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Performance Enhancement of CPV Systems Using Hybrid PCM-Nanoparticle Cooling and Thermoelectric Generator Integration

Meiwa Barena[1], Jihan Syalsabila[1*], Rusdianasari[1]

[1]Applied Master of Renewable Energy Engineering, Politeknik Negeri Sriwijaya, Indonesia

Email address:
syalsabilajihan@gmail.com
[*] Corresponding author

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Abstract: Solar photovoltaic (PV) systems are rapidly being employed as a sustainable energy option, although their efficiency remains highly reliant on operating temperature and surface conditions. High heat accumulation and dust deposits are significant factors in reducing energy conversion efficiency, resulting in lower power output and a shorter module life. To overcome these issues, this study provides an improved solar energy collection strategy that combines light concentration helped by reflectors with an integrated cooling technique based on phase change materials (PCM) and thermoelectric energy recovery. The technology is intended to minimize cell temperature while also limiting efficiency losses caused by environmental exposure and capturing excess heat energy that would otherwise be lost. The evaluation focused on temperature behaviour, electrical output enhancement, and the impact of dust under various working scenarios. The results reveal that PCM integration considerably helps to stabilise panel temperature, whereas the inclusion of a larger surface area increases heat cooling more effectively. When dust is present, performance suffers dramatically, emphasising the significance of surface cleaning and cooling measures. Overall, this integrated system produces more power than typical PV modules, making it more efficient and reliable for long-term use. This approach emphasises the possibility of hybrid passive-active cooling solutions and dust reduction to aid in the application of sustainable solar technology in real-world situations.

Keywords: CPVT System, Cooling System, Thermoelectric Generator, PCM, SWCNT, Parabolic Reflector

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1. Introduction

Energy is one of the main pillars of human civilization, as it plays an important role in supporting various modern life needs and driving global economic and industrial growth. Currently, more than 80% of the world's energy needs are still met by fossil fuels. However, their limited availability and serious environmental impact particularly the increase in greenhouse gas emissions that cause global warming pose a major challenge. According to projections by the International Energy Agency (IEA), the share of fossil fuel use is expected to fall to less than 75% by 2030 and continue to decline to around 60% by 2050, indicating an acceleration in the transition to renewable energy use [1]. Despite ongoing efforts to transition to renewable energy, Indonesia remains heavily dependent on fossil fuels. Recent data shows that approximately 75–85% of total national energy consumption still comes from fossil fuels, making decarbonization and the development of clean energy strategic challenges that must be addressed in the coming decades [2]. The burning of fossil fuels is a major contributor to greenhouse gas emissions, such as carbon dioxide (CO_2), methane (CH_4), and nitrogen oxide (N_2O). These gases are trapped in the atmosphere and cause the greenhouse effect, which ultimately increases the average temperature of the earth. This rise in global temperature triggers various adverse effects, including melting ice in the polar regions, rising sea levels, and the emergence of extreme climate change in various parts of the world [3].

According to Rahman et al., the transition from fossil fuels to solar energy is an important step, given that Indonesia's final energy consumption in 2019 reached 989.9 million BOE and most of it still depends on fossil fuels, which cause an increase in emissions and the risk of global warming of up to around 3°C. The use of solar energy is seen as a strategic solution, especially through the implementation of systems that can efficiently convert solar radiation into electrical energy. Indonesia, as a tropical country with high solar radiation intensity throughout the year, has great potential to develop solar energy and begin the transition from fossil fuels to optimal and sustainable solar energy [4].

