
ENHANCING PHOTOVOLTAIC PERFORMANCE USING TITANIUM DIOXIDE BASED NANO- ENHANCED PCM FOR PASSIVE COOLING APPLICATIONS

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ABSTRACT

The performance of photovoltaic (PV) modules is significantly affected by the increase in operating temperature, which leads to reduced power output and overall efficiency. Therefore, passive cooling strategies are required to maintain stable energy conversion in solar systems. One widely investigated approach is the use of phase change materials (PCM) due to their ability to absorb and release latent heat, although their low thermal conductivity remains a major limitation. This study aims to evaluate the effectiveness of incorporating titanium dioxide nanoparticles into PCM, known as nano-enhanced PCM (NePCM), in improving the cooling performance of PV modules. The experimental method was conducted on a 50 Wp polycrystalline PV module under three conditions: without cooling, with pure PCM, and with titanium dioxide-based NePCM. The preparation of NePCM was carried out using a two-step method involving mechanical stirring and ultrasonic sonication to achieve a homogeneous nanoparticle dispersion. The results demonstrated that the addition of titanium dioxide improved the thermal conductivity of PCM, leading to lower operating temperatures, more stable voltage and power output, and higher energy conversion efficiency compared to both pure PCM and the uncontrolled condition. These findings highlight the potential of titanium dioxide-based NePCM as an effective, economical, and sustainable material for passive cooling applications in photovoltaic systems.

KEYWORDS

Photovoltaic, Passive Cooling, PCM, NePCM, Titanium Dioxide



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INTRODUCTION

The continuous growth of global energy demand has driven the utilization of renewable energy as a sustainable solution. Among various renewable sources, solar energy holds an important position due to its abundance, environmental friendliness, and zero emissions (Adjiski et al., 2023; Afif & Martin, 2022). The conversion of solar energy into electricity is generally carried out through photovoltaic (PV) systems. However, the performance of PV modules is strongly influenced by operating temperature conditions (Laksana et al., 2022). In crystalline silicon-based modules, an increase in cell temperature above the standard condition can reduce conversion efficiency with a coefficient of about 0.45% per °C relative to standard test conditions (Hudişteanu et al., 2024; Prayogi et al., 2023). This emphasizes the importance of thermal management in maintaining PV performance under real environmental conditions.

Various strategies have been developed to overcome the problem of increasing PV temperature, ranging from active cooling methods (using fluids, fans, or thermoelectric systems) to passive cooling approaches (Bukar et al., 2025; Pomares-Hernández et al., 2021). Active cooling methods are generally effective but increase energy consumption and operational costs. In contrast, passive cooling approaches are considered simpler, more energy-efficient, and easier to integrate (Alktranee & Bencs, 2023; Muhammad Fuad Abdul Hakim, 2025). One of the most widely studied passive methods is the use of Phase Change Materials (PCM), which can absorb and release latent heat during the phase transition process, thereby helping to maintain the temperature stability of PV modules (Ibrahim et al., 2024). However, the main limitation of pure PCM is its low thermal conductivity, which restricts the rate of heat transfer.

To overcome this limitation, several studies have developed Nano-Enhanced Phase Change Materials (NePCM), in which PCM is combined with nanoparticles to improve thermal conductivity and heat transfer properties (Mebarek - Oudina & Chabani, 2023; Unnikrishnan & Rohinikumar, 2022). Previous studies have shown that integrating NePCM with Al₂O₃ and ZnO nanoparticles can significantly reduce the operating temperature of PV modules and improve their efficiency (Seto et al., 2024). In earlier work, NePCM-ZnO was proven to be the most effective, achieving an efficiency gain of 3.08% compared to PV without cooling.

On the other hand, research on the use of TiO₂ as an additive in NePCM remains relatively limited. Titanium dioxide is known for its high chemical stability, wide availability, relatively low cost, and good thermal conductivity. Several studies have reported that the addition of TiO₂ to PCM can accelerate melting and solidification rates while improving heat distribution within the thermal storage medium (Alotaibi et al., 2022). These characteristics make TiO₂ a potential candidate for enhancing the performance of passive PV cooling systems.

