COMPARISON OF RECENT COOLING TECHNIQUES FOR ENHANCING THE PERFORMANCE OF PHOTOVOLTAIC CELLS

ASWIN K[1], ARJUN KALLATH[2], ADITHYAN P[3], ADITHYA DAYAL[4]

Mechanical engineering department

Government college of engineering kannur

Abstract- Solar energy is an abundant, renewable, and eco-friendly resource that can be harnessed to generate electricity through photovoltaic (PV) and photo-thermal methods. However, the efficiency of photovoltaic panels tends to decline as panel temperature increases, primarily due to higher solar irradiation intensity. To mitigate this challenge and enhance both the efficiency and lifespan of PV panels, effective cooling strategies are necessary. This study focuses on the comparative analysis of different passive cooling techniques for photovoltaic panels and identifies the most effective method in improving panel performance.

Three passive cooling methods were investigated: phase change materials (PCM), extended surfaces (fins), and a hybrid system combining both PCM and fins. OM 35 was selected as the PCM, chosen based on the ambient temperature conditions of the experimental region. Fins were incorporated to enhance heat dissipation via conduction, convection, and radiation. The performance of each system was evaluated in terms of power output, temperature reduction, and efficiency enhancement.

Experimental results showed that all cooling methods contributed to improved PV panel performance. Among them, the fin-cooled system demonstrated the highest efficiency improvement and the greatest temperature reduction of 10.37°C. The hybrid PCM-fins system and the standalone PCM system achieved temperature reductions of 5.5°C and 4.4°C, respectively. The integration of passive cooling techniques not only improved the electrical performance of the PV panels but also reduced thermal stresses, potentially extending the operational lifespan of the panels. These findings highlight the effectiveness of passive cooling strategies, particularly fin-based cooling, for enhancing the efficiency and durability of photovoltaic systems.

***Index Terms*- Photovoltaic panel, Passive cooling, Phase change material (PCM), Fins, Hybrid cooling system, Thermal management, Solar energy, Efficiency enhancement, OM 35, Temperature reduction.**

1. INTRODUCTION

In today’s world, fossil fuels remain the most widely used sources of energy. However, these resources are depleting at an alarming rate. According to the Millennium Alliance for Humanity and the Biosphere (MAHB), global oil reserves are projected to run out by 2052, natural gas by 2060, and coal by 2090. This imminent scarcity underscores the urgent need to transition towards alternative and sustainable energy sources. Among the most promising alternatives are renewable energy sources (RES), which include solar, wind, hydro, geothermal, and biomass energy.

The combustion of fossil fuels is a significant contributor to greenhouse gas emissions, which are the primary drivers of climate change. In contrast, renewable energy sources produce little to no greenhouse gas emissions during operation, helping to reduce carbon dioxide and other harmful pollutants in the atmosphere. In addition to their environmental benefits, renewable energy systems offer greater energy security. Many countries heavily depend on imported fossil fuels, making their energy supply vulnerable to price fluctuations and geopolitical tensions. Renewable energy provides a decentralized and domestic energy solution, reducing reliance on foreign energy imports and enhancing national energy security. Among various renewable energy options, solar energy stands out as one of the most abundant and versatile sources available globally. It is a limitless resource that does not deplete over time. Solar energy currently accounts for approximately 11.5% of the world’s total renewable energy share. Compared to other renewable technologies, photovoltaic (PV) systems are highly adaptable and can be integrated into a wide range of applications — from buildings and vehicles to electronic devices. Additionally, large-scale solar energy harvesting is possible through solar farms, highlighting its vast potential for future energy production. According to research projections, solar energy contributed around 2% of renewable energy capacity in 2015, with expectations of reaching approximately 18% by 2040. Once installed, solar PV systems generate electricity at no additional fuel cost since sunlight is free and abundantly available. This makes solar energy an economically attractive long-term solution. By generating electricity on-site, homeowners, businesses, and communities can reduce their dependence on grid electricity and lower their energy bills. Moreover, solar PV systems can be rapidly deployed, especially in small-scale applications such as residential or commercial installations. Modular designs and standardized components enable efficient and streamlined installation processes, minimizing the time required from planning to energy generation. The underlying mechanism of solar PV systems is based on the photovoltaic effect — a phenomenon where certain semiconductor materials generate an electric current when exposed to light. This effect forms the foundation of solar photovoltaic technology, allowing for the direct conversion of sunlight into electricity.