Solar energy is now one of the most promising and sustainable energy sources, as it can meet the growing global energy demand without compromising environmental sustainability. Solar energy is a renewable energy source derived from solar radiation and is used to generate electricity through the photovoltaic effect [5]. Concentrating photovoltaic (CPV) technology improves the performance of photovoltaic systems by combining solar panels and parabolic reflectors. This combination serves to strengthen the intensity of sunlight directed at solar cells, thereby producing higher power output. However, concentrating light in this manner can increase the temperature of PV cells, which has the potential to reduce electrical efficiency and shorten the operational life of the system [6]. In addition, dust on solar panels needs to be scientifically studied because particulate matter deposited on the surface of the modules has the potential to induce shading phenomena, inhibit solar radiation transmission, and reduce photovoltaic conversion efficiency. Findings in a study conducted by Nurjanah et al. show that dust accumulation causes degradation in power and output efficiency, with panels that are cleaned regularly producing up to 3.2 W more power and approximately 1.57% higher efficiency than panels that are continuously exposed to dust. Therefore, cleaning the surface is crucial to maintaining the operational performance of PV systems [7].

Habib et al. concluded that the parabolic tracker system, which combines photovoltaic (PV) and solar thermal (T) panels with the use of heat transfer fluid (HTF), can significantly improve energy conversion performance. This model is effective in maintaining stable panel surface temperatures despite weather fluctuations, thereby maintaining panel efficiency. In addition, the system produces higher average power compared to conventional flat PV panels, with an output increase of approximately 17.98% during peak load periods [8]. Solar panel systems require cooling to extend the life of the solar panels. Cooling of solar panels is necessary to lower the operating temperature so that efficiency and output voltage increase and to keep the temperature of the solar panels low, thereby preventing overheating and increasing efficiency and power output [9]. Output increases and becomes more effective when combined with Peltier and heatsink [10]. A cooling system is needed to lower the temperature of the solar panel system. However, the heat contained in solar panels can be utilized, as in research conducted by P. Jha et al., the Photovoltaic Thermal Collector (PVTC) system shows that cooling is very much needed because the increase in temperature on the panel reduces electrical efficiency, while thermal control allows for increased output and more optimal utilization of solar energy [11].

A study conducted by Suseno et al. proved that cooling plays a significant role in improving solar panel performance, where the immersion cooling method using mineral oil combined with a heat sink can reduce the surface temperature of the panel, thereby increasing voltage, current, power output, and efficiency in both monocrystalline and polycrystalline types. This cooling system provides an average performance increase of 3.57% in power and 3.28% in efficiency for polycrystalline panels, and 4.46% in power and 4.63% in efficiency for monocrystalline panels compared to without cooling and is superior to the use of heatsinks alone. Thus, immersion cooling + heatsink is an effective method for addressing temperature increases, which have been the cause of reduced photovoltaic efficiency [12]. Recent advancements indicate that thermoelectric generators (TEGs) are increasingly being integrated into concentrating photovoltaic (CPV) systems, giving rise to a novel configuration known as CPVT–TEG. To enhance thermal regulation and overall system efficiency in CPVT applications, researchers have developed cooling materials based on nanoparticle-enhanced phase change material (NEPCM) paraffin. Owing to its superior thermal conductivity and latent heat storage capability, this material effectively absorbs excess heat from PV cells and releases it when needed, thereby stabilizing operating temperatures and improving CPVT performance [13]. Aziz et al. studied the performance of PVT-PCM systems with spiral flow configurations and concluded that this design can increase overall efficiency by up to approximately 67.6%, making it superior to conventional water-based cooling systems [14]. Prakash et al. studied a hybrid PV/T system combined with PCM and a heat pump to meet the heating, cooling, and power supply needs of buildings. The results showed that this combination was able to significantly improve electrical and thermal performance compared to conventional systems [15].

