structural analysis based on economic benefits indicates that the PV/T/PCM system can yield considerable economic advantages over time. Although initial costs may exceed those of traditional PV systems, their higher efficiency translates into increased energy generation and decreased maintenance expenses throughout the system's

Power System Technology
ISSN:1000-3673

Received: 16-11-2025 *Revised: 05-12-2025* *Accepted: 30-12-2025*

lifetime. Additionally, the ability of PCM to absorb and release thermal energy during cooler periods reduces the reliance on mechanical heating equipment for cooling internal spaces, resulting in further cost savings.

V. Conclusion

The PCM incorporated in PV/T systems represents one of the most viable alternatives for enhancing the overall performance and durability of PV/T systems. The former study has proven that PCM could improve the systems' performance and reach an optimal electrical efficiency of 17.52% and thermal efficiency of 79.93%. A second study considered the dust problem, which affected the performance of the PV/T/PCM system, and obtained a maximum electrical efficiency of 14.83% and a thermal efficiency of 73%.

Both research works highlight the relevance of thermal management in the PV system and the key role played by the PCM in preventing overheating. However, another investigation also points out the drawbacks of PCM in dusty locations: Dust accumulates on the surface under these conditions. This results in a blockage of sunlight absorption and decreased system efficiency. Economic calculations indicate that despite the high initial cost of PCM-based PV/T systems, the resulting savings and increased efficiency justify their use in solar systems, particularly in sunny regions. In short, combining PCM with PV/T systems can significantly improve solar energy technologies. However, further research is necessary to determine optimal operational strategies for these systems in practical scenarios, such as managing dust accumulation.

Reference

[1] P. T. Ogunboyo and O. Ogunlade, "Review of photovoltaic energy access for sustainable growth in the agricultural sector: Economic, market and employment opportunities for rural communities of Sub-Saharan African," Applied Photovoltaic Technology, vol. 1, no. 1, 2024.

[2] S. Sinha and Y. M. Lee, "Challenges with developing and deploying AI models and applications in industrial systems," Discover Artificial Intelligence, vol. 4, no. 1, p. 55, 2024.

[3] K. Hasan, S. B. Yousuf, M. S. H. K. Tushar, B. K. Das, P. Das, and M. S. Islam, "Effects of different environmental and operational factors on the PV performance: A comprehensive review," Energy Science Engineering, vol. 10, no. 2, pp. 656-675, 2022.

[4] L. M. Shaker, A. A. Al-Amiery, M. M. Hanoon, W. K. Al-Azzawi, and A. A. H. Kadhum, "Examining the influence of thermal effects on solar cells: a comprehensive review," Sustainable Energy Research, vol. 11, no. 1, p. 6, 2024.

[5] K. Pielichowska and K. Pielichowski, "Phase change materials for thermal energy storage," Progress in materials science, vol. 65, pp. 67-123, 2014.

[6] M. Herrando et al., "A review of solar hybrid photovoltaic-thermal (PV-T) collectors and systems," Progress in Energy Combustion Science, vol. 97, p. 101072, 2023.

Power System Technology
ISSN:1000-3673

Received: 16-11-2025 *Revised: 05-12-2025* *Accepted: 30-12-2025*

[7] H. A. Kazem, M. T. Chaichan, A. H. Al-Waeli, R. Al-Badi, M. A. Fayad, and A. Gholami, "Dust impact on photovoltaic/thermal system in harsh weather conditions," Solar Energy, vol. 245, pp. 308-321, 2022.

[8] S. Z. Said, S. Z. Islam, N. H. Radzi, C. W. Wekesa, M. Altimania, and J. Uddin, "Dust impact on solar PV performance: A critical review of optimal cleaning techniques for yield enhancement across varied environmental conditions," Energy Reports, vol. 12, pp. 1121-1141, 2024.

[9] S. Ying, X. Zhang, Y. Wu, and Z. Pan, "Solar photovoltaic/thermal (PV/T) systems with/without phase change materials (PCMs): A review," Journal of Energy Storage, vol. 89, p. 111582, 2024.

[10] Y. R. Fang et al., "Performance and economic analysis of photovoltaic/thermal systems with phase change materials and a parallel serpentine design in dusty conditions," Applied Thermal Engineering, vol. 268, p. 125890, 2025.

[11] S. K. Pathak, P. O. Sharma, V. Goel, S. Bhattacharyya, H. Ş. Aybar, and J. P. Meyer, "A detailed review on the performance of photovoltaic/thermal system using various cooling methods," Sustainable Energy Technologies Assessments, vol. 51, p. 101844, 2022.

[12] R. K. Rajamony et al., "Progress in research and technological developments of phase change materials integrated photovoltaic thermal systems: the allied problems and their mitigation strategies," Sustainable Materials Technologies, p. e00921, 2024.

[13] H. Xu, N. Wang, C. Zhang, Z. Qu, and F. Karimi, "Energy conversion performance of a PV/T-PCM system under different thermal regulation strategies," Energy Conversion Management, vol. 229, p. 113660, 2021.

[14] K. Akter, S. M. A. Motakabber, A. H. M. Z. Alam, and S. H. B. Yusoff, "Design and investigation of high power quality PV fed DC-DC boost converter," e-Prime - Advances in Electrical Engineering, Electronics and Energy, vol. 9, p. 100649, 2024/09/01/ 2024.

[15] B. Leland and T. Anthony, "Engineering Economy, https://razak.utm.my/shamsul/wp-content/uploads/sites/189/2016/03/Engineering-Economy.pdf," *Prentice Hall,* 1998.