2. EXPERIMENTAL SET UP

a b

Figure 1: (a) 50W 12V photovoltaic panel (b) Tiltable stand for keeping the photovoltaic panel.

Here, a monocrystalline PV panel was used for the experiment. This type of photovoltaic panel is manufactured from a single-crystal silicon structure. The semiconductor material, silicon, is arranged in a continuous and uninterrupted crystal lattice, which facilitates higher electron mobility and improves the efficiency of converting sunlight into electrical energy. The specific PV panel model employed in this study is the 50W, 12V ANDSLITE AS 5012 monocrystalline panel, as shown in Figure 1 (a) The key specifications of the panel are as follows:

- Open circuit voltage (Voc): 22.6 V
- Short circuit current (Isc): 2.82 A
- Maximum power voltage (Vmp): 18.8 V
- Maximum power current (Imp): 2.7 A
- Maximum system voltage: 1000 V
- Panel dimensions: 62 cm × 50 cm

The stand used in this experiment is designed using angled iron bars, providing a sturdy and durable framework to support the solar panel. U-clamps are securely attached to the structure to facilitate easy tilting of the panel, as shown in the figure. The tiltable range of the stand extends from 10° to 75°, allowing the panel to be adjusted for optimal alignment with the sun’s position throughout the day. This adjustable feature helps maximize solar exposure, improving energy capture and overall system efficiency. The robust construction ensures stability even under varying weather conditions, making it suitable for both experimental and practical applications.

Figure 2: Thermal camera used for measuring the temperature developed on the PV panel

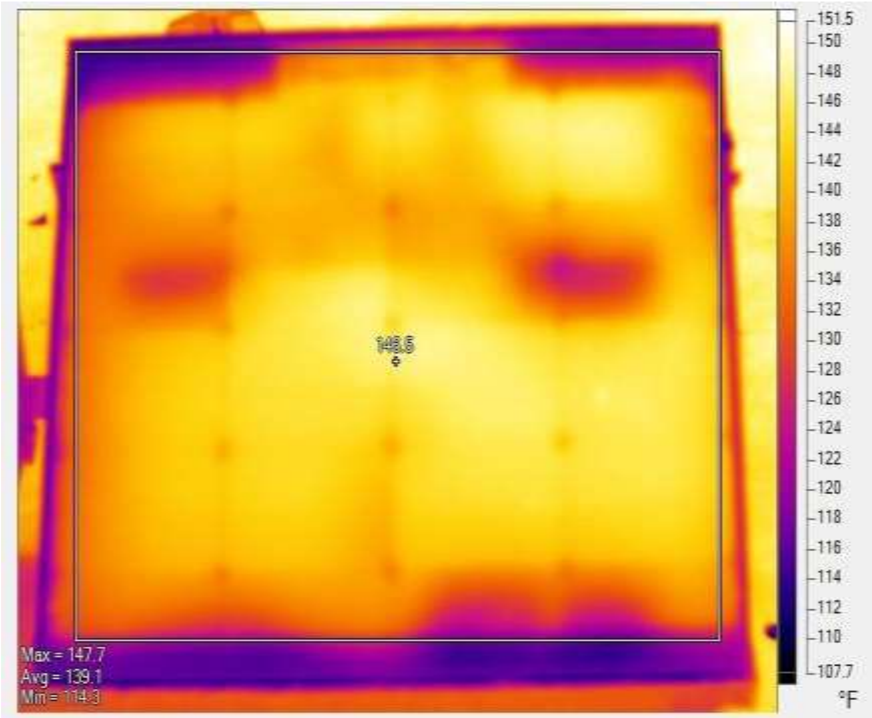
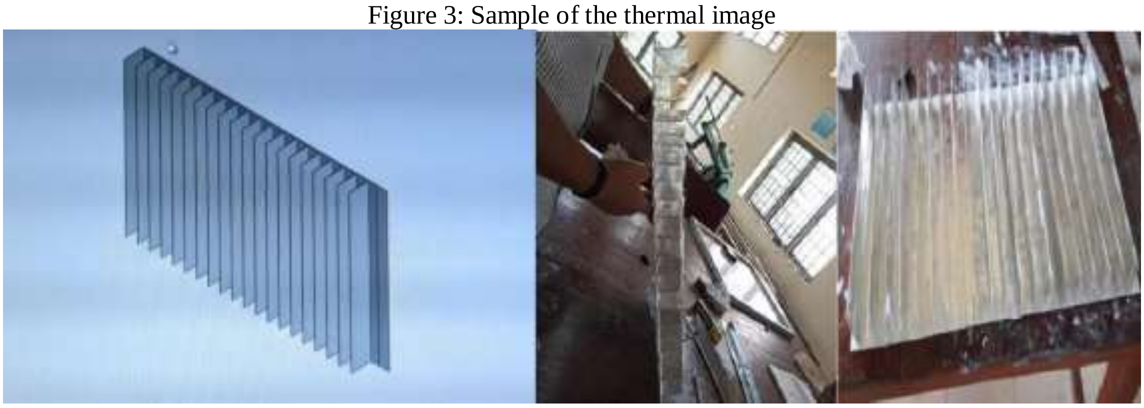


