IIETA International Information and Engineering Technology Association

International Journal of Heat and Technology
Vol. 43, No. 6, December, 2025, pp. 2147-2157
Journal homepage: http://iieta.org/journals/ijht

Optimizing Photovoltaic Thermal Systems with Phase Change Materials: A Comparative Study of Fin Geometries

Zainal Arifin[1*], Dominicus Danardono Dwi Prija Tjahjana[1], Chico Hermanu Brillianto Apribowo[2], Mochamad Choifin[3], Eflita Yohana[4], Denny Widyiyanuriyawan[5], Yuki Trisnoaji[6], Noval Fattah Alfaiz[1], Singgih Dwi Prasetyo[6]

[1] Department of Mechanical Engineering, Universitas Sebelas Maret, Surakarta 57126, Indonesia
[2] Department of Electrical Engineering, Universitas Sebelas Maret, Surakarta 57126, Indonesia
[3] CV Energy Surya Indonesia, Sidoarjo 61256, Indonesia
[4] Department of Mechanical Engineering, Universitas Diponegoro, Semarang 50275, Indonesia
[5] Department of Mechanical Engineering, Universitas Brawijaya, Malang 65145, Indonesia
[6] Power Plant Engineering Technology, State University of Malang, Malang 65145, Indonesia

Corresponding Author Email: zainal_arifin@staff.uns.ac.id

https://doi.org/10.18280/ijht.430614

Received: 16 August 2025
Revised: 13 November 2025
Accepted: 21 November 2025
Available online: 31 December 2025

Keywords:
PVT, PCM, CFD, ANSYS

ABSTRACT

This study uses numerical simulations coupled between ANSYS Fluent and Transient Thermal. This study examines the thermal and electrical performance of Photovoltaic Thermal (PVT) systems combined with Phase Change Materials (PCM). The study focused on the influence of the three finless, quadrilateral, and honeycomb fin geometric configurations on temperature distribution and overall system efficiency. Paraffin is used as a PCM due to its suitable thermophysical properties and good thermal stability in the operating range of solar panels. Simulations were carried out at variations in the intensity of solar radiation (400, 600, 800, and 1000 W/m²) to reflect real conditions. The results showed that the honeycomb configuration resulted in the highest thermal efficiency of 18.58% and electrical efficiency of 14.63% at maximum radiation intensity, outperforming the other two designs. Statistical analysis with Analysis of Variance (ANOVA) proves that radiation intensity and the fins' geometric shape significantly influence the system's efficiency. These findings confirm the importance of passive thermal design optimization in improving PVT-PCM system performance for sustainable solar energy applications.

1. INTRODUCTION

The use of solar energy continues to develop rapidly as a key alternative in the clean and sustainable energy transition. System Photovoltaic Thermal (PVT) emerged as an innovative technology that not only generates electricity, but is also capable of harvesting heat energy from sunlight [1-3]. However, one of the biggest challenges in PVT systems is the increase in the temperature of photovoltaic panels, which leads to a decrease in electricity conversion efficiency [4-6]. Therefore, a thermal engineering approach is needed to effectively maintain the stability of the operating temperature of the solar cell. One of the solutions that is widely studied is the integration of Phase Change Material (PCM) due to its ability to absorb and release heat latently in the phase transition process [7]. Previous studies have shown the great potential of the technology PVT-PCM, which is presented in Table 1 as the basis for further research directions in this field.

Various PCM modeling and material approaches have been tested in several studies to improve the thermal performance and electrical efficiency of PVT systems [8, 9]. Use of numerical simulation-based Computational Fluid Dynamics (CFD), mathematical modeling, and PCM type variations are the primary commonly used methods [10, 11]. These studies show that the addition of thermal support materials or the development of geometric configurations can improve thermal efficiency by up to tens of percent [12]. However, most of the existing studies focus more on the efficiency of the system in general, without exploring in depth the influence of the geometric shape of the PCM container on temperature distribution and thermal stability [11, 13]. Geometric factors have an essential role in regulating heat flow and expanding the area of heat transfer [14, 15]. Therefore, further research that examines specifically the variations of geometric design is needed to enrich the existing literature.

Fin geometry design on container PCM can be crucial in improving heat dissipation efficiency and supporting passive cooling of the system PVT [16-18]. In practice, geometries such as finless, quadrilateral, and hollow structures like honeycomb can affect the system's temperature distribution pattern and overall efficiency [19]. However, few studies have combined these geometric variations in a single systematic analysis based on two-way coupled numerical simulations. In addition, changing environmental conditions and varying radiation intensity at all times also need to be modeled to determine the system's dynamic performance [20]. Therefore, a numerical simulation approach that simultaneously models phase change and conductivity-convection is crucial [21]. This research will fill this gap by simulating the PVT-PCM system using software ANSYS Fluent integrated with Transient Thermal, coupled [22].

Table 1. PVT-PCM related research

Approach	PCM	Obtained Data	Ref.
CFD study on porous metal foam insertions for PCM-based PVT systems	Paraffin	Porous fillers enhance thermal efficiency by 66.70%, with a slight effect on electrical efficiency	[23]
3D unsteady numerical model for aerogel-based PV/T-PCM system	Paraffin RT35	Improved thermal/electrical efficiency by up to 90.8% with an aerogel-based system	[24]
Mathematical model for PV/PCM system using MATLAB with a simplified approach for faster computation	RT42 PCM	The proposed model computes in under 14s and is validated against CFD; thermal efficiency increases at lower solar radiation levels.	[25]
3-D CFD model in ANSYS FLUENT for PV/PCM system with different water container thicknesses and orientations	RT42 PCM	Optimal water container thickness of 30mm, with 14.93% increase in electrical efficiency and 5.88% reduction in PV panel temperature	[26]
Numerical simulations using Fluent-Ansys for PCM thermal and electrical efficiency comparison	Paraffin RT35HC, Gallium	Gallium PCM maintains the highest efficiency (12.25%) across angles, RT35HC shows potential at extreme angles with moderate efficiency decline (10.2%)	[27]

Through this approach, the study assesses thermal and electrical efficiency and comprehensively analyzes the temperature distribution for each geometric configuration. The simulation was conducted with various solar radiation intensities to represent real, more realistic conditions. Model validation is carried out by referring to the experimental literature so that the simulation results can be trusted and used as a basis for performance analysis. Statistical analysis in the form of Analysis of Variance (ANOVA) is also an additional quantitative approach to determine the significant influence of geometry variables and radiation intensity. Thus, this study is expected to make a real contribution to the development of the thermal design of PVT-PCM systems and become a reference for developing solar energy technology that is efficient, stable, and applicable in various environmental conditions.

This study provides two unique contributions compared to prior works. First, it systematically compares three distinct fin geometries—finless, quadrilateral, and honeycomb—within a single bidirectional coupled simulation framework. Previous research often examined only one or two designs, whereas this work offers a more comprehensive perspective. Second, integrating ANSYS Fluent with Transient Thermal in a two-way coupled manner enables more accurate modeling of phase-change processes and dynamic heat transfer interactions. By combining these elements, the study deepens the theoretical understanding of passive thermal management and establishes a foundation for practical system optimization.

