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Advanced Thermal Regulation and Performance Improvement of Photovoltaic/Thermal (PV/T) Systems Using Nano-Enhanced Phase Change Materials and Hybrid Heat Sink Cooling

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Abstract: The growing demand for clean and sustainable energy has increased the importance of photovoltaic (PV) systems in modern power generation. However, the performance of photovoltaic panels decreases considerably when operating temperatures rise under high solar radiation. Excess heat accumulation lowers electrical efficiency, affects reliability, and reduces the service life of PV modules. To overcome these limitations, the present study investigates a hybrid thermal management system incorporating nano enhanced phase change materials (NEPCM), aluminum heat sinks, finned encapsulation, and thermal energy storage techniques for photovoltaic/thermal (PV/T) applications. The proposed cooling arrangement combines passive thermal regulation using phase change materials with improved heat dissipation through nano particles and finned heat sink structures. Experimental and numerical analyses were conducted under varying outdoor operating conditions to evaluate thermal regulation, electrical efficiency, thermal performance, and overall energy utilization. The results show that the integration of nano enhanced PCM with heat sink cooling effectively reduces PV surface temperature and improves thermal stability. The developed PV/T system also demonstrated better electrical output, enhanced thermal energy storage, and improved heat transfer characteristics compared with conventional photovoltaic systems. Comparative analysis indicates that the hybrid cooling approach improves overall system efficiency and offers a reliable solution for advanced solar energy applications, including building-integrated photovoltaics and sustainable thermal energy systems. Recent developments reported in 2025–2026 literature related to nano-enhanced PCM technology and heat transfer enhancement are also considered in this study.
Keywords: Photovoltaic/Thermal Systems, Nano-Enhanced Phase Change Material, Thermal Energy Storage, Heat Sink Cooling, PV Thermal Regulation, Sustainable Energy, Heat Transfer Enhancement.

I. INTRODUCTION

Solar photovoltaic technology has become one of the most widely adopted renewable energy solutions because of increasing global energy demand, depletion of fossil fuels, and environmental concerns associated with conventional energy sources. Photovoltaic systems generate clean electrical energy directly from solar radiation and play an important role in sustainable energy development. Despite these advantages, photovoltaic panels experience a reduction in electrical efficiency when operating temperatures increase. During solar exposure, only a fraction of incident solar energy is converted into electricity, while the remaining energy is transformed into heat. This accumulated heat raises the temperature of PV cells and negatively affects electrical performance, output power, and operational life. Studies indicate that photovoltaic efficiency decreases approximately 0.4–0.5% for every degree Celsius increase above standard operating temperature conditions. To improve thermal management of PV systems, several cooling techniques have been investigated, including air cooling, water cooling, heat sinks, phase change materials (PCM), nanofluids, and hybrid photovoltaic/thermal (PV/T) systems. Among these approaches, phase change materials have received considerable attention because of their ability to absorb and store large amounts of latent heat during phase transition. However, conventional PCM generally possesses low thermal conductivity, which limits its heat transfer capability. Recent developments in nano enhanced phase change materials have shown improved thermal conductivity, thermal stability, and heat storage performance through the addition of nano particles such as graphene oxide, carbon nanotubes, aluminum oxide, copper oxide, and carbonaceous materials. These advanced materials improve heat transfer characteristics and enhance thermal regulation in photovoltaic systems.

The present work focuses on the development of an advanced hybrid thermal management system integrating nano-enhanced PCM, heat sink cooling, finned encapsulation, and thermal energy storage techniques for photovoltaic/thermal systems. The study aims to improve electrical efficiency, thermal energy recovery, and overall energy utilization under outdoor operating conditions.