Based on this background, the present study aims to evaluate the effectiveness of TiO₂-based NePCM in reducing the operating temperature and improving the electrical performance of PV modules. The findings are expected to broaden the understanding of TiO₂-NePCM applications in passive cooling systems and serve as a foundation for the development of more efficient and sustainable cooling materials for future solar energy technologies.

RESEARCH METHOD

This research was designed to evaluate the effectiveness of using titanium dioxide (TiO₂)-based nano-enhanced phase change material (NePCM) in improving the

performance of photovoltaic (PV) modules. Three system configurations were tested, namely PV without cooling as the baseline, PV with pure PCM, and PV with PCM enhanced with TiO₂ nanoparticles (NePCM-TiO₂). The purpose of this experimental test was to assess the capability of NePCM-TiO₂ in reducing the operating temperature of the solar panel while simultaneously improving the maximum power output and overall energy conversion efficiency of the PV system.

1. Eksperimental Setup

The experiment was conducted using a polycrystalline PV module, type JS-50, with a capacity of 50 W_p manufactured by PT Yingli Solar. This module has an open-circuit voltage of 22.9 V, a short-circuit current of 2.87 A, and a nominal efficiency of approximately 14%. The cooling system was placed on the back side of the module in the form of an aluminum container with dimensions of 609 × 489 × 50 mm, a wall thickness of 2 mm, and equipped with ten internal fins to increase the heat transfer area. Paraffin was used as the PCM, while TiO₂ nanoparticles were added at 1 wt% of the total PCM mass.

The basic characteristics of the TiO₂ nanoparticles used in this study are shown in Table 1. These data were obtained from the manufacturer's specifications and supporting literature.

Table 1. Basic Characteristics of TiO₂ Nanoparticles (Jenima et al., 2024)

Parameter	Value / Range
Purity	≥ 99 %
Crystal Phase	Anatase / Rutile
Particle Size	20–30 nm
Specific Surface Area	50–100 m ² /g
Density	~4.2 g/cm ³
Thermal Conductivity	8.4 W/m·K
Form / Color	Fine white powder

2. NePCM Preparation

The preparation of NePCM-TiO₂ was carried out using the two-step method. In the initial stage, paraffin was heated until fully melted on a magnetic stirrer (Figure 1). TiO₂ powder was then gradually added while stirring for approximately sixty minutes until a homogeneous mixture was obtained.



Figure 1. Mixing process of PCM and TiO₂ nanoparticles using a magnetic stirrer.

Subsequently, the mixture was further processed in an ultrasonic bath (Figure 2) for sixty minutes to ensure a more uniform dispersion of nanoparticles and to minimize the possibility of agglomeration. After the mixing process was completed, the NePCM was poured into an aluminum container and allowed to cool until it reached a solid state before being attached to the PV module.



Figure 2. Homogenization process of the PCM–TiO₂ mixture using an ultrasonic bath.

The experimental procedure was carried out repeatedly with consistent steps. In each variation, the module was first mounted on the testing frame, followed by instrument calibration. The solar simulator was turned on until the light intensity stabilized at 470, 625, 900, and 1000 W/m². The panel was then exposed for fifteen minutes as an initial stabilization stage. After that, data collection was conducted for the next fifteen minutes, with panel temperature recorded every ten seconds and I–V curve measurements taken every five minutes. All scenarios were tested in three independent trials to obtain more reliable average results.

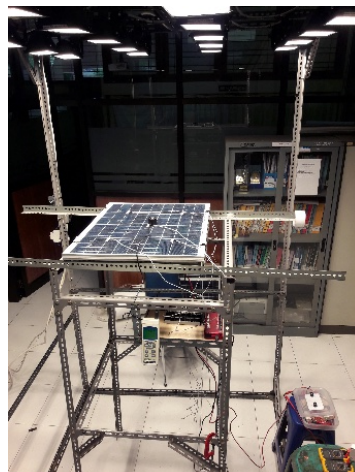


Figure 3. Experimental setup of the PV testing system equipped with sensors and electrical measuring devices.