Figure 3: Sample of the thermal image



a b

Figure 4 (a) designed fins (b) Fabricated fins made up of aluminium.

The L-shaped fins were designed and fabricated as a passive cooling solution to enhance heat dissipation from the photovoltaic panel. Aluminium was selected as the material due to its high thermal conductivity and ease of fabrication. The dimensions and geometry of the fins were determined based on the amount of heat expected to be transferred from the PV panel, ensuring effective thermal management.

The L-shaped configuration increases the surface area for heat exchange, promoting efficient convective heat transfer. The fins were arranged to allow airflow through the channels between them, further improving cooling performance. To minimize thermal resistance and improve heat conduction, a thermal paste was applied between the fins and the aluminium sheet, ensuring better thermal contact and reducing air gaps.

Figure 5: A pyranometer was used to measure the solar irradiance

A pyranometer is an instrument classified as an actinometer, used to measure solar irradiance at a specific location by determining the solar radiation flux density. It records this flux density in units of watts per square meter (W/m²) across a spectral range of 300 nm to 3000 nm. The device features a flat spectral response, allowing it to accurately capture radiation across the entire wavelength range.

The operating principle of the pyranometer is based on detecting the temperature difference between two surfaces one dark and one clear. The dark (black) surface on the thermopile absorbs incoming solar radiation, while the clear surface reflects or transmits most of the radiation, resulting in less heat absorption. This temperature differential generates a measurable signal that corresponds to the intensity of solar radiation.

a b

c

Figure 6:(a) Panel with encapsulated PCM on the rear side (b) Fins attached on the back side of PV panel (c) Hybrid system of PCM and fins

3. EXPERIMENTAL METHODOLOGY:

The experimental study was conducted over three consecutive days, from 26th to 28th April 2023, between 11:00 AM and 3:00 PM each day. The setup was placed in an open area with no obstructions to ensure direct sunlight exposure. A thermal camera was used to monitor surface temperature variations on the photovoltaic (PV) panel, which was tilted at an angle of 25°, chosen based on the latitude of the experimental location for optimal solar capture. A constant load was applied using a rheostat, with voltage and current measured using a voltmeter and ammeter, respectively. A pyranometer recorded the incident solar irradiance.

On the first day, passive cooling using phase change material (PCM) was tested. Approximately 2.5 kg of OM35 PCM, selected through numerical analysis, was applied to the rear side of the PV panel with minimal air gap. The encapsulated PCM was secured using self-adhesive aluminium tape, reinforced with brown tape to prevent displacement during phase transition, as seen in Figure 6a.

On the second day, aluminium fins were attached to the back of the PV panel. Thermal paste was applied to improve contact and enhance thermal conductivity, and aluminium tape was used to secure the fins firmly in place, as seen in Figure 6b.

On the final day, a hybrid cooling system combining fins and PCM was implemented. The PCM was first affixed as done previously, and aluminium fins were mounted on top of it. Thermal paste was applied between the fins and PCM to minimize air gaps and improve heat transfer. The integration of fins aimed to enhance the thermal conductivity of the PCM, improving the overall cooling efficiency of the panel, as seen in Figure 6c.