2. METHODOLOGY

This sub-chapter describes the methods used to research thermal PVTs combined with PCM, using a numerical simulation approach coupled between ANSYS Fluent and ANSYS Transient Thermal. The research began with collecting PCM (paraffin) material parameters, including density, viscosity, thermal conductivity, type of heat, melting temperature, and phase transition temperature. In addition, the design parameters PVT, such as the initial efficiency of the PV module, temperature coefficient, and reference temperature, are also included [28]. Geometric design and environmental conditions are also set as limit conditions, such as ambient temperature, solar radiation variation (400, 600, 800, 1000 W/m²), simulation time (100 s), and convection loss. Furthermore, the CFD simulation is carried out in ANSYS Fluent and bi-directionally coupled with Transient Thermal to analyze real-time temperature distribution. Model validation is carried out through a test of calculating model errors against literature references, with a maximum error threshold of ≤10%. After successful validation, the integration simulation PVT-PCM is carried out to obtain thermal performance output, and evaluation is carried out through the analysis of the main parameters through the ANOVA [29].

2.1 Simulation setup

2.1.1 Modeling

Systems modeling PVT-PCM is shown in Figure 1. It was done to represent the physical condition of combining photovoltaic panels with PCM inserted into a thermally insulated aluminum container. The system optimizes solar panels' thermal performance and energy conversion efficiency by utilizing the PCM's ability to store and dissipate heat latently. Figure 2 shows a general illustration of the system PVT-PCM, which consists of several main layers, namely the upper protective layer, glass, ethylene-vinyl acetate (EVA), PV cell, polyvinyl fluoride (PVF), as well as PCM holding chambers made of aluminum and filled with paraffin [30, 31]. Paraffin was chosen because it has good thermal characteristics for hot energy storage applications, such as high melting heat values and good thermal stability in the operating temperature range of solar panels.

The geometric dimensions of each layer are presented in Table 2, which describes the surface size as well as the thickness of the components. The horizontal dimensions of the system are generally uniform, i.e., 606 × 470 mm², to ensure even heat distribution throughout the area. The thickness of each layer varies according to its role in the conduction process and structural protection. To strengthen the heat dissipation efficiency of paraffin, aluminum containers are designed in three configurations: finless, quadrilateral-shaped fins, and hollow structures such as honeycombs. Figure 3 and Figure 4 show the models of each fin variation and the geometric details used in the simulation.

The thermophysical characteristics of all materials in this system are shown in Table 3. The parameters included are density, type of heat capacity, thermal conductivity for each layer, and viscosity for paraffin in the liquid phase. Specifically for paraffin, additional data such as melting heat, solidus temperature, and liquidus temperature are also included to allow transient phase change analysis during the simulation process. This numerical data is integrated into the ANSYS Workbench software as the basis for modeling and simulation configuration coupled between ANSYS Fluent and Transient Thermal. The accuracy of including these material properties is critical to ensure that the simulation results can realistically represent the thermal behavior of the PVT-PCM system and evaluate the effect of fin geometry variations on heat dissipation effectiveness and overall thermal stability.

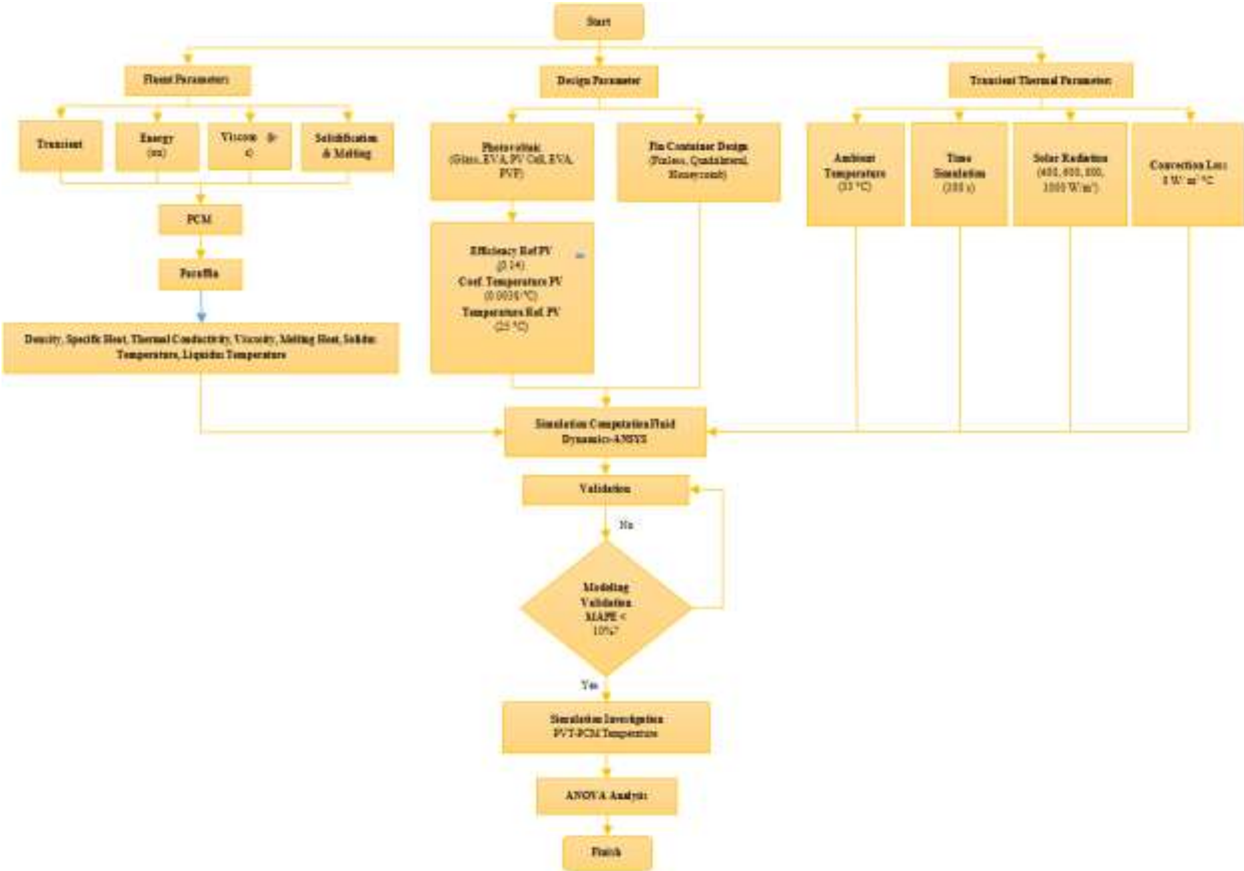


Figure 1. Flow diagram of the research process

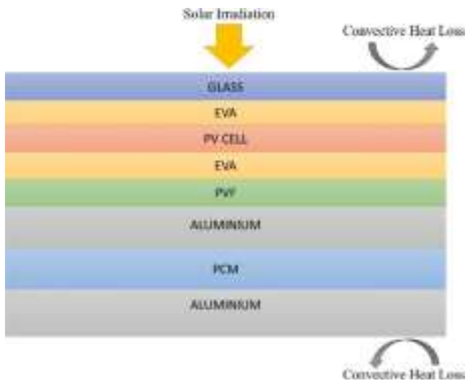


Figure 2. Illustration of the PVT-PCM system

Table 2. Detail geometry PVT-PCM

Layer	Value
Glass (mm^2)	606 × 470 × 3.2
EVA (mm^2)	606 × 470 × 0.5
PV Cell (mm^2)	606 × 470 × 0.21
PVF (mm^2)	606 × 470 × 0.3
Container (mm^2)	606 × 470 × 52
PCM thickness (mm)	50