Omar et al. reported that the integration of photovoltaic/thermal (PV/T) systems with solar water distillation significantly enhances freshwater production, achieving an increase of up to 161.5%. Their results also showed thermal efficiencies of approximately 75.11% and electrical efficiencies above 20%, highlighting the strong potential of this technology to simultaneously supply energy and clean water [16]. Sajjad et al. investigated the performance enhancement of conventional solar stills through the incorporation of cylindrical water heaters and Cu/Al_2O_3 hybrid nanofluids as the heat transfer medium. Their findings demonstrated a substantial improvement in the heat transfer coefficient as well as a notable increase in distilled water yield compared with the baseline system [17]. Research conducted by Amidu et al. shows that the use of a nanofluid-based cooling system (water + MWCNT) in PVT modules can significantly improve thermal and electrical performance, as evidenced by a 9.2% increase in power output compared to conventional water cooling systems, thereby reducing efficiency losses due to heat and improving overall panel performance [18]. Based on research by Zhao et al., a new solar system was developed using a carbon-activated–methanol working fluid pair. They built a two-dimensional numerical model for analysis through simulation, and the results showed that the use of finned pipes produced a more even heat distribution, characterized by a much smaller temperature difference only about 4°C compared to the design without fins [19].

This study proposes an innovative method to enhance the performance of photovoltaic (PV) solar panels by integrating a parabolic reflector with a dual cooling and energy recovery system. The cooling unit employs paraffin-based phase change material (PCM) enhanced with single-walled carbon nanotube (SWCNT) nanoparticles and is coupled with a thermoelectric generator (TEG) to convert excess thermal energy into supplementary electrical power. Unlike conventional PV systems, which experience efficiency degradation due to elevated operating temperatures and dust accumulation, the proposed configuration simultaneously mitigates thermal stress while harvesting otherwise wasted heat. Most existing research has investigated reflectors or cooling techniques independently, making the combined application of parabolic reflectors, nanoparticle-enhanced PCM, and TEG relatively unexplored. Furthermore, prior studies typically focused on a single performance enhancement strategy and rarely examined heat flux variations or the long-term impact of dust deposition, both of which significantly affect PV efficiency. The novelty of this work lies in the comprehensive system integration and the use of SolTrace for precise reflector modelling, detailed heat distribution analysis across PV layers, and evaluation of system performance under dust accumulation conditions. The cooling approach utilizes RT35HC paraffin augmented with SWCNT nanoparticles and fin structures, achieving superior heat dissipation compared to conventional PCM or fin-based cooling methods alone. Additionally, the incorporation of a TEG enables effective utilization of residual heat, thereby increasing the total electrical output. Overall, the integrated system addresses key limitations of previous studies by reducing thermal and dust-related losses, prolonging panel lifespan, and enhancing power generation, offering a robust and sustainable solution for advanced PV technologies.

2. Methods

2.1. Parabolic Reflector

Parabolic reflectors in the context of solar power systems are used to concentrate sunlight onto a focal point or receiver area, thereby significantly increasing the intensity of solar radiation compared to conventional flat solar panels. This principle enables solar systems to generate high heat or increase energy conversion efficiency, for example, for heating water, cooking, boiling, or as part of a concentrated solar power (CSP) or concentrated photovoltaic system [20].

2.2. PCM RT35HC

Containers filled with RT35HC paraffin phase change material (PCM) is positioned beneath the photovoltaic (PV) panels to absorb excess thermal energy generated by the PV cells. When exposed to solar irradiation, a portion of the incident energy is converted into heat, increasing cell temperature and consequently reducing electrical efficiency. The RT35HC PCM mitigates this effect by storing the excess heat through its melting process, thereby limiting the rise in PV surface temperature and minimizing performance losses. To address the inherent limitation of paraffin, namely its low thermal conductivity single-walled carbon nanotube (SWCNT) nanoparticles are incorporated into PCM. This enhancement improves thermal conductivity, accelerates heat absorption and melting rates and results in more effective cooling, particularly during periods of high solar irradiance [21].