Due to continuous solar irradiation, the temperature of the photovoltaic (PV) panel increases, which necessitates the implementation of cooling systems to mitigate temperature rise. Although both active and passive cooling systems are available, prior analyses indicate that active systems tend to be costly to install and maintain, especially for smaller-scale solar power plants. Consequently, passive cooling systems, which do not require an external energy source, are preferred. Among the various passive cooling methods, fins and phase change materials (PCM) are commonly used. Previous studies have explored these methods, but gaps were identified, such as the improper selection of PCM or insufficient integration with other cooling systems. To address these gaps, this study aims to optimize the cooling efficiency of solar PV panels by experimenting with conventional fin-based cooling, PCM-based cooling, and a hybrid of both techniques. Additionally, a cost analysis will be conducted to determine the most economically feasible cooling method.

Assumptions Made in the Study

- **PV Panel:** The reflection of radiation from the glazing surface is assumed to be 3%, and the absorption of solar radiation by the glazing layer is neglected. Emitted longwave radiation from the glazing surface is also neglected. All transmitted solar radiation is assumed to be absorbed by the PV silicon layer. The conversion efficiency of the PV panel is expressed as a function of cell temperature, based on a referenced efficiency at 25°C under laboratory conditions.
- **PCM:** Both the liquid and solid phases of the PCM are considered isotropic and homogeneous. Thermo-physical properties are assumed to remain constant in each phase, and there is no air gap between the encapsulated PCM and the rear surface of the PV panel.

- **Fins:** The thermal conductivity of the fins is assumed to be constant throughout, with no air gap between the fins and the rear surface of the PV panel.

Equations Used

Power =VX I Efficiency

=VI/EA. [1]

V= voltage, I= current, E= irradiance, A=area

Power Enhancement Percentage (PEP):

$$PEP\% = [(P_{EXP}-P_{REF})/P_{REF}] \times 100 \quad [1]$$

P_{EXP} = power output of panel with cooling system, P_{REF} = power output of reference panel

Efficiency Enhancement Percentage (EEP):

$$EEP\% = [(\eta_{EXP}-\eta_{REF})/\eta_{REF}] \times 100 \quad [1]$$

η_{EXP} = efficiency of panel with cooling system, η_{REF} = efficiency of reference panel [1]

Procedure

1. On the first day, the temperature developed on the reference PV panel (Panel 1) and the temperature developed on the PV panel incorporated with PCM (Panel 2) will be evaluated. The efficiency of the PCM-integrated panel will be compared to the reference panel.
2. On the second day, provided that the climate conditions remain consistent, aluminium fins will be integrated onto the rear surface of Panel 2, and its efficiency will be compared to that of the reference panel (Panel 1).
3. On the third day, a hybrid cooling system consisting of both fins and PCM will be integrated onto the rear surface of Panel 2. The efficiency of the hybrid system will then be compared to that of the reference panel (Panel 1).
4. Following the completion of the experiments, the cooling system that provides the highest performance improvement in terms of power output and efficiency will be identified and analysed.

4. RESULT AND DISCUSSION:

Note : Initially there is a negative temperature in the tables below which means initially the temperature of the reference panel was less as compared to panels cooled by using passive cooling technique.

Table 1: Reference panel vs panel with PCM

Time	Power output of the reference panel (watt)	Power output of the panel cooled by using PCM	Temperature difference between the two panel	Efficiency of the reference panel (η)	Efficiency of the panel cooled by using PCM (η_{pcm})
11:00	27.9	27	-2	7.9	7.7
11:15	30.38	32.928	-.88	8.8	9.55
11:30	30.38	32.928	.26	8.7	9.52
11:45	32.144	33.6	3.4	8.95	9.36

12:00	32.144	32.928	2.66	8.45	8.66
12:15	32.144	32.928	2.66	9.2	9.49
12:30	32.144	32.144	4.441	9.7	9.71
12:45	32.144	32.144	2.773	9.73	9.49
1:00	32.144	32.928	1.6	9.71	9.95
1:15	32.144	31.948	0.4	9.81	9.74
1:30	29.792	29.792	1	9.37	9.37
1:45	32.144	31.948	0.1	10.03	9.97
2:00	15.84	18.032	0	10.62	12.09
2:15	14.08	16.464	3.7	10.16	11.88