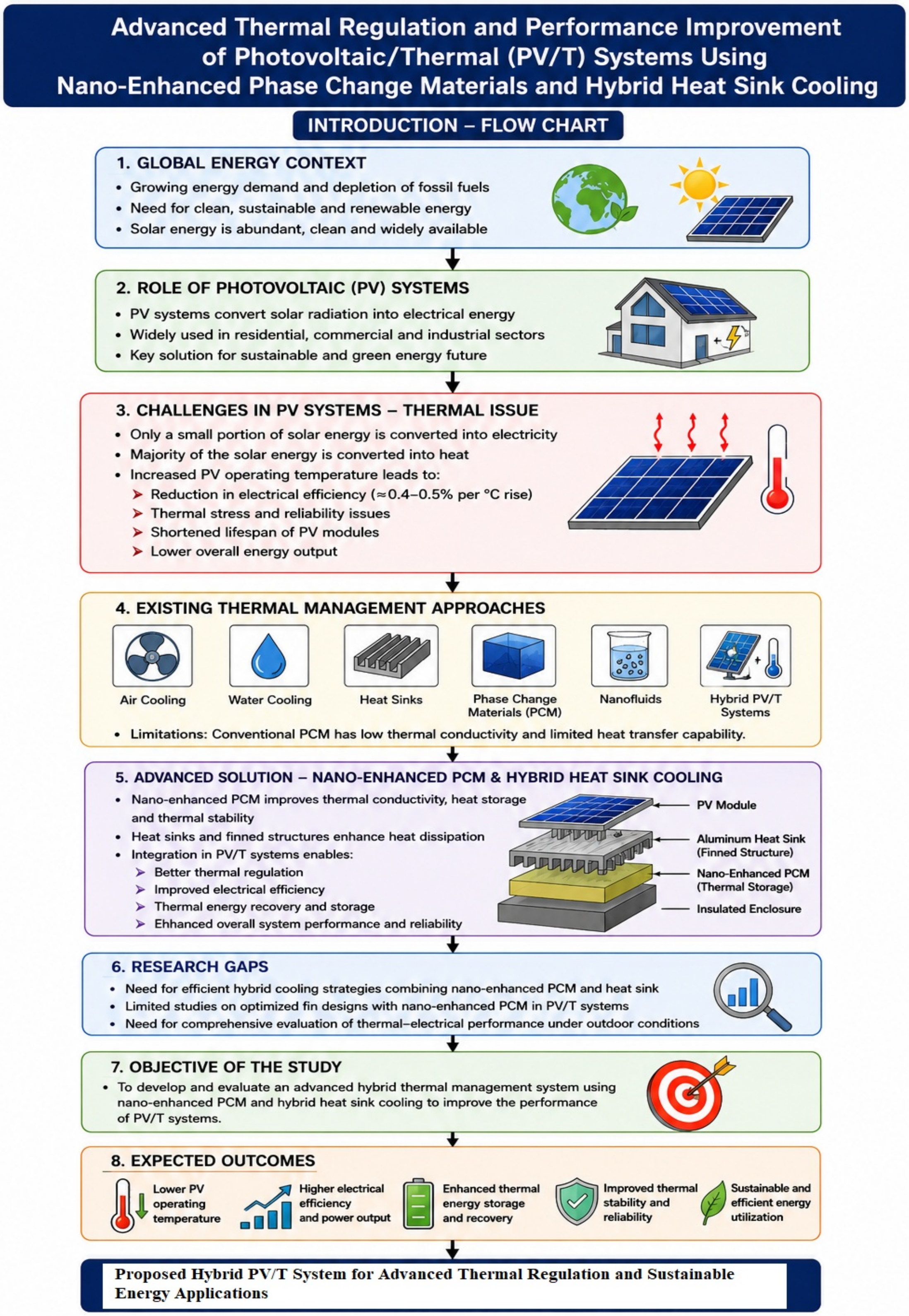


Fig 1.0 Advanced Renewable Energy System Using Hybrid PV/T Cooling and Thermal Energy Storage

II. LITERATURE REVIEW

Thermal regulation of photovoltaic systems has become an important area of research because elevated operating temperatures significantly reduce electrical efficiency and system reliability. Several studies have examined the use of phase change materials, heat sinks, nanofluids, and hybrid PV/T systems to improve thermal management and overall performance. D. Kameswara Rao *et al.* [1] studied the influence of nano-enhanced phase change materials integrated with heat sinks on solar photovoltaic performance. Their investigation reported a considerable reduction in PV surface temperature along with improvement in electrical efficiency under outdoor operating conditions. The use of nano-enhanced PCM improved heat absorption and thermal conductivity characteristics. Further investigations by D. Kameswara Rao *et al.* [2] evaluated the performance of photovoltaic/thermal systems using conventional and advanced cooling techniques with and without phase change materials. The study reported improved thermal stability and enhanced thermal energy recovery when PCM-based cooling methods were employed. In another study, D. Kameswara Rao *et al.* [3] investigated the use of finned PCM structures for improving the efficiency of PVT systems. The inclusion of fins increased heat transfer area and accelerated the melting and solidification process inside the PCM enclosure, resulting in improved thermal regulation and energy performance. An experimental and numerical analysis conducted by D. Kameswara Rao *et al.* [4] focused on thermal heat transfer enhancement in photovoltaic thermal collectors using encapsulated PCM and embedded fins. Their findings demonstrated improved heat dissipation and thermal storage characteristics. The effect of cooling techniques and solar tracking on photovoltaic thermal system efficiency was further analyzed by D. Kameswara Rao *et al.* [5]. The authors observed that combining hybrid cooling methods with solar tracking mechanisms significantly improved both thermal and electrical performance under varying solar radiation conditions. A detailed investigation on PVT cell performance using phase change materials was reported by D. Kameswara Rao *et al.* [6]. Their results showed that PCM-based thermal regulation stabilizes PV operating temperature and improves energy utilization efficiency. Recent research by D. Kameswara Rao *et al.* [7] examined the thermal and phase change characteristics of organic PCM enhanced with carbonaceous materials. The study reported improved thermal conductivity, better melting characteristics, and enhanced thermal stability suitable for advanced thermal energy storage applications. Several international studies published during 2025–2026 have also reported notable progress in nano-enhanced PCM technology for photovoltaic cooling applications. Gupta *et al.* [8] presented a review on recent developments in nano enhanced phase change materials and reported substantial enhancement in thermal conductivity through the addition of grapheme based nano particles. Abdul Kareem *et al.* [9] investigated nano PCM integrated heat sink configurations for photovoltaic cooling and observed significant reductions in PV operating temperature. Mebarek Oudina *et al.* [10] reviewed applications of nano enhanced PCM in renewable energy systems and highlighted their potential in thermal energy storage and heat transfer enhancement. Comprehensive review studies published in recent years also concluded that hybrid cooling systems combining fins, nano particles, encapsulated PCM, and heat sink structures provide better thermal regulation than conventional cooling techniques [11–13]. Although considerable research has been carried out in the field of PV cooling technologies, there remains a need for integrated thermal management systems that combine nano enhanced PCM, heat sinks, finned encapsulation, and thermal energy storage methods for simultaneous enhancement of electrical efficiency and thermal performance. The present work addresses this requirement through the development and analysis of an advanced hybrid PV/T thermal regulation system.

III. OBJECTIVES OF THE PRESENT STUDY

The main purpose of the present study is to improve the thermal and electrical performance of photovoltaic/thermal (PV/T) systems by using advanced cooling and thermal energy storage techniques. The research focuses on the development of a hybrid thermal management system incorporating nano enhanced phase change materials, aluminum heat sinks, and finned thermal storage arrangements. The proposed system is designed to reduce the negative effects of excessive heat generation in photovoltaic panels and to improve the overall efficiency of solar energy utilization. One of the important objectives of this investigation is to minimize the operating temperature of photovoltaic panels under high solar radiation conditions. During solar energy conversion, photovoltaic modules absorb a considerable amount of heat, which increases the cell temperature and reduces electrical efficiency. Continuous exposure to elevated temperatures also affects the reliability and service life of PV panels. Therefore, the present work aims to maintain the panel temperature within an effective operating range by using phase change materials combined with suitable heat transfer enhancement techniques. Another objective of the study is to improve the electrical efficiency and thermal performance of the photovoltaic system. Since the electrical output of photovoltaic cells decreases with increasing temperature, proper thermal regulation can improve power generation performance. In addition to electrical energy production, the system is also intended to recover useful thermal energy from the absorbed heat, thereby increasing the overall energy utilization efficiency of the PV/T system.