3. Data Analysis

The collected data were analyzed to determine the electrical performance of the solar panel. The maximum power (P_{MPP}) was obtained from the highest power point on the I–V curve, while the fill factor (FF) was calculated from the ratio of P_{MPP} to the product of V_{oc} and I_{sc} . The energy conversion efficiency (η) was calculated by comparing the maximum power generated to the incident radiation power received by the panel. The results from the three configurations were then compared to assess the extent to which the addition of TiO_2 to PCM could enhance the effectiveness of passive cooling in PV modules.

The electrical performance was calculated from the I–V curve results using the following equation:

$$P_{MPP} = V_{MPP} \times I_{MPP} \quad (1)$$

$$FF = \frac{P_{MPP}}{V_{oc} \cdot I_{sc}} \quad (2)$$

$$\eta = \frac{P_{MPP}}{G \cdot A} \cdot 100 \% \quad (3)$$

Where P_{MPP} is the maximum power (W), V_{MPP} and I_{MPP} are the voltage and current at the maximum power point, V_{oc} is the open-circuit voltage (V), I_{sc} is the short-circuit current (A), G is the solar irradiance (W/m^2), and A is the active area of the panel (m^2).

The comparison was carried out among the three scenarios to evaluate the effect of using TiO_2 -based NePCM on reducing the operating temperature and enhancing the energy conversion efficiency of the PV module.

RESULT AND DISCUSSION

1. Temperature Profile of PV Panel

The surface temperature measurements of the PV panel showed a clear difference among the three cooling system variations. Under the condition without cooling, the panel temperature increased significantly with irradiation time. The use of pure PCM was able to reduce the temperature rise, while NePCM- TiO_2 provided a greater reduction compared to pure PCM.

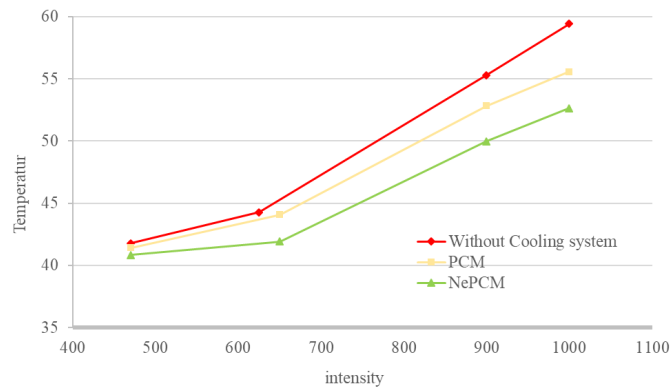


Figure 4. Temperature variation of the PV panel over time for the three test configurations..

From the graph, it can be observed that under $1000 W/m^2$ irradiance, the panel temperature without cooling reached approximately $59 ^\circ C$, while with pure PCM it was around $55\text{--}56 ^\circ C$. In contrast, the use of NePCM- TiO_2 successfully suppressed the panel temperature to about $51 ^\circ C$. This indicates that the addition of TiO_2 nanoparticles into PCM

effectively enhances the thermal conductivity of the material, thereby optimizing the heat storage and release process. Similar results were reported by *Alotaibi and Heliyon* (Alotaibi et al., 2022; Jenima et al., 2024), where the integration of nano-metal oxide particles into PCM significantly improved heat transfer and reduced the thermal load of PV panels.

These findings are consistent with previous studies reporting that the incorporation of nanoparticles into PCM can accelerate heat transfer rates, reduce internal temperature gradients, and improve the thermal stability of the system. The superior performance of NePCM-TiO₂ compared to pure PCM further confirms its potential as an effective additive in passive cooling systems for PV modules.