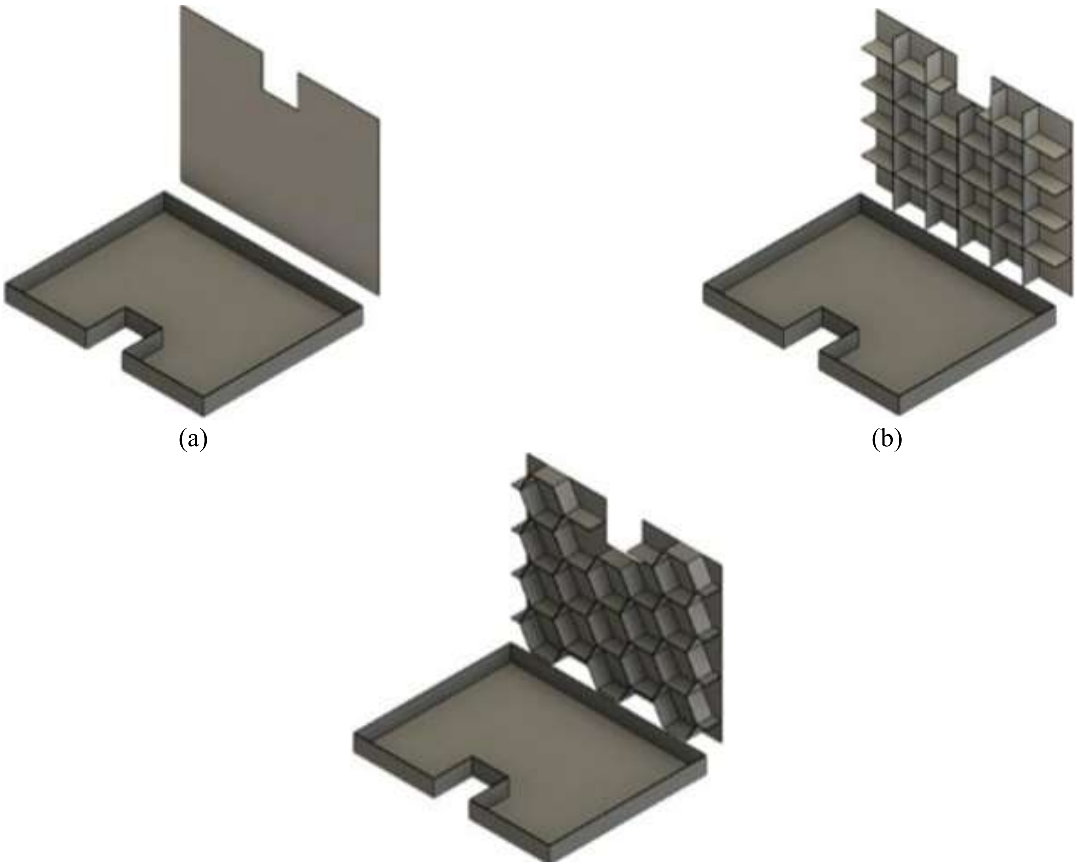
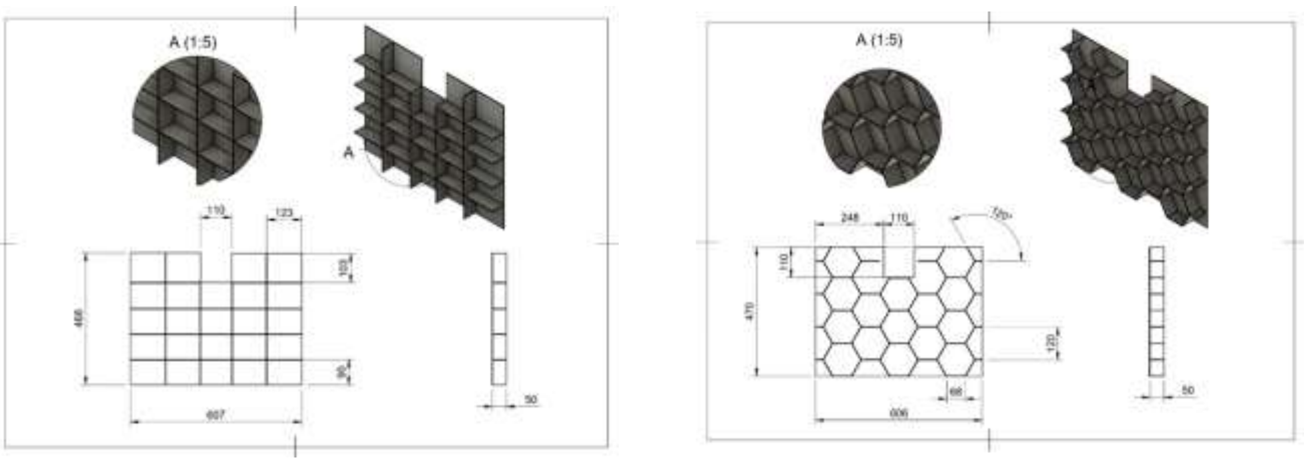


Figure 3. Model of the fin container (a) finless (b) quadrilateral, and (c) honeycomb



(a) (b)

Figure 4. Detailed geometry of the (a) quadrilateral, and (b) honeycomb

Table 3. Thermophysical characteristics of PVT-PCM [32-34]

Layer	Density (kg/m^3)	Specific Heat Capacity (J/kg-K)	Thermal Conductivity (W/m-K)	Viscosity (kg/m-s)	Pure Solvent Melting Heat (J/kg)	Solidus Temperature (K)	Liquidus Temperature (K)
Glass	2450	790	0.7	-	-	-	-
EVA	960	2090	0.311	-	-	-	-
PV cells	2330	677	130	-	-	-	-
EVA	960	2090	0.311	-	-	-	-
PVF	1200	1250	0.15	-	-		-
Paraffin	@800 @790	2150	0.2	0.01	240800	313.6	317.7
Container (aluminium)	2719	871	202.4	-	-	-	-
Thin (aluminum)	2719	871	202.4	-	-	-	-

2.1.2 Boundary condition

The simulation in this study uses a cell-based Green-Gauss method-based coupled approach to model the thermal interaction between fluids and solids simultaneously. The coupling model is applied in ANSYS Fluent integrated with Transient Thermal, with a target convergence value (residual convergence) set at 10^{-6} for energy parameters and 10^{-4} for pressure. The PCM or PCM used is paraffin, chosen for its thermal characteristics, suitable for latent heat storage applications. The ambient temperature is set at 33°C, with thermal loads simulated through heat flux of 400, 600, 800, and 1000 W/m², which are applied to the upper surface of the glass layer to represent the intensity of solar radiation.

In addition, heat loss due to natural convection around the system was modeled using a convection loss value of 8 W/m²·°C applied evenly over the entire surface of the PVT system. Three fin designs were used in the simulation: finless, quadrilateral-shaped fin, and honeycomb structure. The mesh relevance setting is set at the center level, and the span angle center is selected at the acceptable level to improve numerical accuracy. The number of nodes and elements for the PCM domain are (13,650; 10,840), (15,666; 10,650), and (14,508; 9,690) for the finless, quadrilateral, and honeycomb models, respectively. Meanwhile, for PVT domains, the number of nodes and elements is (152,003; 39,969), (210,760; 74,827), and (232,945; 86,287). The selection of these parameters is designed to ensure computational stability and the accuracy of the system's physical representation of the conduction, convection, and phase change processes.