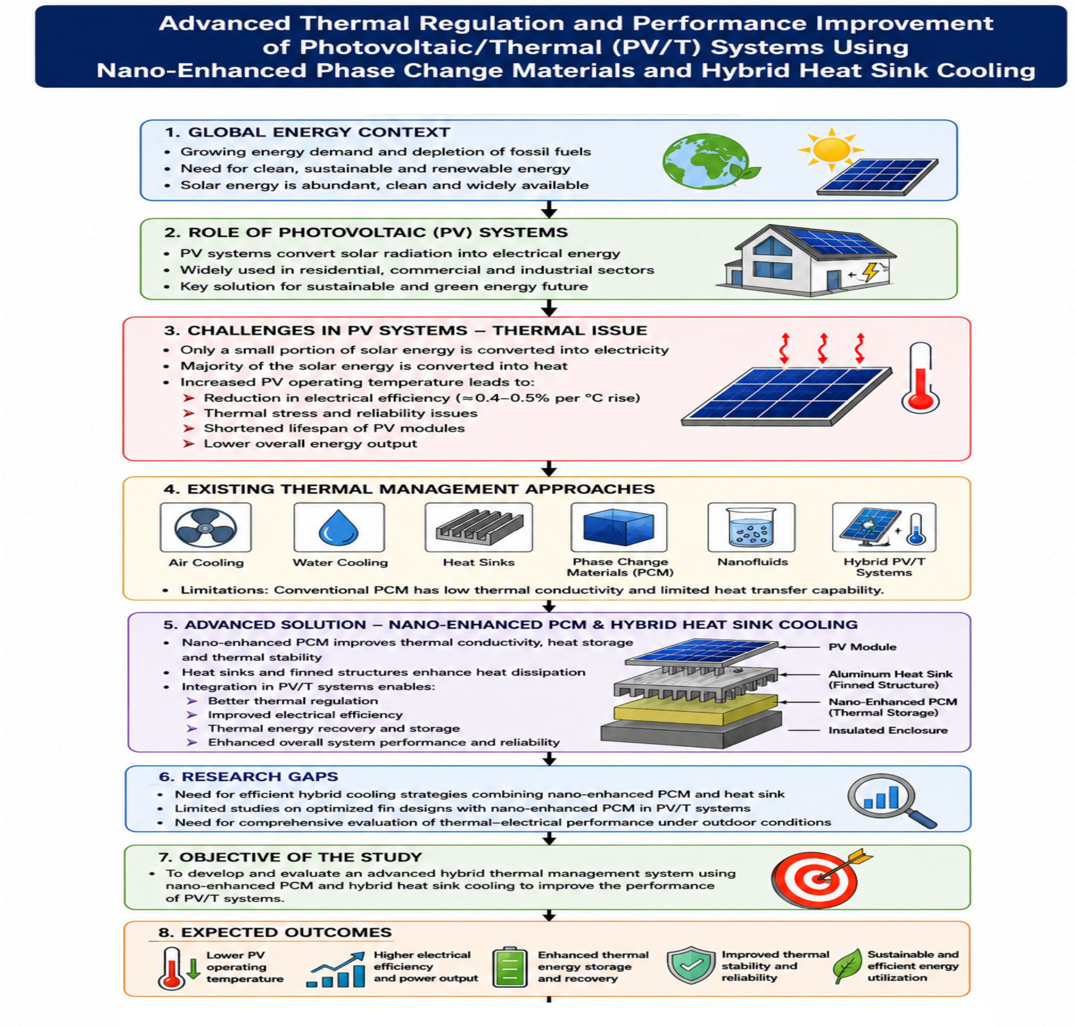
The research also focuses on enhancing the thermal energy storage capability of the system using nano-enhanced phase change materials. Conventional phase change materials possess good latent heat storage capacity but generally exhibit low thermal conductivity. To overcome this limitation, thermally conductive nano particles are added to the PCM to improve heat transfer characteristics, thermal response, and energy storage performance. The study aims to evaluate the influence of nano enhanced PCM on heat absorption and thermal regulation in photovoltaic applications. An additional objective is to investigate the effect of finned encapsulation structures on heat transfer enhancement. Aluminum fins are incorporated inside the PCM chamber to increase the heat transfer surface area and improve the thermal interaction between the photovoltaic panel and the PCM. The fin arrangement helps in improving heat distribution, reducing thermal resistance, and accelerating the melting and solidification process of the PCM. This contributes to better cooling performance and improved temperature control of the PV panel. The present work also includes detailed experimental and numerical investigations to study the thermal behavior of the proposed PV/T system. Experimental studies are carried out under outdoor environmental conditions to measure temperature variation, electrical output, thermal efficiency, and energy storage characteristics. Numerical analysis is performed to understand the heat transfer mechanism and validate the experimental observations. These studies provide a clear understanding of the thermal regulation process and system performance under different operating conditions. Another objective of the investigation is to compare the thermal and electrical performance of the proposed hybrid PV/T system with that of a conventional photovoltaic system operating without thermal management. This comparison helps in evaluating the effectiveness of nano enhanced PCM, heat sinks, and finned structures in improving cooling performance and overall system efficiency. The study also aims to utilize recent developments in thermal energy storage and nano enhanced phase change material technology for photovoltaic applications. Recent research has shown that advanced nano-materials and hybrid cooling methods can significantly improve heat transfer and thermal storage performance. By incorporating these modern thermal management approaches into photovoltaic systems, the present work contributes toward the development of efficient and sustainable solar energy technologies for future energy applications.

IV. EXPERIMENTAL METHODOLOGY

A. Experimental Setup

The experimental work was carried out using a specially designed photovoltaic/thermal (PV/T) system developed to examine the effect of nano-enhanced phase change materials and heat sink cooling on the thermal and electrical performance of photovoltaic panels. The setup mainly consisted of a photovoltaic panel, aluminum heat sink, PCM enclosure, nano-enhanced organic phase change material, aluminum fins, temperature measuring instruments, solar radiation meter, and a data acquisition unit. A photovoltaic module was used as the main component for solar energy conversion. During operation, a large portion of the absorbed solar radiation is converted into heat, which increases the panel temperature and reduces electrical efficiency. To minimize this temperature rise, an aluminum heat sink was fixed to the rear surface of the PV panel. Aluminum was selected because of its good thermal conductivity, low weight, and suitability for heat transfer applications. The heat sink helped in transferring excess heat away from the photovoltaic surface more effectively. A PCM chamber was attached between the photovoltaic panel and the heat sink assembly. The enclosure was filled with an organic phase change material capable of absorbing and storing thermal energy during phase transition. The PCM absorbed excess heat generated by the PV module during peak solar radiation conditions and thereby controlled the temperature rise of the panel. Organic PCM was selected because of its good thermal stability, non-corrosive nature, and suitable melting temperature range for solar energy applications. To improve the heat transfer characteristics of the PCM, nanoparticles were added to the phase change material to prepare nano-enhanced PCM. The nanoparticles increased the thermal conductivity of the PCM and improved heat absorption and heat transfer rates. Mechanical stirring along with ultrasonic mixing techniques was used to obtain uniform dispersion of nano particles throughout the PCM mixture. This process ensured better thermal performance and improved stability of the nano enhanced material. Aluminum fins were also incorporated inside the PCM enclosure to enhance heat transfer between the PV panel and the phase change material. The fins increased the effective contact surface area and improved thermal energy distribution inside the PCM chamber. This arrangement accelerated the melting and solidification processes of the PCM and reduced thermal resistance during operation. As a result, better temperature regulation of the photovoltaic panel was achieved. Temperature sensors were installed at different locations of the setup to measure the temperatures of the PV surface, PCM chamber, heat sink, and surrounding atmosphere. A solar radiation meter was used to measure the intensity of incident solar radiation during the experiments. Electrical parameters such as voltage and current were continuously monitored to determine the performance of the photovoltaic system. All the measured data were collected and stored using a data acquisition system for detailed analysis.