2. Electrical Characteristics of PV (I–V and P–V Curves)

The electrical performance of PV modules is directly affected by the cell operating temperature. As the temperature increases, the open-circuit voltage (V_{oc}) tends to decrease, which ultimately influences the maximum power output (P_{MPP}).

Figure 5 illustrates the effect of cooling variations on V_{oc}. The condition without cooling produced the lowest V_{oc} at all irradiance levels. The use of pure PCM provided an improvement in V_{oc}, while the NePCM-TiO₂ configuration showed the highest values, with more pronounced differences at higher light intensities. For instance, at 1000 W/m², NePCM-TiO₂ maintained V_{oc} at approximately 20.3 V, which was higher compared to pure PCM (20.15 V) and the condition without cooling (20.08 V). This confirms that the temperature reduction achieved by NePCM-TiO₂ effectively mitigates voltage degradation caused by overheating.

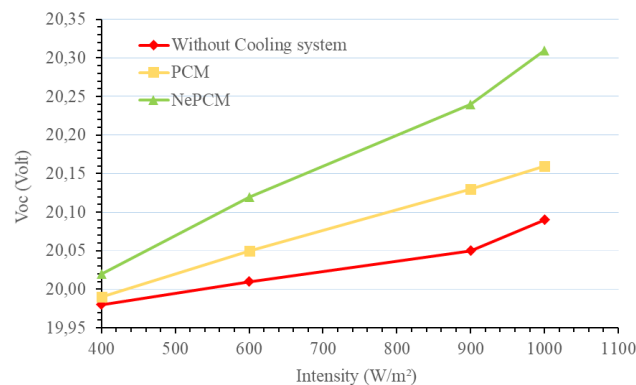


Figure 5. Open-circuit voltage (V_{oc}) of the PV module under different cooling configurations.

Meanwhile, Figure 6 presents the comparison of maximum power (P_{MPP}). It is clearly shown that the maximum power increases with higher irradiance; however, the highest values were consistently obtained under cooling conditions. At 470, 625, 900, and 1000 W/m², the panel without cooling generated only about 35 W, whereas the use of pure PCM increased the output to 42 W. The NePCM-TiO₂ configuration delivered the best performance, with P_{MPP} reaching approximately 46 W.

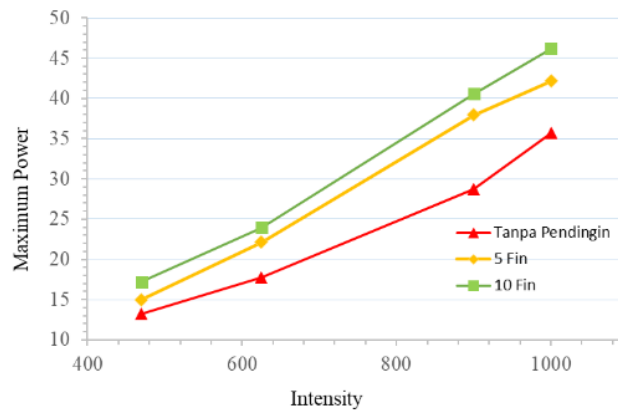


Figure 6. Maximum power output (PMPP) of the PV module under different cooling configurations.

These results demonstrate that the integration of TiO₂ into PCM not only helps to reduce the module temperature but also contributes to enhancing both voltage and power output. This effect is consistent with the fundamental mechanism of temperature influence on PV performance, where a reduction in cell temperature decreases carrier recombination, thereby maintaining Voc and PMPP at higher values.

3. Efficiency Improvement Analysis

The energy conversion efficiency of the PV module was calculated as the ratio between the maximum power output (PMPP) and the incident radiation power. Figure 7 shows the comparison of PV module efficiency under the three testing variations.