2.2 Mathematical formulation

Energy performance analysis in the system PVT-PCM is focused on two main parameters: Thermal and electrical efficiency. Thermal efficiency indicates how effectively the system absorbs and utilizes solar thermal energy through the working fluid. In contrast, electrical efficiency suggests the performance of photovoltaic panels in converting solar energy into electrical energy, which is greatly influenced by the working temperature of the solar cell. These two formulations are used to evaluate the thermal response of systems under variations in solar radiation intensity and geometric configurations, and end at the container [35].

Thermal efficiency (η_{th}) is calculated based on the heat energy absorbed by the working fluid. In it, $\dot{m}$ is the mass flow rate of the PCM (kg/s), c_p the specific heat capacity (J/kg·K), T_o the output temperature (°C), and T_{ref} is the reference temperature, which is 25°C. The value I indicates the intensity of solar radiation (W/m²), and A is the cross-sectional area of the PVT panel (m²). This equation describes the ratio between the thermal energy successfully absorbed by the fluid and the total solar energy received by the panel surface [36].

$$\eta_{th} = \frac{\dot{m} \times c_p (T_o - T_{ref})}{IA} \tag{1}$$

$$\eta_{el} = \eta_{ref} [1 - \beta_{ref} (T_{ref} - T_o)] \tag{2}$$

The electrical efficiency of the photovoltaic panel (η_{el}) was calculated by considering the effect of temperature on the electrical energy conversion performance. A reference efficiency value (η_{ref}) is used as a reference at a standard temperature of 25°C, which is 0.14 (14%), with a coefficient of efficiency decrease with temperature (β_{ref}) of 0.0038°C. In this case, T_o represents the operational temperature of the PV cell obtained from the simulation results, while T_{ref} is the reference temperature. This formulation enables the evaluation of PV panels' electrical performance under changing thermal conditions, which generally occur due to fluctuations in solar radiation and system thermal conductivity. Thus, thermal efficiency and electrical efficiency become two complementary key parameters to assess the effectiveness of PVT-PCM systems, both in terms of thermal energy utilization and the ability to optimally convert solar energy into electricity [37].

2.3 Validation based on reference dataset

Numerical model validation is crucial in assessing how simulations can accurately represent physical phenomena. In this study, the validation process was carried out by comparing the results of the simulation of the average PVT temperature with experimental reference data from the literature [38], at several levels of irradiation intensity, namely 400, 600, 800, and 1100 W/m². Figure 5 shows the comparison of PV surface temperature between the simulation results and the reference data, as well as the relative error rate in the form of a percentage. The simulation results follow a trend consistent with the reference data, where an increase in radiation intensity leads to an increase in panel temperature. The maximum error obtained is 5.11%, indicating an acceptable deviation level for a CFD-based numerical approach. The success of this validation suggests that the configuration of the physical and thermal parameters entered into the model, including material properties, boundary conditions, and numerical discretization methods, has corresponded to the experimental conditions. Thus, it can be started for further simulation and analysis of the effect of the fin design and use of PCM on the thermal performance and energy conversion efficiency of PVT-PCM systems.

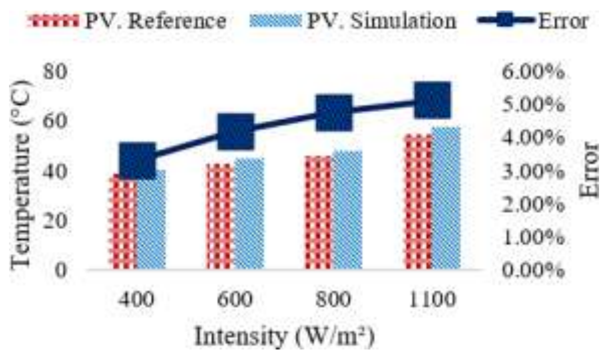


Figure 5. Simulation validation against reference data [38]

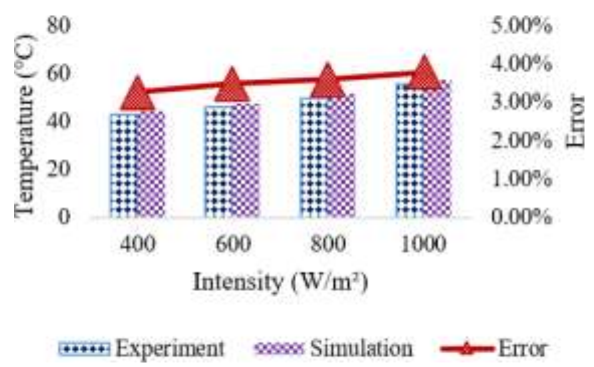


Figure 6. Experimental validation with previous studies [39]

Figure 6 presents the comparison between experimental data obtained from previous studies and the corresponding simulation results for four levels of solar radiation intensity [39]. The experimental results at 400, 600, 800, and 1000 W/m² show close agreement with the simulation outcomes, with a maximum error of only 3.79%. Across all intensities, the deviation remains below 4%, indicating a high level of accuracy in the coupled CFD model. The consistency of trends between experimental and numerical data confirms that the model can reliably capture the thermal behavior of the PVT-PCM system. This strengthens the validation process and supports the credibility of using the numerical approach as a predictive tool for system optimization. Moreover, conducting numerical simulations demonstrates that the method can be trusted as a preliminary reference for future experimental work, reducing the cost and risk of trial-and-error during prototype development.

3. RESULT AND DISCUSSION

3.1 Simulation result

Figure 7 shows the temperature distribution on the PV surface for three configurations: finless, quadrilateral fin, and honeycomb fin. The color of the contour depicts the temperature gradation, where blue represents low temperature, and red signifies high temperature. Finless systems tend to have a more even heat distribution with a predominance of green and yellow colors, indicating the absence of extreme heat accumulation. On the other hand, the honeycomb configuration shows the appearance of hotspots, as seen from the more dominant red color. This is most likely due to its complex geometric shape, which inhibits heat release efficiently. Meanwhile, the quadrilateral fin is somewhere between the two, with a heat distribution that is still controlled but less effective than a finless system.

The average PVT system temperature for each fin configuration at the radiation intensity variation is shown in Figure 8. Based on the data, at an intensity of 400 W/m², the highest temperature occurred in the honeycomb structure (34.278℃), followed by the quadrilateral (33.998℃), and the finless (33.824℃). Similar trends are seen at 600, 800, and 1000 W/m² intensities, suggesting that honeycomb structures maintain higher temperatures than others. This can be attributed to the complexity of the honeycomb geometry, which, while increasing the surface area of heat transfer, also creates a stagnant area that slows heat transfer from the PCM to the environment. In contrast, finless structures exhibit the lowest temperatures due to the absence of geometric barriers in heat dispersion. However, they are thermally less efficient in maintaining the temperature stability of the system. This quantitative analysis is essential in evaluating each fin design's role in the PVT-PCM system's overall thermal performance.