2.2.1. Thermoelectric Generator (TEG)

In research such as you described, photovoltaic (PV) panel systems are combined with Thermoelectric Generators (TEGs) as part of a hybrid system to harvest excess heat generated on the panels due to intense sunlight, which typically reduces the electrical conversion efficiency of PV cells. TEGs are able to utilize temperature gradients (the temperature difference between the top and bottom of the panel) through the Seebeck effect to generate additional electricity from residual heat. Thus, the hybrid system not only cools the panels (reducing efficiency loss due to high temperatures) but also converts some of that heat into electrical power, resulting in a higher total energy output [22].

2.2.2. The Present CPV Solar System

This research developed an integrated system to improve the efficiency of solar panels (PV) by utilizing various energy capture and management techniques. A parabolic reflector is used to focus sunlight onto the PV surface, thereby increasing radiation and electrical output. To prevent the panels from overheating due to concentrated sunlight, a cooling module is installed beneath the panels: a container filled with paraffin (RT35HC) reinforced with SWCNT nanoparticles to improve thermal conductivity, equipped with fins to accelerate heat dissipation across the panel surface. The optical behavior of the reflector was simulated using SolTrace software to model variable heat flux in each PV layer, including realistic effects such as dust accumulation on the panel glass. In addition, a thermoelectric generator (TEG) was added to convert excess heat into additional electricity. A three-dimensional unsteady simulation (Finite Volume Method) was used to analyze the transient thermal behaviour in the PV module under various scenarios (clean vs. dusty, with/without fins), to evaluate the improvement in thermal and electrical performance under real operating conditions [23].

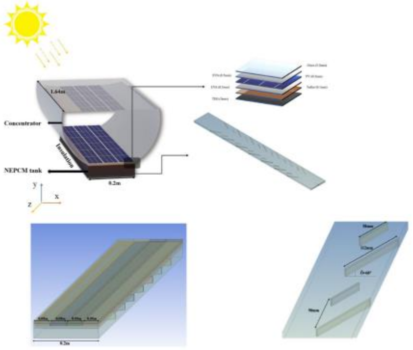


Figure 1. CPVT unit in the presence of NEPCM containers

Several conditions that will be examined can be seen in the following table.

Table 1. Research Variables

Case	PV	NEPCM	FIN	DUST
1	Yes			
2	Yes	Yes		
3	Yes	Yes	Yes	
4	Yes			Yes
5	Yes	Yes		Yes
6	Yes	Yes	Yes	Yes

The thermophysical properties used as data for this study are as follows [24], [25], [26].

Table 2. Fluid and Solids Zone Thermo Physical Properties

Parameter	Density (kg m^{-3})	Thermal Conductivity (W m^{-2} K^{-1})	Specific Heat (Jkg^{-1} K^{-1})	Viscosity (Pa s^{-1})	Latent Heat (J kg^{-1})	Melting Temperature (K)
Glass	2200	0.76	830	-	-	-
Tedlar	1200	0.2	1250	-	-	-
Silicon	2330	148	700	-	-	-
EVA	960	0.35	2090	-	-	-
TEG	93	0.92	708	-	-	-
Absorber (copper)	8960	401	385	-	-	-
SWCNT (nano particle)	2600	6600	425	-	-	-
RT-35 HC	880 (solid) 770 (liquid)	0.2	2000	0.0044	2,40,000	308

3. Result and Discussions

3.1. Values of Temperatur Photovoltaic for CPV System

The application of the CPV (concentrating photovoltaic) system has a significant effect on the increase in the operating temperature of solar panels (TPV), as shown in Figure 2. In the third CPV configuration, the panel temperature increased by approximately 10.14% as the operating time increased. When comparing the first to third configurations, the temperature increase observed was 3.71% at 10 minutes and reached approximately 7.23% at 60 minutes. It should be noted that the maximum temperature limit that the panels in this study could tolerate was 90 °C. If the temperature exceeds this value, energy conversion performance may decrease and the panel's service life may be shortened. Therefore, thermal control and cooling technology are essential to prevent the panel from reaching this critical temperature. These findings confirm that the use of a cooling system in conjunction with CPV technology not only helps improve electrical performance but also maintains the stability of the panel structure when receiving concentrated solar radiation.