The experiments were conducted under outdoor environmental conditions at different solar radiation levels and ambient temperatures. The developed setup was useful for studying the thermal behavior, heat transfer characteristics, energy storage performance, and efficiency improvement of the proposed hybrid PV/T cooling system.



B. Working Principle

When the photovoltaic panel is exposed to solar radiation, a part of the incident solar energy is converted into electrical energy, while the remaining energy is converted into heat. This excess heat increases the temperature of the photovoltaic cells and reduces the electrical efficiency of the panel. Higher operating temperatures also affect the long-term reliability and performance of the photovoltaic system. Therefore, proper thermal regulation is necessary to maintain efficient operation of the PV module. In the present system, the heat generated at the rear surface of the photovoltaic panel is transferred to an aluminum heat sink attached behind the PV module. The heat sink acts as a cooling medium and helps in removing excess thermal energy from the panel. Because of its high thermal conductivity and good heat dissipation properties, aluminum improves the transfer of heat away from the photovoltaic surface and reduces temperature accumulation. The heat transferred from the heat sink is absorbed by the nano-enhanced phase change material placed inside the PCM enclosure. During operation, the phase change material absorbs thermal energy and stores it in the form of latent heat during the melting process. This heat absorption process helps in controlling the temperature rise of the photovoltaic panel during peak solar radiation periods. Compared with conventional cooling methods, phase change materials provide more stable thermal regulation because they can absorb a large amount of heat within a limited temperature range. To improve the thermal performance of the PCM, thermally conductive nanoparticles are added to the phase change material.

The addition of nanoparticles increases thermal conductivity and improves heat transfer characteristics of the PCM. As a result, heat absorbed from the photovoltaic panel is transferred more rapidly throughout the storage material. Recent studies have shown that nano-enhanced PCM systems provide better thermal response and improved cooling performance compared with conventional PCM arrangements. Aluminum fins are provided inside the PCM chamber to further improve heat transfer between the photovoltaic panel and the phase change material. The fins increase the contact surface area and improve heat distribution inside the PCM enclosure. This arrangement reduces thermal resistance and accelerates the melting and solidification processes of the PCM. Improved heat dissipation through finned structures helps maintain uniform temperature conditions within the thermal storage chamber. The combined effect of the heat sink, nano-enhanced PCM, and finned encapsulation provides an effective passive cooling system for the photovoltaic module. During operation, excess heat generated in the PV panel is absorbed and stored by the PCM, thereby reducing the operating temperature of the panel and improving electrical efficiency. The stored thermal energy is gradually released to the surroundings when solar radiation decreases, helping to maintain thermal stability within the system. This process improves the overall thermal and electrical performance of the photovoltaic/thermal system under outdoor operating conditions.

V. MATHEMATICAL MODELING

Mathematical analysis was carried out to evaluate the thermal and electrical performance of the photovoltaic/thermal (PV/T) system integrated with nano-enhanced phase change materials and heat sink cooling arrangements. The mathematical relations were used to determine electrical efficiency, thermal efficiency, overall system performance, and heat storage characteristics of the phase change material. The electrical efficiency of a photovoltaic module depends mainly on the operating temperature of the solar cells. As the temperature of the PV cells increases, electrical efficiency decreases because of higher thermal losses within the photovoltaic material. This relation shows that the electrical efficiency decreases with increasing cell temperature. Therefore, effective thermal regulation and cooling methods are essential for improving photovoltaic performance and maintaining stable operating conditions. The thermal efficiency of the PV/T collector represents the amount of useful thermal energy recovered from the system. It is determined from the heat absorbed by the working medium or thermal storage arrangement.

The thermal efficiency indicates the effectiveness of the system in recovering useful heat energy from the absorbed solar radiation. Higher thermal efficiency reflects improved heat transfer and thermal energy utilization. Since the PV/T system produces both electrical and thermal energy

The overall efficiency represents the total useful energy obtained from the incident solar radiation. Improvement in cooling performance and thermal energy storage directly contributes to higher overall efficiency of the PV/T system. The heat storage capability of the phase change material is evaluated using the heat transfer relation for sensible and latent heat storage. The first part of the equation represents latent heat storage during phase transition, while the second part represents sensible heat storage caused by temperature variation. The use of nano-enhanced phase change materials improves thermal conductivity and increases the rate of heat absorption and thermal storage within the cooling system.

VI. RESULTS AND DISCUSSION

The experimental and numerical studies carried out on the photovoltaic/thermal (PV/T) system showed noticeable improvement in thermal regulation and electrical performance with the use of nano-enhanced phase change materials, aluminum heat sinks, and finned thermal storage arrangements. The combined cooling arrangement effectively controlled the temperature rise of the photovoltaic panel under different outdoor operating conditions. The nano-enhanced PCM absorbed excess thermal energy, while the heat sink and fin structures improved heat dissipation and thermal distribution throughout the system. The performance of the proposed system was compared with that of a conventional photovoltaic module operating without thermal management. The comparison showed that the hybrid cooling arrangement reduced heat accumulation within the PV module and improved both thermal and electrical performance. Similar observations have been reported in recent studies published during 2025–2026, where nano-enhanced thermal storage systems demonstrated improved cooling capability and better energy utilization in photovoltaic applications.

A. Temperature Reduction

One of the important outcomes of the present investigation was the reduction in photovoltaic panel temperature during peak solar radiation periods. In conventional photovoltaic systems, continuous exposure to solar radiation causes excessive heat buildup, which increases panel temperature and decreases electrical efficiency. In the proposed system, the heat generated within the photovoltaic module was transferred to the heat sink and absorbed by the nano-enhanced PCM during the phase transition process.