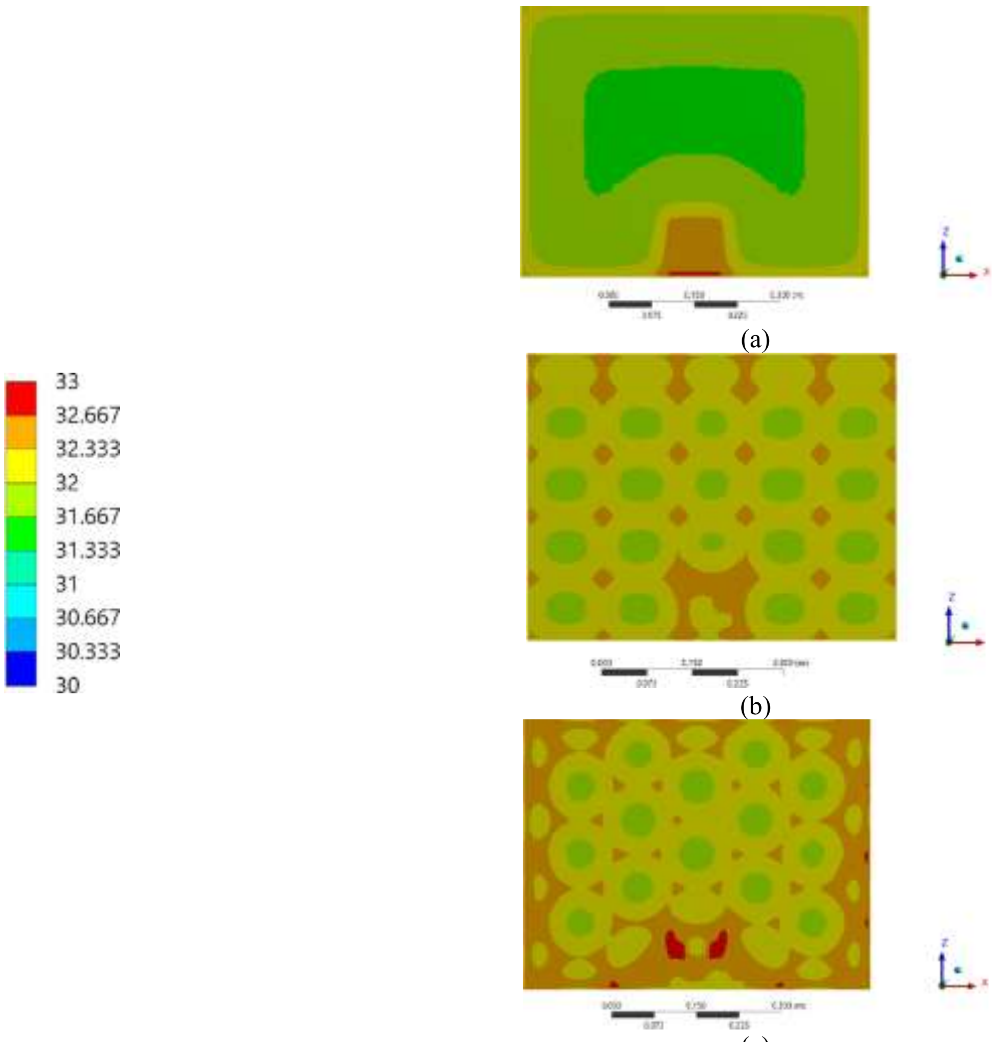


Figure 7. Thermal contour of PV (a) finless, (b) quadrilateral, and (c) honeycomb

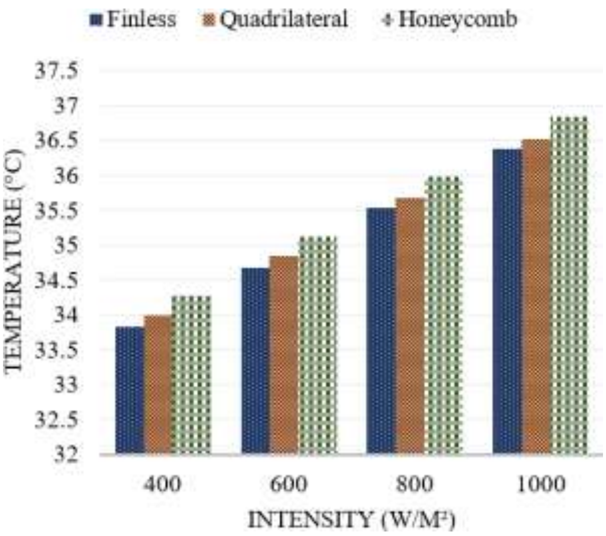


Figure 8. Average temperature profile of the PVT system

3.2 Evaluation of thermal and electrical efficiency

Thermal efficiency is an essential parameter in evaluating the performance of a PVT system, as it shows how effectively solar energy can be converted into sound heat energy. Based on Figure 9 and the data provided, it can be seen that the thermal efficiency of the system increases as the intensity of solar radiation increases, from 400 to 1000 W/m². This pattern of efficiency improvement applies to all types of designs, but with varying degrees of effectiveness. The honeycomb design consistently performs the highest compared to the quadrilateral and finless systems. At an intensity of 400 W/m², the thermal efficiency of the honeycomb system was recorded at 12.48%, then increased to 18.58% when the intensity reached 1000 W/m². Compare that to the finless design, which only achieves an efficiency of 17.53% at the highest intensity, showing that fins' presence significantly affects thermal efficiency. The honeycomb fins provide a larger heat transfer surface area and optimize the flow of thermal fluids around the panels, thereby improving convective efficiency. Meanwhile, the quadrilateral system occupies the middle position, indicating that geometric shapes affect efficiency. This increase in thermal efficiency is crucial in PVT systems, as lower temperatures also indirectly help maintain the electrical performance of PV modules. Thus, it can be concluded that the honeycomb fin design is the best choice in optimizing the thermal performance of high radiation-based PVT systems.

In addition to thermal efficiency, electrical efficiency is also a key aspect in the performance assessment of PVT systems, as it is directly related to the conversion of light energy into electrical energy. Figure 10 and the electrical efficiency data show that an increase in solar intensity from 400 to 1000 W/m² is followed by an increase in electrical efficiency, albeit in a relatively small range. The honeycomb system again showed the highest efficiency among the three designs, with a value of 14.49% at an intensity of 400 W/m² and an increase of 14.63% at 1000 W/m². Although the difference may seem small, 0.17% between honeycomb and finless systems at the highest intensity is significant in long-term optimization and large-scale system operation. The fin design, especially the honeycomb, keeps the PV panel's temperature low through an efficient passive cooling process. Lower temperatures directly affect the temperature coefficient of the PV cell, which means that electricity performance will decline more slowly despite an increase in ambient temperature. This proves that good thermal efficiency indirectly favors stability and improved electrical efficiency. A comparison between the designs shows that the geometric structure of the fins can be utilized as a passive design strategy to improve the system's electrical performance. Overall, although the increase in electrical efficiency is not as significant as the thermal efficiency, the combination of optimal thermal design still provides significant overall advantages to PVT systems.