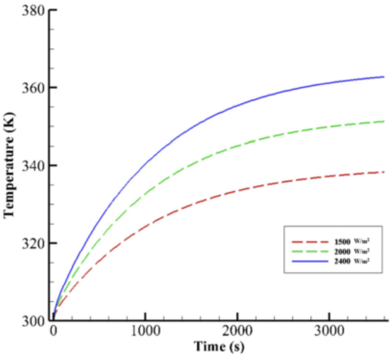
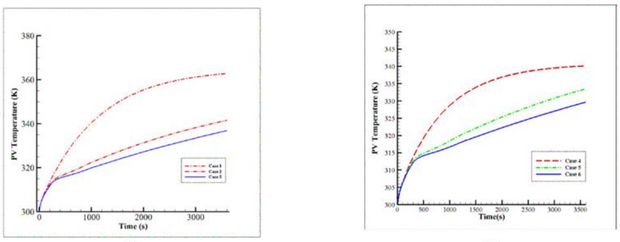


Figure 2. Tpv for various CPV System

Figure 3 shows the temperature variation of the photovoltaic panel (TPV) across all simulation scenarios. Under clean panel conditions without dust, the presence of a cooling zone was able to reduce the operating temperature by approximately 3.84% at the 10th minute and reached around 7.15% at the 60th minute. These findings indicate that the cooling system is effective in maintaining low panel temperatures, thereby increasing conversion efficiency and panel lifespan. Conversely, when the panels are covered with dust, the PVP still decreases, although the level of effectiveness is reduced. In dusty conditions, the temperature only drops by about 2.17% after 10 minutes and 3.07% after 60 minutes. This indicates that although the cooling system helps slow down the temperature increase, the layer of dust that sticks to the panels acts as an insulator, thereby inhibiting optimal heat release. After 60 minutes of dust exposure, an additional temperature decrease of approximately 2.13% was recorded, reinforcing the evidence that dust substantially affects the thermal performance of the panels. Overall, these results emphasize the importance of effective thermal management to maintain high efficiency and prevent panel damage from excessive heat, both in clean conditions and dusty environments.



(a) (b)

Figure 3. Behavior of panel temperature when (a) clean, (b) dust case

3.2. Electrical Photovoltaic (PV) Efficiency

Figure 4 shows the changes in photovoltaic electrical efficiency (ηel,PV) across all simulation scenarios. The presence of a cooling zone significantly reduces the temperature of the silicon layer, and the effectiveness of cooling increases further when fins are added. Due to this temperature reduction, the use of paraffin provides a clear increase in electrical efficiency, especially in systems equipped with cooling fins. However, the presence of dust has a detrimental effect because dust particles block solar radiation from entering the silicon layer, thereby reducing power output. The pattern of ηel,PV decline in dusty conditions also changes over time, with efficiency continuing to decline in each configuration as the duration of exposure increases. Under clean, dust-free conditions, the addition of a cooling system can increase ηel,PV by around 6.62% at 10 minutes and reach around 16.46% at 60 minutes. When dust is present, efficiency still increases, albeit to a lesser extent, by around 7.7% at 10 minutes and 5.79% at 60 minutes. The application of fins in the paraffin zone provides an additional increase of approximately 2.62% in clean conditions and approximately 2.04% in dusty conditions.

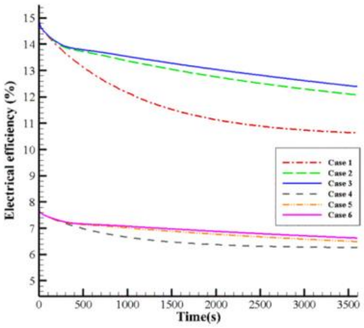


Figure 4. Electrical Efficiency reduction with time

Figure 5 shows the variation in electrical power generated in each configuration. After 60 minutes of operation, the addition of fins resulted in a power increase of approximately 2.04%. When the cooling system was applied, the power output increased even more, by approximately 5.89% in dusty conditions and reaching approximately 12.38% when the panel was clean.