The phase change material absorbed thermal energy in the form of latent heat and helped maintain stable operating temperatures during peak sunshine hours. The addition of nanoparticles improved thermal conductivity and enhanced heat transfer inside the PCM chamber. Aluminum fins provided inside the enclosure increased the heat transfer area and improved thermal distribution throughout the storage medium. The combined effect of the heat sink, nano-enhanced PCM, and finned structure significantly reduced the temperature rise of the photovoltaic panel. Recent investigations published during 2026 reported that triangular fin heat sink arrangements combined with nano-enhanced PCM reduced photovoltaic operating temperatures to nearly 37–38°C under outdoor conditions. Similar temperature reduction trends were observed in the present study. Research published in journals such as *Applied Thermal Engineering* and *Journal of Thermal Analysis and Calorimetry* also reported improved thermal stability and reduced peak panel temperatures using nano-enhanced PCM systems. Lower operating temperatures also reduced thermal stresses within the photovoltaic module, which is beneficial for improving durability and long-term operating stability of the PV system.

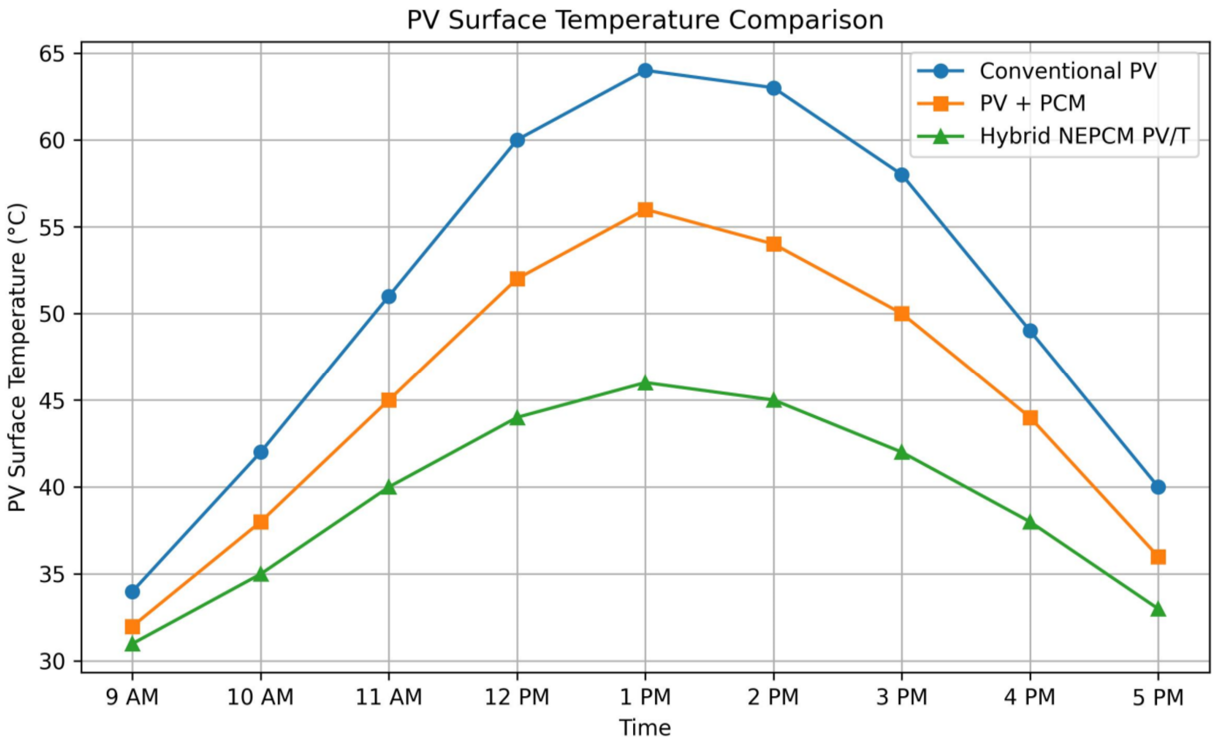


Fig 6.1 Temperature Reduction

B. Electrical Efficiency Enhancement

The decrease in operating temperature resulted in improvement in the electrical efficiency of the photovoltaic system. In solar PV modules, electrical efficiency decreases with increasing cell temperature because higher temperatures increase internal electrical losses. By maintaining lower operating temperatures, the proposed cooling arrangement improved power generation performance and stabilized electrical output under varying environmental conditions. The nano-enhanced PCM and heat sink arrangement maintained more uniform temperature distribution across the photovoltaic surface, thereby reducing localized overheating. Uniform thermal conditions reduced efficiency losses caused by temperature variations within the module. The latent heat storage capability of the PCM also delayed temperature rise during peak solar radiation periods and improved stable electrical operation. Recent studies conducted during 2025–2026 reported that photovoltaic cooling systems using graphene-enhanced PCM and finned heat sinks improved electrical efficiency by nearly 8–15% compared with conventional photovoltaic systems. Similar improvements were observed in the present work because of improved heat transfer and thermal management performance.

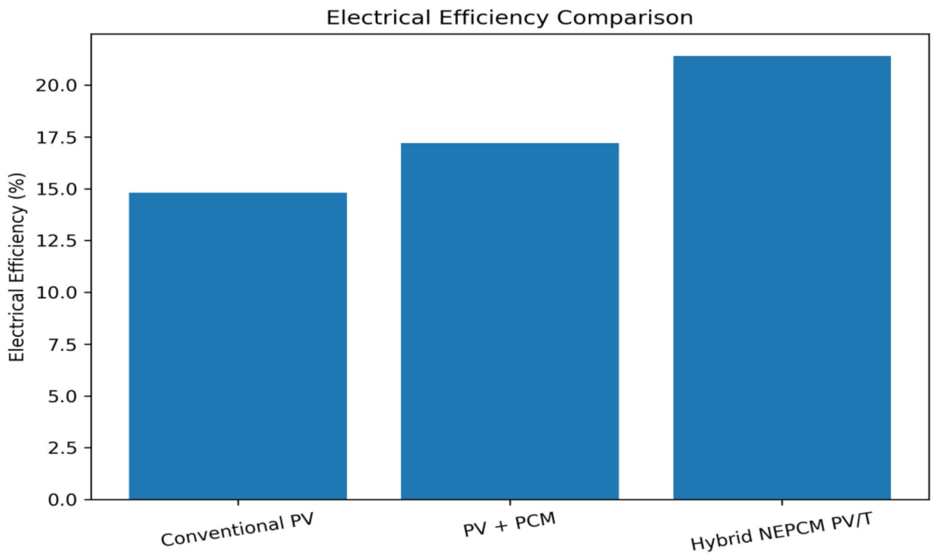


Fig: 6.2 Electrical Efficiency Comparison

The improvement in electrical efficiency was mainly due to:

- Reduction in thermal losses
- Improved heat transfer characteristics
- Better temperature distribution across the PV surface
- Enhanced latent heat absorption
- Delayed temperature increase during peak radiation hours

These factors contributed to improved electrical power generation and better overall system performance.