Table 2: Reference panel vs panel with fins

Time	Power output of the reference panel	Power output of the panel cooled by using fins	Temperature difference between the two panel	Efficiency of the reference panel (η)	Efficiency of the panel cooled by using fins (η_{fins})
11:00	29.30	29.30	-0.1	12.9	12.8
11:15	27.36	26.6	-0.51	12	13
11:30	27.36	28.992	0	11.1	11.8
11:45	27.36	28.992	5.66	13.2	13.2
12:00	14.96	15.84	4.72	7.2	10.33
12:15	27.44	28.22	0.82	12.5	9.76
12:30	27.44	29.53	0.5	8.5	10.3
12:45	27.44	29.53	7.98	8.66	13.5
1:00	27.44	29.55	10	8.2	9.3
1:15	27.44	29.4	10.37	8.69	9.3
1:30	28.22	29.4	2.95	9.2	9.5
1:45	27.44	29.4	2.91	9.1	9.8
2:00	27.44	29.4	5.39	9.3	9.9
2:15	27.44	29.4	1.55	8.8	9.4
2:30	27.44	29.4	2.73	10.1	10.8
2:45	27.44	29.4	0.77	9.9	10.7

3:00	26.656	28.71	2.22	10.3	11.11

Table 3: Reference panel vs panel with hybrid combination of fins and PCM

Time	Power output of the reference panel	Power output of the panel cooled by using hybrid PCM-fins	Temperature difference between the two panel	Efficiency of the reference panel (η)	Efficiency of the panel cooled by using hybrid PCM-fins ($\eta_{pcm-fins}$)
11:00	29.1	29.55	0.5	9.09	9.24
11:15	29.1	29.55	-1.3	9.98	10.1
11:30	29.1	31.4	0.1	8	8.6
11:45	23.852	25.56	1.66	6.59	7.06
12:00	26.864	29.4	5.5	7.27	8.7
12:15	26.864	29.4	2	7.35	8.05
12:30	26.864	29.4	1.62	7.23	8.64
12:45	27.6	29.4	1.4	7.6	8.1
1:00	26.864	29.4	0.09	7.42	8.12
1:15	26.864	29.4	1.3	7.97	8.72
1:30	26.128	28.8	2.4	8.4	8.97
1:45	26.128	28.5	1.63	8.5	9.54
2:00	26.128	28.324	2.7	8.38	9.08
2:15	26.128	28.324	1.4	8.86	9.6
2:30	26.864	28.324	2.1	8.73	9.22
2:45	26.864	28.324	0.5	9.41	9.97
3:00	26.128	28.324	0.6	9.28	10.06

4.1 Panel with PCM

The power output of the panel cooled by using PCM is found to be higher as compared to reference panel. The PCM incorporated to the panel reduced the temperature of the panel and indirectly enhanced the power output. The power vs time graph is plotted below in Figure 7.