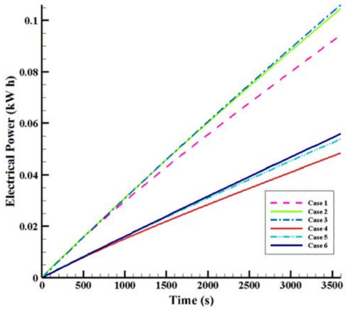


Figure 5. Electrical power for all various

The total system efficiency (η_{tot}) is obtained by summing all efficiency components, and the complete results can be seen in Figure 6. After operating for 60 minutes, the η_{tot} value decreased by approximately 20.92% due to dust accumulation on the glass surface, indicating that environmental factors greatly affect solar energy conversion performance. Placing a finned paraffin container at the bottom of the panel significantly increases η_{tot}, by approximately 6.77% in clean conditions and 3.78% in dusty conditions. This confirms the important role of thermal management in reducing efficiency losses caused by dust.

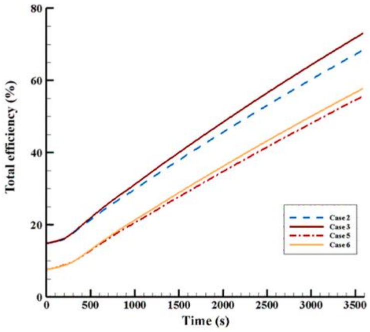
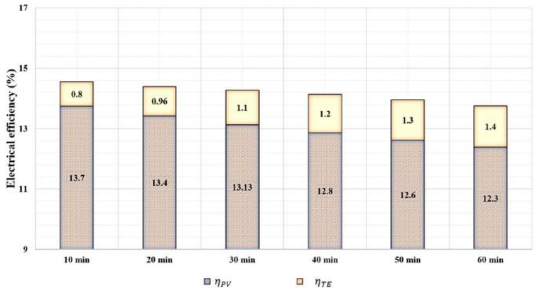
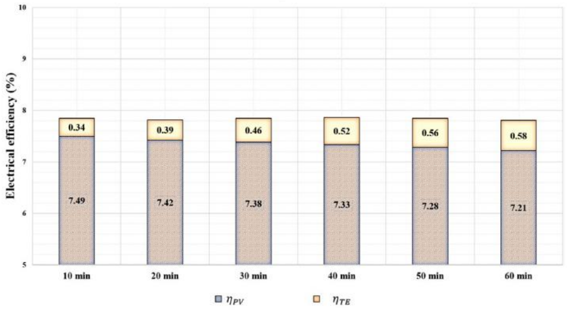


Figure 6. Effect of fin installation on total efficiency in clean and dusty conditions

Figure 7 also illustrates the variation in total electrical efficiency for Cases 3 and 6 over different operating times. After 60 minutes, the incorporation of a thermoelectric generator (TEG) resulted in an efficiency increase of approximately 11.07% under clean conditions and 8.15% under dusty conditions. These results demonstrate that the TEG effectively converts residual thermal energy into additional electrical power, thereby enhancing overall system performance. Nevertheless, as the operating time increased from 10 to 60 minutes, the total efficiency exhibited a gradual decline of about 5.43% in Case 3 and 0.52% in Case 6. This trend highlights the critical role of effective cooling and regular maintenance in sustaining optimal performance, particularly in environments prone to dust accumulation. Overall, the findings emphasize the significance of integrating cooling mechanisms and TEGs to enhance both the efficiency and durability of PV systems under diverse operating conditions.