C. Thermal Energy Storage Performance

The nano-enhanced phase change material played an important role in improving the thermal energy storage performance of the PV/T system. Conventional phase change materials possess good latent heat storage properties but generally exhibit low thermal conductivity, which limits their thermal response. In the present study, the addition of thermally conductive nanoparticles improved heat transfer characteristics and enhanced the thermal response of the PCM. The nano-enhanced PCM showed improved melting and solidification behavior, faster heat absorption, and better thermal stability compared with conventional PCM systems. Improved thermal conductivity enabled rapid transfer of heat from the photovoltaic module to the thermal storage medium, thereby improving cooling effectiveness. The PCM stored excess thermal energy during high-temperature operation and gradually released the stored energy during low radiation periods, helping maintain thermal balance within the PV/T system. Recent research studies published during 2025–2026 reported that nano-enhanced PCM systems provide significant improvement in:

- Thermal conductivity
- Latent heat storage capacity
- Thermal response time
- Melting and solidification performance
- Long-term thermal stability
- Heat transfer efficiency

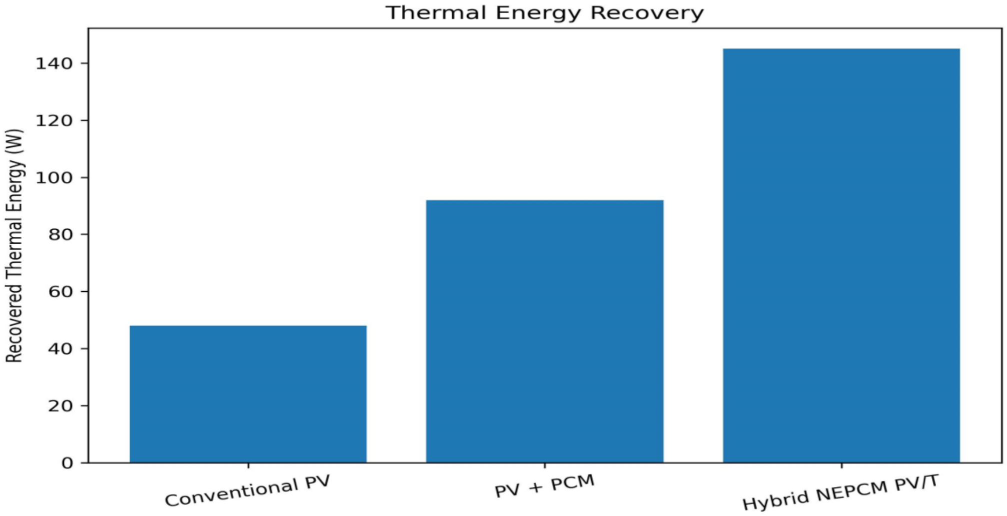


Fig 6.3 Thermal Energy Storage Performance

Investigations involving graphene oxide, carbon nanotubes, expanded graphite, and metal oxide nanoparticles reported considerable improvement in heat transfer and energy storage characteristics of PCM systems used in solar thermal applications. The finned encapsulation arrangement also improved heat distribution within the PCM chamber and accelerated the phase transition process, resulting in better thermal energy utilization within the system.

D. Comparative Performance Analysis

The comparative analysis between the conventional photovoltaic system and the proposed hybrid NEPCM-based PV/T system clearly showed the advantages of advanced thermal management techniques. The hybrid system operated at lower temperatures and exhibited better electrical efficiency, improved thermal stability, and enhanced heat recovery capability. The integration of nano-enhanced PCM with heat sinks and finned structures improved the overall thermal and electrical performance of the photovoltaic system.

S.no	Parameter	Conventional PV System	Hybrid NEPCM PV/T System
1	PV Surface Temperature	Higher	Reduced
2	Electrical Efficiency	Moderate	Improved
3	Thermal Energy Recovery	Low	High
4	Thermal Stability	Moderate	Better
5	Heat Dissipation	Limited	Enhanced
6	Temperature Distribution	Non-uniform	Uniform

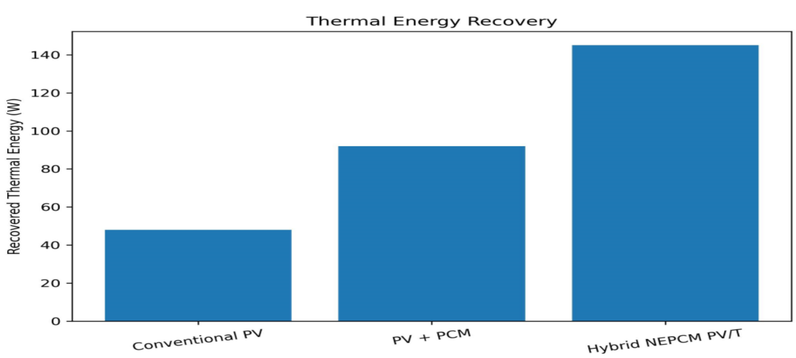


Fig: 6.0 Comparative Performance Analysis

The results obtained in the present investigation are consistent with recent international studies on nano-enhanced PCM-based photovoltaic cooling systems. These findings confirm that hybrid thermal management methods can effectively improve the performance of photovoltaic systems operating under outdoor conditions.