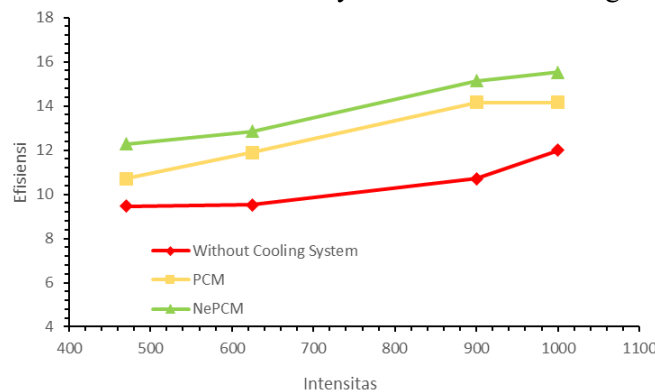


Figure 7 Efficiency of the PV module under conditions without cooling, with pure PCM, and with NePCM-TiO₂.

From the graph, it is evident that the panel without cooling exhibited the lowest efficiency across all irradiance levels. The use of pure PCM resulted in a noticeable improvement in efficiency, while the NePCM-TiO₂ configuration demonstrated the best performance. At 1000 W/m², the efficiency of the module without cooling was only about 12%, whereas with pure PCM it reached 14.2%, and with NePCM-TiO₂ it increased to 15.6%.

At the irradiance of 1000 W/m², the efficiency of the PV panel without cooling was only around 12%. The application of pure PCM improved the efficiency to 14.2%, while the use of NePCM-TiO₂ yielded the highest efficiency of 15.6%. Accordingly, there was an efficiency gain of 2.2% when using pure PCM compared to no cooling, and an

improvement of 3.6% when using NePCM-TiO₂. In direct comparison, NePCM-TiO₂ also provided an additional 1.4% improvement over pure PCM.

These improvements indicate that the reduction in module operating temperature directly contributes to enhanced electrical conversion performance. The addition of TiO₂ into PCM plays a role in improving the thermal conductivity of the material, allowing faster and more uniform heat transfer. As a result, the open-circuit voltage (Voc) can be maintained at higher levels, which ultimately increases PMPP and the overall system efficiency.

CONCLUSION

This study has demonstrated that the integration of titanium dioxide (TiO₂)-based nano-enhanced phase change material (NePCM) can improve both the thermal and electrical performance of photovoltaic modules. The experimental results showed that NePCM-TiO₂ consistently reduced the operating temperature of the panel compared to pure PCM and the module without cooling. This cooling effect contributed to the enhancement of open-circuit voltage (Voc), maximum power output (PMPP), and overall energy conversion efficiency.

At an irradiance of 1000 W/m², the use of pure PCM increased efficiency by approximately 2.2% compared to the condition without cooling, while NePCM-TiO₂ provided a greater improvement of 3.6%. In addition, NePCM-TiO₂ offered an extra gain of about 1.4% compared to pure PCM. These findings confirm the role of TiO₂ as an effective additive in improving the thermal conductivity of PCM, while simultaneously enhancing the stability of passive cooling performance in PV modules.

Overall, the results of this research reinforce the potential of TiO₂-based NePCM as a cost-effective and sustainable alternative material for passive cooling applications in solar panels. For future work, it is recommended to explore variations in TiO₂ concentration, combinations with other types of nanoparticles, and long-term field testing to evaluate the durability of the material under real operating conditions.

REFERENCES

- Adjiski, V., Kaplan, G., & Mijalkovski, S. (2023). Assessment of the Solar Energy Potential of Rooftops Using LiDAR Datasets and GIS Based Approach. *International Journal of Engineering and Geosciences*, 8(2), 188–199. <https://doi.org/10.26833/ijeg.1112274>
- Afif, F., & Martin, A. (2022). Tinjauan Potensi Dan Kebijakan Energi Surya Di Indonesia. *Jurnal Engine Energi Manufaktur Dan Material*, 6(1), 43. <https://doi.org/10.30588/jeemm.v6i1.997>
- Alktranee, M., & Bencs, P. (2023). Experimental comparative study on using different cooling techniques with photovoltaic modules. *Journal of Thermal Analysis and Calorimetry*, 148(9), 3805–3817. <https://doi.org/10.1007/s10973-022-11940-1>
- Alotaibi, M. R., Alsuhybani, M., Khayyat, M. M., & AlOtaibi, B. (2022). Performance of Nanocomposites of a Phase Change Material Formed by the Dispersion of MWCNT/TiO₂ for Thermal Energy Storage Applications. *Materials*, 15(9), 3063. <https://doi.org/10.3390/ma15093063>
- Bukar, A. M., Almerbati, A., Shuja, S. Z., & Zubair, S. M. (2025). Enhancing solar PV panel performance through active and passive cooling techniques: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 216, 115611. <https://doi.org/10.1016/j.rser.2025.115611>