(a)



(b)

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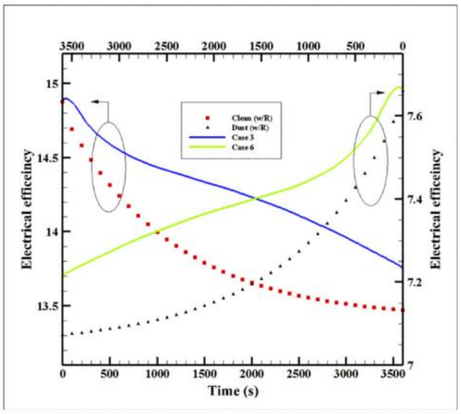
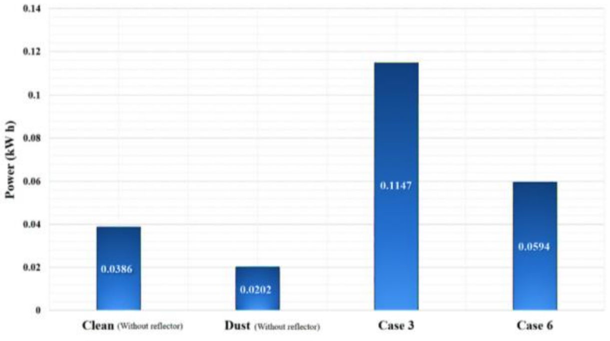
Figure 7. Impact of TEG addition on total electrical efficiency in (a) case 3, (b) case 6

The comparison in Figure 8 shows the performance of several of the best configurations compared to standard PV panels without cooling or reflectors. The combination of a parabolic reflector and a finned NEPCM cooler was found to generate approximately 2.9 times more electrical power than unmodified panels. This significant increase occurs because the reflector increases the intensity of radiation received by the panel, while the cooling unit lowers the temperature so that efficiency does not decrease due to overheating. The combination of the two provides a significant performance improvement and shows that integrated solutions such as this can dramatically and more stably increase PV efficiency for use in real field conditions.



(a)



(b)

Figure 8. Comparison present CPVT with transitional PV without cooling in view of (a) electrical efficiency, (b) power generation between.

4. Conclusion

The evaluation focused on temperature behaviour, electrical output enhancement, and the impact of dust under various working scenarios. The results reveal that PCM integration considerably helps to stabilise panel temperature, whereas the inclusion of a larger surface area increases heat cooling more effectively. When dust is present, performance suffers dramatically, emphasising the significance of surface cleaning and cooling measures. Overall, this integrated system produces more power than typical PV modules, making it more efficient and reliable for long-term use. This approach emphasises the possibility of hybrid passive-active cooling solutions and dust reduction to aid in the application of sustainable solar technology in real-world situations.

The results of this research indicate that the use of parabolic reflectors, phase change materials, and hybrid cooling systems can improve the efficiency and longevity of PV panels. To investigate the impacts of cooling and dust, six scenarios were tested: (1) no cooling-no dust, (2) NEPCM without dust, (3) finned NEPCM without dust, (4) no cooling-with dust, (5) NEPCM with dust, and (6) finned NEPCM with dust. Dust can lower ηel,PV by up to ~46.48%, requiring mitigation and regular cleaning. In clean conditions, cooling increased ηel,PV by 6.62% (10 minutes) and 16.46% (60 minutes). Panels with reflectors and cooling generated 2.9 times as much electricity as normal PV.

However, within the first 10-60 minutes of operation, efficiency decreased by 5.43% (Case 3/no dust) and 0.52% (Case 6/with dust). TEG installation improved efficiency by 11.07% in clean conditions and 8.15% in dusty conditions. Fins boosted stored energy by 4.06% while dusty and 8.47% when clean. The cooling zone also decreased TPV by 3.84% (10 minutes) and 7.15% (60 minutes) in dust-free conditions. To summarise, integrating cooling systems, dust management, and TEG can improve panel performance and lengthen operational longevity, making it appropriate for use in real-world PV systems.

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