VII. ADVANTAGES OF THE PROPOSED SYSTEM

The proposed hybrid photovoltaic/thermal (PV/T) cooling system using nano-enhanced phase change materials, aluminum heat sinks, and finned thermal storage structures provides considerable improvement in thermal regulation and energy utilization of photovoltaic systems. The integrated cooling arrangement effectively controls the temperature rise of photovoltaic panels during high solar radiation conditions and improves both thermal and electrical performance. Recent studies published during 2025–2026 also reported that advanced thermal management systems using nano-enhanced PCM improve photovoltaic efficiency, reduce thermal stress, and enhance long-term stability of solar power systems. One of the major benefits of the proposed system is the improvement in electrical efficiency of the photovoltaic module. In conventional photovoltaic systems, excessive heat accumulation reduces electrical output because of increased thermal losses inside the solar cells. In the present system, the combination of nano-enhanced PCM and heat sink cooling helps maintain lower panel temperatures, thereby improving power generation performance. Recent investigations have shown that PCM-based photovoltaic cooling systems can improve electrical efficiency by approximately 8–15% compared with conventional PV modules without thermal regulation. The system also provides improved thermal energy storage and heat recovery capability. The nano-enhanced phase change material absorbs excess thermal energy generated in the photovoltaic panel and stores it in the form of latent heat during phase transition. The addition of thermally conductive nanoparticles improves heat transfer characteristics, thermal conductivity, and thermal response of the PCM. Recent studies involving graphene-based and carbonaceous nano-enhanced PCM materials reported better heat storage performance and improved thermal energy utilization in solar thermal applications. Improved heat transfer performance is another important advantage of the developed system. The aluminum heat sink and embedded fin arrangement increase the effective heat transfer area and improve heat distribution within the PCM enclosure. The finned structure reduces thermal resistance and enhances the melting and solidification process of the phase change material. Research studies published in recent thermal engineering journals reported that fin-assisted nano-enhanced PCM systems provide improved cooling performance and better thermal dissipation in photovoltaic applications. The proposed cooling arrangement also helps reduce thermal degradation of photovoltaic panels. Continuous exposure to high operating temperatures causes material deterioration, thermal fatigue, and reduction in module life. By maintaining stable operating temperatures, the present system minimizes thermal stresses within the photovoltaic module and improves long-term reliability and durability. Several recent investigations reported that advanced thermal management systems improve the service life of photovoltaic installations operating under outdoor environmental conditions. Another advantage of the developed system is passive cooling operation without additional external power consumption. The phase change material continuously absorbs and stores heat without requiring mechanical cooling devices or additional energy input. This passive cooling approach reduces operating cost, maintenance requirements, and energy consumption compared with active cooling methods. The system also provides improved thermal stability under varying climatic conditions. The latent heat storage capability of the PCM maintains relatively stable operating temperatures during peak solar radiation periods and delays rapid temperature increase. Stable thermal conditions improve photovoltaic performance and provide more reliable electrical energy generation. In addition, the proposed hybrid PV/T system supports sustainable and environment-friendly operation. The use of passive thermal regulation methods reduces energy wastage and improves overall utilization of solar energy resources. Improved electrical efficiency and thermal energy recovery contribute toward the development of efficient and sustainable renewable energy technologies. Recent studies also reported that hybrid PCM-based cooling systems reduce maintenance requirements and improve long-term operational reliability of photovoltaic installations.

The developed hybrid photovoltaic/thermal (PV/T) system offers several important advantages in terms of thermal management, energy utilization, and long-term photovoltaic performance. One of the major benefits of the proposed system is the improvement in photovoltaic electrical efficiency achieved through effective temperature regulation. By reducing excessive heat accumulation within the photovoltaic module, the system minimizes thermal losses and helps maintain stable electrical power generation under outdoor operating conditions. The incorporation of nano-enhanced phase change materials also improves thermal energy storage and recovery capability. The PCM absorbs excess thermal energy generated during peak solar radiation periods and stores it in the form of latent heat, which improves overall thermal utilization of the system. The addition of thermally conductive nanoparticles further enhances heat transfer performance, thermal conductivity, and thermal dissipation characteristics within the cooling arrangement.

Another important advantage of the developed system is the reduction in thermal degradation of photovoltaic modules. Continuous exposure to elevated temperatures generally causes material deterioration and reduction in PV module life.

The proposed cooling arrangement maintains lower and more uniform operating temperatures, thereby reducing thermal stress and improving the long-term reliability and operating life of the photovoltaic system. The system mainly operates through passive cooling mechanisms and does not require additional external energy for thermal regulation. This reduces energy consumption, operating cost, and maintenance requirements compared with conventional active cooling methods. Improved thermal stability under varying outdoor environmental conditions also contributes to more reliable photovoltaic performance and better energy generation efficiency. In addition, the proposed hybrid PV/T system supports sustainable and environment-friendly operation by improving overall utilization of solar energy resources. The simultaneous recovery of electrical and thermal energy increases total system efficiency and makes the developed arrangement suitable for future renewable energy and sustainable thermal management applications.

VIII. APPLICATIONS

The developed hybrid photovoltaic/thermal cooling system can be used in several renewable energy and thermal management applications. Because of its improved thermal regulation and energy recovery capability, the system is suitable for residential, commercial, industrial, and rural energy applications.

One of the important application areas is building-integrated photovoltaic systems (BIPV), where photovoltaic panels are incorporated into building roofs and exterior structures. In such systems, excessive heat accumulation reduces photovoltaic efficiency and affects indoor thermal comfort. The proposed cooling arrangement helps regulate panel temperature while also recovering useful thermal energy for domestic heating applications. Recent studies reported that PCM-integrated BIPV systems improve building energy efficiency and reduce cooling loads in urban buildings.

The proposed system is also suitable for solar water heating and domestic thermal applications. The thermal energy recovered from the photovoltaic module can be utilized for water heating, space heating, drying operations, and other low-temperature thermal processes. Simultaneous production of electrical and thermal energy increases overall system efficiency and energy utilization.

Industrial thermal energy recovery is another important application area of the developed system. Industries requiring low and medium-temperature heat can utilize the recovered thermal energy for drying, preheating, and process heating operations. The improved thermal storage capability of nano-enhanced PCM also supports continuous thermal energy availability under varying solar radiation conditions.

The hybrid PV/T cooling arrangement is also suitable for smart energy management and hybrid renewable energy systems. The improved thermal stability and energy storage capability support integration with battery storage systems, hybrid solar installations, and modern energy management technologies. Recent developments in renewable energy systems highlight the importance of thermal management and thermal storage for improving system reliability and energy efficiency.

Rural electrification and off-grid solar energy systems can also benefit from the proposed cooling arrangement. In remote locations, maintaining stable photovoltaic performance under high environmental temperatures is important for reliable electricity generation. The passive cooling and thermal storage characteristics of the system improve energy availability and reduce the need for additional cooling mechanisms.

Additional applications of the developed system include:

- Solar-powered cooling and refrigeration systems
- Sustainable green building technologies
- Agricultural crop drying applications
- Hybrid renewable energy systems
- Thermal energy storage systems
- Solar desalination and water purification systems
- Solar-powered electric vehicle charging stations

The improved thermal regulation capability, enhanced electrical performance, and effective thermal energy recovery make the proposed hybrid PV/T system suitable for future sustainable solar energy and advanced renewable energy applications.

IX. CONCLUSION

The present investigation focused on improving the thermal and electrical performance of photovoltaic/thermal (PV/T) systems through the integration of nano-enhanced phase change materials, aluminum heat sinks, and finned thermal storage arrangements.

Experimental and numerical analyses confirmed that the proposed hybrid cooling system effectively controlled photovoltaic operating temperature and improved overall system efficiency under outdoor environmental conditions. The study demonstrated that excessive heat generated in photovoltaic modules can be effectively absorbed, stored, and dissipated using nano-enhanced PCM combined with advanced heat transfer enhancement techniques.