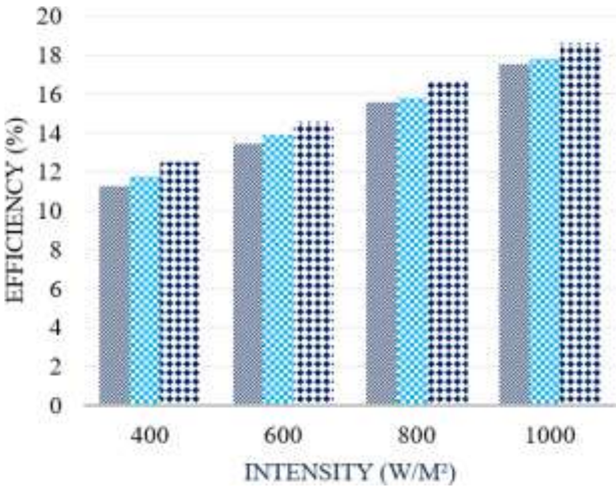


Figure 9. Thermal efficiency of the PVT system

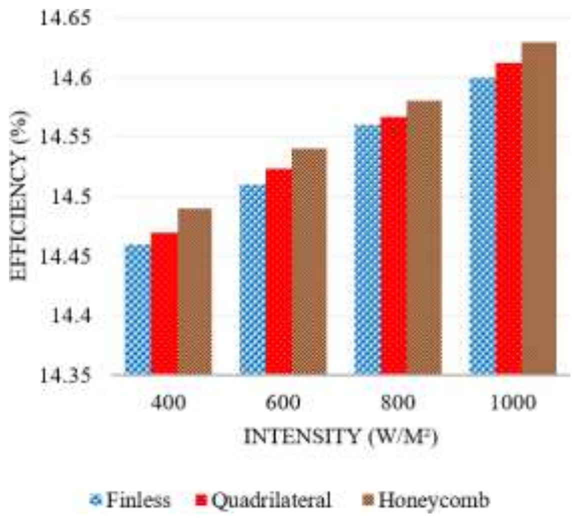


Figure 10. Electrical efficiency of the PVT system

Beyond the average efficiency results, additional heat-transfer indicators were analyzed to strengthen the findings. A simplified thermal resistance network was constructed to evaluate each fin geometry's dominant heat flow pathways. The results indicate that the honeycomb configuration exhibits the lowest overall resistance, which explains its superior thermal performance. Furthermore, local Nusselt-number distributions were derived from the CFD model to assess convective enhancement near fin surfaces. These analyses reinforce that geometric optimization reduces operating temperatures and improves heat transfer mechanisms, thereby validating the honeycomb design as the most effective.

Table 4. ANOVA on the thermal efficiency of the PVT system

Source of Variation	Degree of Freedom (df)	Sum of Squares (SS)	Mean Square (MS)	F	P-Value
Intensity of Solar Radiation	3	62.4035	20.8012	7556.43	0.0000000000405
Geometry	2	2.5252	1.2626	458.67	0.0000002744
Error	6	0.0165	0.00275		
Total	11	64.9453			

Table 5. ANOVA on the electrical efficiency of the PVT system

Source of Variation	Degree of Freedom (df)	Sum of Squares (SS)	Mean Square (MS)	F	P-Value
Intensity of Solar Radiation	3	0.032700	0.010900	1557.14	0.0000000046
Geometry	2	0.001541	0.000770	110.00	0.0000187
Error	6	0.000041	0.000007		
Total	11	0.034282			

Table 4 shows the results of the ANOVA on the thermal efficiency of the PVT system based on two main factors, namely the intensity of solar radiation and the geometry of the cooling fin. The results of the analysis showed that the intensity of solar radiation had a very significant influence on thermal efficiency, with an F value of 7556.43 and a p-value of 0.0000000000405, which was much smaller than the significance level of 0.05. This suggests that changes in radiation values, ranging from 400 to 1000 W/m², statistically contribute significantly to differences in thermal efficiency. The geometric factor also showed a significant influence with an F-value of 458.67 and a p-value of 0.0000002744, which indicates that fin designs such as finless, quadrilateral, and honeycomb have a tangible impact on improving heat dissipation efficiency. A tiny mean square error (MSE) value of 0.00275 indicates the data variability is relatively low, so the simulation results can be considered very consistent.

Table 5 presents the ANOVA results for the electrical efficiency of PVT systems based on variations in radiation intensity and geometry. Although the absolute value of the change in electrical efficiency is not as great as the thermal efficiency, the statistical results show that both factors remain significantly influential. The F-value for radiation intensity reached 1557.14 with a p-value of 0.0000000046, which indicates that the increase in the intensity of sunlight statistically affects the electrical efficiency output, although the rise is gradual. In addition, the geometry of the fins also shows a noticeable influence on electrical efficiency, with an F value of 110.00 and a p-value of 0.0000187. These results reinforce the assumption that temperature control through thermal design directly impacts the stability of solar panels' electrical energy conversion performance. This aligns with the concept of the temperature coefficient of silicon solar cells. The minimal error value confirms that the variance between groups stems from treatment differences, not measurement or simulation errors.

3.3 Research limitations

This study was conducted entirely based on numerical simulations using ANSYS Fluent and Transient Thermal software, so it did not include direct experimental tests as additional verification. The validation used is indirect, i.e., comparing the simulation results with previous literature data, which can leave inaccuracies regarding the accuracy of environmental parameters and real material variations. In addition, ideal assumptions such as uniform heat distribution and constant conduction during the transient process can differ from real conditions in the field. The simulation also uses constant thermophysical properties and does not consider the long-term degradation of PCM or PV panel materials. Therefore, the results of this study are best used as a starting basis for further experimental design development.

Another limitation lies in the variation of fin geometry design that includes only three main shapes: finless, quadrilateral fin, and honeycomb fin, so it does not yet represent the possibility of optimizing other geometric shapes. The simulation was conducted with a limited time duration (100 seconds), which did not reflect the behavior of the PVT-PCM system in a complete daily cycle or various real-weather conditions. In addition, fluid variables are not dynamically modeled (e.g., PCM fluid flow is not explicitly included), which can affect the predictive accuracy of latent heat transfer. The absence of integration with energy management or electricity storage systems is also a limitation in assessing system efficiency holistically. Considering these limitations, further research development is strongly recommended to include experimental approaches, wider geometric design variations, and integration of PVT-PCM systems in the context of real renewable energy applications.

3.4 Practical implications

The findings of this study provide significant implications for the practical design of PVT-PCM systems. Incorporating honeycomb fins into PVT-PCM modules can significantly improve passive cooling performance, especially under hot-climate conditions where overheating frequently reduces efficiency. Lower operating temperatures slow down thermal degradation of PV cells, extend the service life of modules, and reduce maintenance costs. These improvements in large-scale applications such as solar farms lead to higher system reliability and lower operational expenditure. From a design standpoint, such geometric optimization offers a low-cost, energy-free cooling solution that enhances long-term sustainability.

The improved thermal management also contributes to more stable and reliable electrical output, highly relevant to distributed generation and hybrid renewable energy systems. Maintaining consistent PV performance is critical to balancing energy supply and demand in regions with high solar intensity but unstable grid infrastructure. By reducing fluctuations in panel efficiency, honeycomb fins support smoother grid integration and compatibility with energy storage technologies. Furthermore, this approach aligns well with developing innovative grid applications that require predictable and stable renewable energy inputs. These results confirm that passive thermal strategies can directly benefit modern energy systems.

Beyond technical benefits, the outcomes of this study also carry significant implications for policy and industry practices. Since honeycomb fin designs in PVT-PCM systems function without requiring external power, they align closely with energy efficiency targets and carbon reduction strategies. Policymakers can promote the adoption of such passive cooling technologies through standards and incentives in solar energy deployment. Meanwhile, industry stakeholders can apply these insights to develop commercial PVT-PCM modules to improve competitiveness in renewable energy markets. Overall, the practical implications of this research go beyond laboratory simulations and offer a clear pathway toward more efficient, sustainable, and cost-effective solar energy systems in real-world applications.