- Hudişteanu, S. V., Cherecheş, N.-C., Ţurcanu, F.-E., Hudişteanu, I., & Romila, C. (2024). Impact of Temperature on the Efficiency of Monocrystalline and Polycrystalline Photovoltaic Panels: A Comprehensive Experimental Analysis for Sustainable Energy Solutions. *Sustainability*, *16*(23), 10566. <https://doi.org/10.3390/su162310566>
- Ibrahim, T., Akrouch, M. A., Hachem, F., Ramadan, M., Ramadan, H. S., & Khaled, M. (2024). Cooling Techniques for Enhanced Efficiency of Photovoltaic Panels—Comparative Analysis With Environmental and Economic Insights. *Energies*, *17*(3), 713. <https://doi.org/10.3390/en17030713>
- Jenima, J., Dharshini, M., Ajin, M., Moses, J. J., Priya, R. K., Arunachalam, K. P., Avudaiappan, S., & Muñoz, R. F. A. (2024). A Comprehensive Review of Titanium Dioxide Nanoparticles in Cementitious Composites. *Heliyon*, *10*(20), e39238. <https://doi.org/10.1016/j.heliyon.2024.e39238>
- Laksana, E. P., SANJAYA, O., SUJONO, S., BROTO, S., & FATH, N. (2022). Sistem Pendinginan Panel Surya Dengan Metode Penyemprotan Air Dan Pengontrolan Suhu Air Menggunakan Peltier. *Elkomika Jurnal Teknik Energi Elektrik Teknik Telekomunikasi & Teknik Elektronika*, *10*(3), 652. <https://doi.org/10.26760/elkomika.v10i3.652>
- Mebarek-Oudina, F., & Chabani, I. (2023). Review on Nano Enhanced PCMs: Insight on nePCM Application in Thermal Management/Storage Systems. *Energies*, *16*(3), 1066. <https://doi.org/10.3390/en16031066>
- Muhammad Fuad Abdul Hakim, O. N. (2025). *JIIF (Jurnal Ilmu dan Inovasi Fisika) EFFECT OF THERMOELECTRICS AS A COOLING SYSTEM ON PHOTOVOLTAIC EFFICIENCY AND ECONOMIC ANALYSIS*. *09*(01), 56–63.
- Pomares-Hernández, C., Zuluaga-García, E. A., Escorcia-Salas, G. E., Robles-Algarín, C., & Sierra-Ortega, J. (2021). Computational Modeling of Passive and Active Cooling Methods to Improve PV Panels Efficiency. *Applied Sciences*, *11*(23), 11370. <https://doi.org/10.3390/app112311370>
- Prayogi, S., Silviana, F., & Zainuddin, Z. (2023). Peningkatan Performa Sel Surya Dengan Sistem Peredam Panas. *Jambura Journal of Electrical and Electronics Engineering*, *5*(2), 143–147. <https://doi.org/10.37905/jjee.v5i2.18802>
- 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 (Ireme)*, *18*(1), 20. <https://doi.org/10.15866/ireme.v18i1.24149>
- Unnikrishnan, K. S., & Rohinikumar, B. (2022). Thermal Management of Photovoltaic Panel With Nano-Enhanced Phase Change Material at Different Inclinations. *Environmental Science and Pollution Research*, *29*(23), 34759–34775. <https://doi.org/10.1007/s11356-021-18075-0>