The developed cooling arrangement showed significant reduction in photovoltaic panel temperature during peak solar radiation periods. The incorporation of nano-enhanced PCM improved thermal conductivity, latent heat storage capability, and thermal response characteristics compared with conventional phase change materials. The aluminum heat sink provided efficient heat transfer from the photovoltaic panel, while embedded fin structures improved thermal distribution and accelerated the melting-solidification process within the PCM chamber. These combined effects resulted in improved thermal regulation and stable operating conditions for the photovoltaic module. The reduction in panel temperature directly improved the electrical conversion efficiency of the photovoltaic system. Lower operating temperatures reduced thermal losses and enhanced photovoltaic power generation performance under varying solar radiation conditions. The proposed hybrid PV/T arrangement also improved thermal energy recovery and overall energy utilization efficiency through simultaneous generation of electrical and thermal energy. Experimental observations confirmed that the system maintained better temperature uniformity and reduced thermal fluctuations compared with conventional photovoltaic systems operating without thermal management.

The present research findings are consistent with recent international studies published during 2025–2026 on nano-enhanced PCM-based photovoltaic cooling systems. Recent investigations reported that grapheme enhanced PCM and carbonaceous nano-materials significantly improve thermal conductivity and heat transfer performance in photovoltaic thermal applications. The experimental results obtained in the present work confirmed several important improvements in system performance, including reduction in photovoltaic operating temperature, enhancement of electrical conversion efficiency, improvement in thermal energy storage capability, and better thermal stability during continuous outdoor operation. The proposed passive cooling arrangement also reduced thermal degradation of photovoltaic modules and improved the expected operational life of the PV system. Because the developed cooling system operates without additional external energy input, it provides a sustainable and energy-efficient solution for advanced photovoltaic thermal management applications. The investigation further demonstrated that nano-enhanced phase change material systems integrated with heat sinks and finned encapsulation structures can be effectively utilized for future renewable energy and thermal management applications. The improved thermal and electrical performance, combined with better energy storage capability and passive cooling operation, make the proposed PV/T system suitable for building-integrated photovoltaics, smart energy systems, industrial thermal recovery, rural electrification, and sustainable solar energy applications.

Overall, the present study confirms that hybrid PV/T cooling systems using nano-enhanced phase change materials provide an effective approach for improving photovoltaic performance, thermal regulation, and overall energy utilization. Recent advancements reported during 2025–2026 further support the application of nano-enhanced thermal energy storage systems for next-generation solar photovoltaic technologies. The developed system offers a reliable, passive, and environmentally sustainable solution for improving the efficiency and long-term stability of future solar energy systems.

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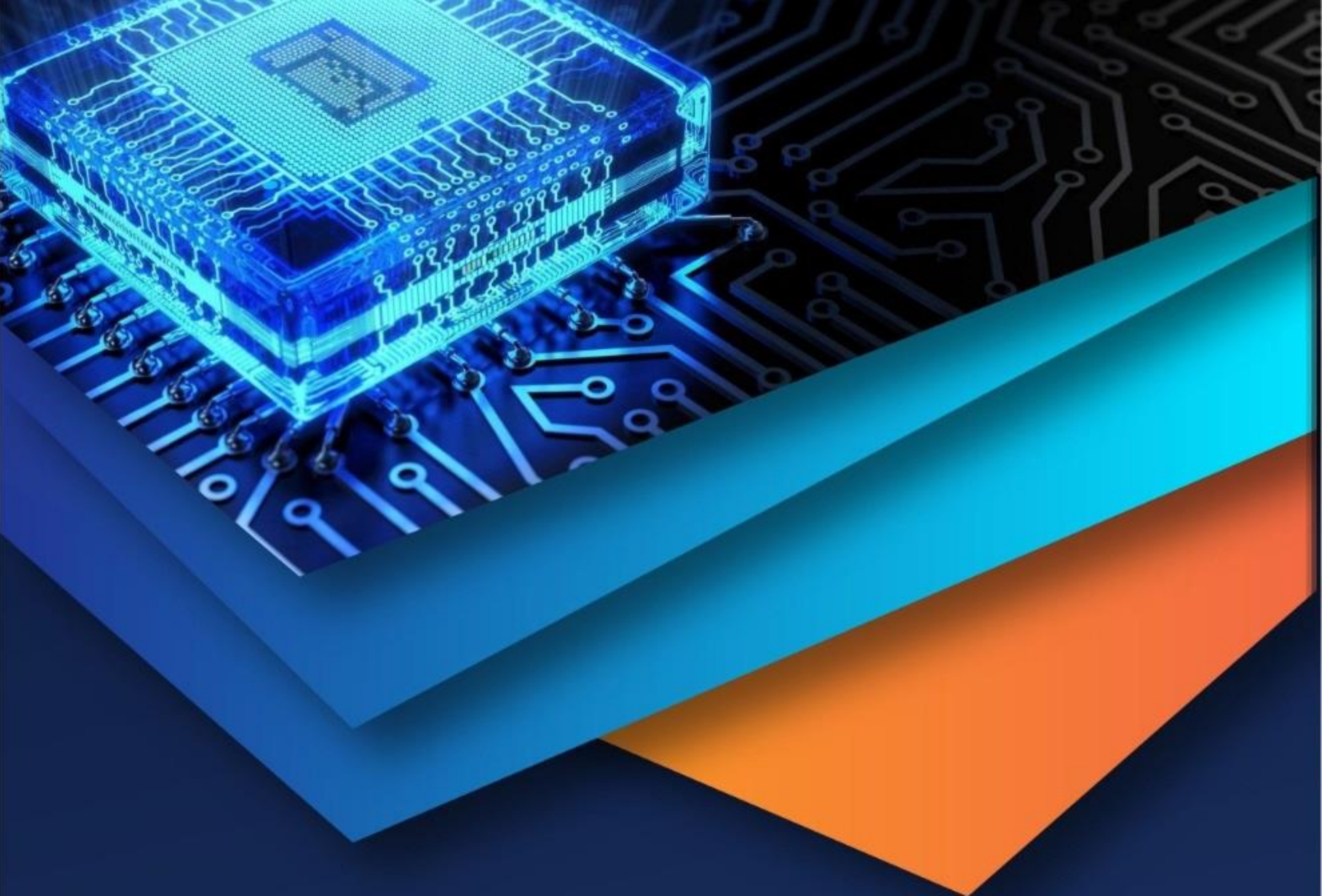

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