4. CONCLUSIONS

This study has successfully evaluated the performance of the PVT system combined with paraffin PCM using three fin design variations: finless, quadrilateral fin, and honeycomb fin. The simulation showed that fin design variations significantly influenced temperature distribution, thermal, and electrical efficiency. At a radiation intensity of 1000 W/m², the system with a honeycomb design showed the highest average temperature of 36.92 degrees Celsius, followed by the quadrilateral and finless, which recorded 36.45 and 35.15 degrees Celsius, respectively. The thermal efficiency of the honeycomb system reached the highest value of 18.58%, while the quadrilateral and finless designs reached 17.94% and 17.53%, respectively. Regarding electrical efficiency, the honeycomb system also excels at 14.63%, slightly higher than the quadrilateral 14.55% and finless 14.46%. Thus, the honeycomb geometric design has been proven to improve thermal performance and keep the PV operating temperature stable, supporting optimal electrical energy conversion efficiency.

This finding is reinforced by the results of the ANOVA or ANOVA test, which shows that the intensity of solar radiation and the geometric shape of the fins significantly influence the system's efficiency. The F-value for radiation intensity on thermal efficiency reached 7556.43 with a probability value or p-value of 0.0000000000405. At the same time, the influence of geometry produced an F-value of 458.67 with a p-value of 0.0000002744. For electrical efficiency, the radiation intensity has an F value of 1557.14 and a p-value of 0.0000000046, while geometry produces an F of 110.00 and a p-value of 0.0000187. In addition, the minimal Mean Squared Error values of 0.00275 for thermal efficiency and 0.000007 for electrical efficiency indicate that the simulation results have high consistency and precision. Therefore, it can be concluded that the honeycomb-structured fin design is the most promising alternative to improve the passive efficiency of PVT-PCM systems. However, as this study is still limited to a short-term simulation approach without experimental testing and without considering daily operational conditions, further research is needed for empirical verification and testing in real-world scenarios.

Future research should incorporate direct experimental testing to verify the numerical predictions under real operating conditions. Experimental validation will allow researchers to evaluate the accuracy of the coupled CFD model in dynamic environments, such as daily and seasonal solar variations. In addition, multi-physics extensions such as fluid–structure interaction or the integration of dust accumulation models could provide a more comprehensive representation of PVT-PCM performance. These advanced approaches will ensure the model reflects theoretical efficiency and practical challenges in real applications. Ultimately, these future directions will strengthen the scientific foundation and facilitate the transition of PVT-PCM technologies into large-scale practical implementation.

ACKNOWLEDGMENT

This paper is the result of research entitled “Application of Phase Change Material (PCM) in Photovoltaic for Public Electric Vehicle Charging Stations (SPKLU) with Hybrid Solar Power” funded by Sebelas Maret University through the Applied Excellence Research A (puta-uns) scheme (Grant numbers: 369/UN27.22/PT.01.03/2025).

REFERENCES

[1] Azimi, N., Sharifzadeh, E., Rahimi, M., Nouira, M. (2024). Improving the performance of photovoltaic panels integrated with ultrasound and phase change materials: Experimental study and CFD modeling. Journal of Thermal Analysis and Calorimetry, 149(15): 8193-8213. https://doi.org/10.1007/s10973-024-13295-1

[2] Abdelrazik, A.S., Osama, A., Allam, A.N., Shboul, B., Sharafeldin, M.A., Elwardany, M., Masoud, A.M. (2023). ANSYS-Fluent numerical modeling of the solar thermal and hybrid photovoltaic-based solar harvesting systems. Journal of Thermal Analysis and Calorimetry, 148(21): 11373-11424. https://doi.org/10.1007/s10973-023-12509-2

[3] Prasetyo, S.D., Trisnoaji, Y., Arifin, Z. Mahadi, A.A. (2025). Harnessing unconventional resources for large-scale green hydrogen production: An economic and technological analysis in Indonesia. Unconventional Resources, 6: 100174. https://doi.org/10.1016/j.uncres.2025.100174

[4] Maarof, H.A., Maree, I.E., Jadallah, A.A. (2025). Multiphysics CFD modeling of an optimized double-pass PVT system with phase change materials and wavy fins for enhanced thermal and electrical efficiency. Journal of Energy Storage, 118: 116245. https://doi.org/10.1016/j.est.2025.116245

[5] Kang, Y.K., Jo, S.Y., Park, H.L., Jeong, J.W. (2023). Optimization of building integrated photovoltaic and thermoelectric hybrid energy harvesting system for different climatic regions. Journal of Physics: Conference Series, 2600(4): 042011. https://doi.org/10.1088/1742-6596/2600/4/042011

[6] Prasetyo, S.D., Arifin, Z., Prabowo, A.R., Budiana, E.P. (2025). The impact of cavity in finned thermal collector on PVT performance using Al_2O_3 nanofluid. International Journal of Thermofluids, 27: 101284. https://doi.org/10.1016/j.ijft.2025.101284

[7] Hu, Z., Liu, R., Li, K., Wang, Z., Gu, K., He, W. (2025). Performance analysis and design optimization of a novel Trombe wall system using CFD and response surface method. Energy, 324: 136031. https://doi.org/10.1016/j.energy.2025.136031

[8] Jurčević, M., Nižetić, S., Marinić-Kragić, I., Arıcı, M. (2025). An impact of phase change material type on photovoltaic-thermal collector performance and economy: A comparative study. Solar Energy, 295: 113557. https://doi.org/10.1016/j.solener.2025.113557

[9] Rahmanian, S., Moein-Jahromi, M., Rahmanian-Koushkaki, H., Sopian, K. (2021). Performance investigation of inclined CPV system with composites of PCM, metal foam and nanoparticles. Solar Energy, 230: 883-901. https://doi.org/10.1016/j.solener.2021.10.088

[10] Farzan, H., Iranmanesh, A., Dehaj, M.S. (2025). A comparative study on performance of porous and non-porous photovoltaic/thermal collector using capsulated phase change material/steel wool composite: An experimental study. Applied Thermal Engineering, 277: 127071. https://doi.org/10.1016/j.applthermaleng.2025.127071

[11] Díaz, F.A., Moraga, N.O., Cabrales, R.C. (2022). Computational modeling of a PV-PCM passive cooling system during a day–night cycle at arid and semi-arid climate zones. Energy Conversion and Management, 270: 116202. https://doi.org/10.1016/j.enconman.2022.116202

[12] Chang, S., Liu, H., Li, G. (2025). Effect of installing porous metal insertion inside the collector tube of a photovoltaic thermal system integrated with PCM-copper foam composite. Energy, 314: 134203. https://doi.org/10.1016/j.energy.2024.134203

[13] Marzouk, S.A., Aljabr, A., Almehmadi, F.A., Sharaf, M.A., Alam, T., Dobrotă, D. (2025). Thermal performance enhancement of phase change material melting using innovative fins. Thermal Science and Engineering Progress, 61: 103585. https://doi.org/10.1016/j.tsep.2025.103585

[14] Attia, M.E.H., Abdel-Aziz, M.M., Khelifa, A. (2025). A numerical approach to enhance the performance of double-pass solar collectors with finned photovoltaic/thermal integration. Applied Thermal Engineering, 268: 125974. https://doi.org/10.1016/j.applthermaleng.2025.125974

[15] Narjabadifam, N., Salemi, S., Adib, M., Bozorgmehri, S. (2022). Techno-economic assessment of a photovoltaic module integrated with a two-layer phase change material unit. Journal of Energy Storage, 51: 104243. https://doi.org/10.1016/j.est.2022.104243

[16] Ishak, M.A.A.B., Ibrahim, A., Din, S.I.U. (2025). Energy and exergy analysis of a reversed circular flow jet impingement bifacial PVT collector: CFD simulation and experimental study. Thermal Science and Engineering Progress, 62: 103602. https://doi.org/10.1016/j.tsep.2025.103602

[17] Ibrahim, T., El Hazar, M., Hachem, F., Khaled, M. (2024). A comprehensive experimental study of cooling photovoltaic panels using phase change materials under free and forced convection–Experiments and transient analysis. Journal of Energy Storage, 81: 110511. https://doi.org/10.1016/j.est.2024.110511

[18] Assaffat, L., Maulidin, M.S., Trisnoaji, Y., Prasetyo, S.D., Rizkita, M.A., Arifin, Z., Choifin, M. (2025). Improving grid stability with hybrid renewable energy and green hydrogen storage: A study of Karimunjawa Island. Mathematical Modelling of Engineering Problems, 12(5): 1524-1534. https://doi.org/10.18280/mmep.120506

[19] Han, Z., Ge, W., Wei, Y., Liu, Q., Ding, S. (2025). Analysis of concentrating photovoltaic thermal management performance under different filling conditions in MF-PCM radiator. International Journal of Heat and Mass Transfer, 246: 127049. https://doi.org/10.1016/j.ijheatmasstransfer.2025.127049

[20] Shahsavar, A., Moradvandi, M., Azimi, N. (2025). Experimental study on ultrasonic-assisted PCM cooling: A novel approach to photovoltaic panel performance improvement. Applied Thermal Engineering, 265: 125642. https://doi.org/10.1016/j.applthermaleng.2025.125642

[21] Jaber, M., Ibrahim, A., Azeez, H.L., Ahmed, B.O., Din, S.I.U., Jarimi, H. (2025). Electrical and thermal analysis of a newly designed photovoltaic thermal collector featuring inner and outer micro-fin surface tube with broken double V-cuts twisted tapes: An experimental study. Applied Thermal Engineering, 274: 126757. https://doi.org/10.1016/j.applthermaleng.2025.126757

[22] Kurniawati, I., Sung, Y. (2025). Numerical analysis of thermal performance enhancement of photovoltaic–thermal system using ternary nanofluid. Case Studies in Thermal Engineering, 72: 106294. https://doi.org/10.1016/j.csite.2025.106294

[23] Sumayli, A., Alshahrani, S.M., Mahdi, W.A. (2023). The effect of the properties of porous fillers on the performance of a PCM-based photovoltaic thermal system: A CFD study. Case Studies in Thermal Engineering, 50: 103444. https://doi.org/10.1016/j.csite.2023.103444

[24] Zheng, X., Zhou, Y. (2023). A three-dimensional unsteady numerical model on a novel aerogel-based PV/T-PCM system with dynamic heat-transfer mechanism and solar energy harvesting analysis. Applied Energy, 338: 120899. https://doi.org/10.1016/j.apenergy.2023.120899

[25] Al-Najjar, H.M.T., Mahdi, J.M. (2022). Novel mathematical modeling, performance analysis, and design charts for the typical hybrid photovoltaic/phase-change material (PV/PCM) system. Applied Energy, 315: 119027. https://doi.org/10.1016/j.apenergy.2022.119027

[26] Bhakre, S.S., Sawarkar, P.D., Kalamkar, V.R. (2023). Numerical study on photovoltaic thermal phase change material system in hot climatic conditions. Applied Thermal Engineering, 227: 120423. https://doi.org/10.1016/j.applthermaleng.2023.120423

[27] Chibani, A., Merouani, S., Laidoudi, H., Dehane, A., Bougriou, C. (2024). Thermal management and electrical efficiency for concentrator photovoltaic systems using multiple phase change materials. Applied Thermal Engineering, 240: 122207. https://doi.org/10.1016/j.applthermaleng.2023.122207

[28] Tuncer, A.D., Amini, A., Khanlari, A. (2023). Experimental and transient CFD analysis of parallel-flow solar air collectors with paraffin-filled recyclable aluminum cans as latent heat energy storage unit. Journal of Energy Storage, 70: 108009. https://doi.org/10.1016/j.est.2023.108009

[29] Yuce, B.E., Nielsen, P.V., Wargocki, P. (2022). The use of Taguchi, ANOVA, and GRA methods to optimize CFD analyses of ventilation performance in buildings. Building and Environment, 225: 109587.

https://doi.org/10.1016/j.buildenv.2022.109587
[30] Peng, H., Lu, H., Chang, X., Zheng, C., Wang, Y. (2022). 3D CFD modelling of dust deposition characteristics and influences on building-mounted photovoltaic system. Case Studies in Thermal Engineering, 35: 102138. https://doi.org/10.1016/j.csite.2022.102138
[31] Abdulmunem, A.R., Samin, P.M., Rahman, H.A., Hussien, H.A., Ghazali, H. (2021). A novel thermal regulation method for photovoltaic panels using porous metals filled with phase change material and nanoparticle additives. Journal of Energy Storage, 39: 102621. https://doi.org/10.1016/j.est.2021.102621
[32] Govindasamy, D., Kumar, A. (2023). Evaluation of the impact of different composite phase change materials on reduction in temperature and enhancement of solar panel efficiency. Journal of Energy Storage, 60: 106631. https://doi.org/10.1016/j.est.2023.106631
[33] Kibria, M.G., Mohtasim, M.S., Paul, U.K., Das, B.K., Saidur, R. (2024). Impact of hybrid nano PCM (paraffin wax with Al_2O_3 and ZnO nanoparticles) on photovoltaic thermal system: Energy, exergy, exergoeconomic and enviroeconomic analysis. Journal of Cleaner Production, 436: 140577. https://doi.org/10.1016/j.jclepro.2024.140577
[34] Bria, A., Raillani, B., Chaatouf, D., Salhi, M., Amraqui, S., Mezrhab, A. (2023). Effect of PCM thickness on the performance of the finned PV/PCM system. Materials Today: Proceedings, 72: 3617-3625. https://doi.org/10.1016/j.matpr.2022.08.409
[35] Yang, S., Zhang, Y., Zhao, Y., Torres, J.F., Wang, X. (2023). PCM-based ceiling panels for passive cooling in buildings: A CFD modelling. Energy and Buildings, 285: 112898. https://doi.org/10.1016/j.enbuild.2023.112898
[36] Khanlari, A., Aytac, I., Tuncer, A.D., Variyenli, H.İ., Şahin, H.N. (2024). Improving the performance of a PCM integrated solar air collector by adding porous fins over the bottom side of the absorber: A transient CFD study. Journal of Energy Storage, 90: 111847. https://doi.org/10.1016/j.est.2024.111847
[37] Hu, Z., Li, K., Wang, Z., He, W., Zhu, M., Liu, X. (2023). Numerical study on using multichannel tube and PCM for improving thermal and electrical performance of a photovoltaic module. Solar Energy, 265: 112058. https://doi.org/10.1016/j.solener.2023.112058
[38] Arifin, Z., Prasetyo, S.D., Tribhuwana, B.A., Tjahjana, D.D.D.P., Rachmanto, R.A., Kristiawan, B. (2022). Photovoltaic performance improvement with phase change material cooling treatment. International Journal of Heat and Technology, 40(4): 953-960. https://doi.org/10.18280/ijht.400412
[39] Seto, D.B., Arifin, Z., Kristiawan, B., Prasetyo, S.D. (2024). Nanoparticle-enhanced phase change materials (NePCM) in passive cooling systems to improve solar panel efficiency. International Review of Mechanical Engineering, 18(1): 20-27. https://doi.org/10.15866/ireme.v18i1.24149