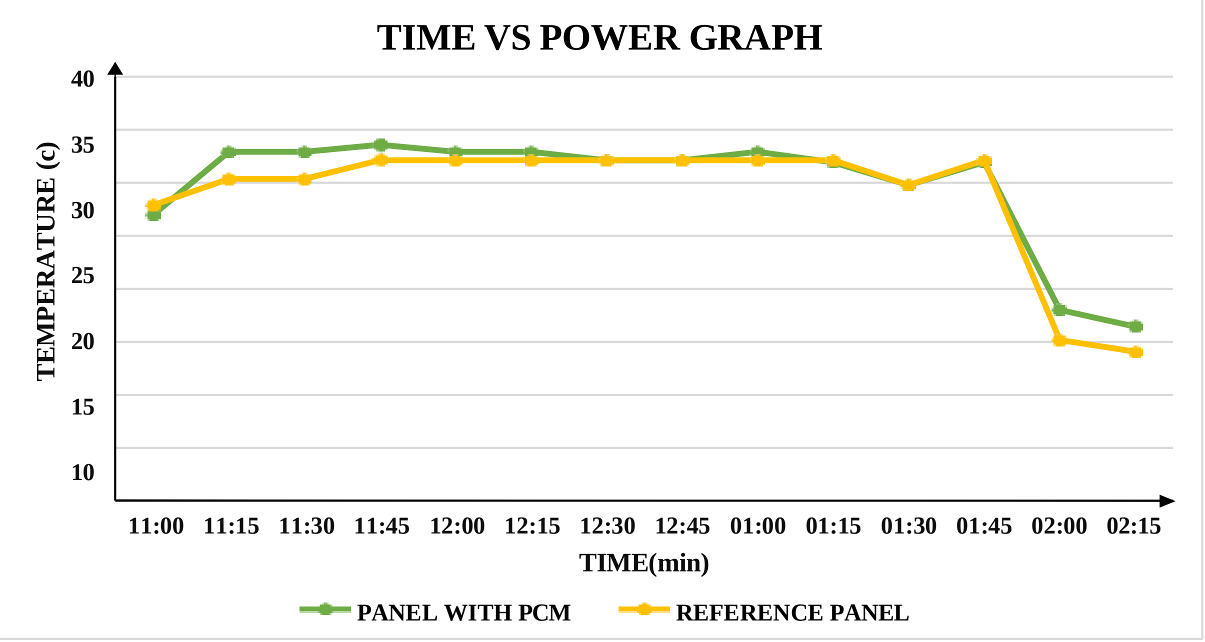


Figure 7:Time vs Power graph (panel with PCM-Reference panel)

From the above graph we can interpret that at first the power output of the reference panel was slightly higher as compared to the panel cooled by using PCM. The reason may be at first the PCM did not melt to produce the appropriate cooling. After a particular time, interval, the PCM undergoes phase transition to produce the appropriate cooling. The maximum power difference was obtained at 11.30 AM, and the maximum power obtained was 32.928 W. From 1:15 PM onwards the power output of both panels was almost similar due to the fact that PCM has absorbed maximum amount of heat and has reached its maximum absorbing capacity. The total increase in power output was 3.024 % compared to reference pane

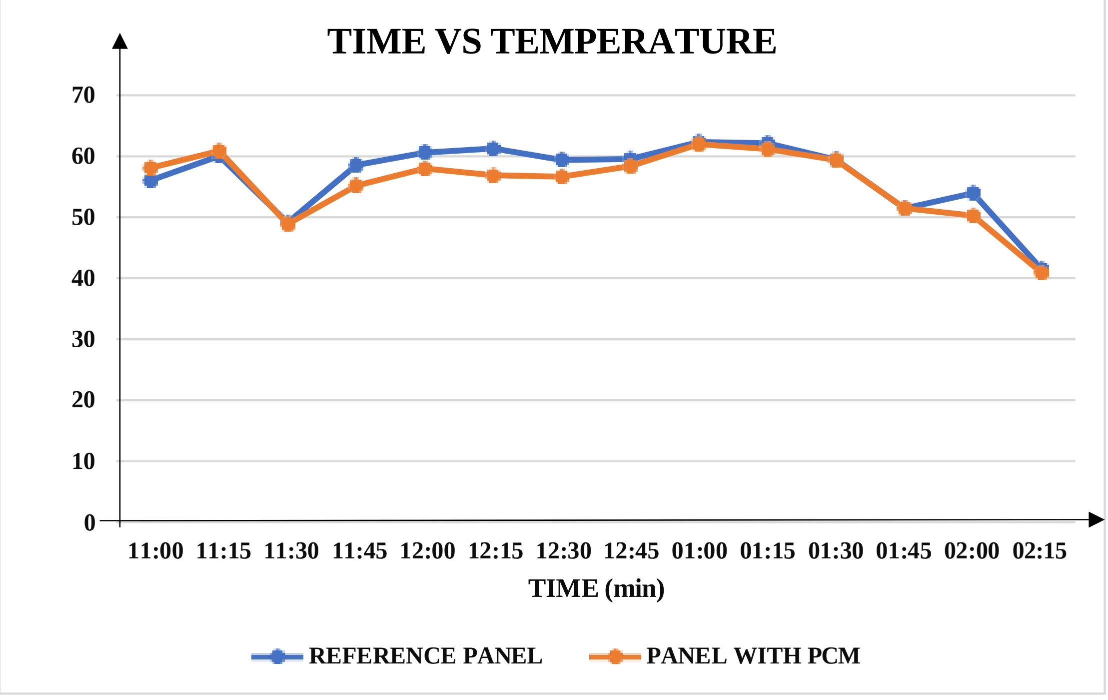


Figure 8 : Time vs Temperature graph (panel with PCM Vs reference panel)

Figure 8 shows variation of temperature with respect to time. Even if the initial temperature of the PCM integrated panel was higher as compared to the reference panel, the temperaturee gradually decreases as time goes. The maximum temperature difference was4.44°C at 12:30 PM.

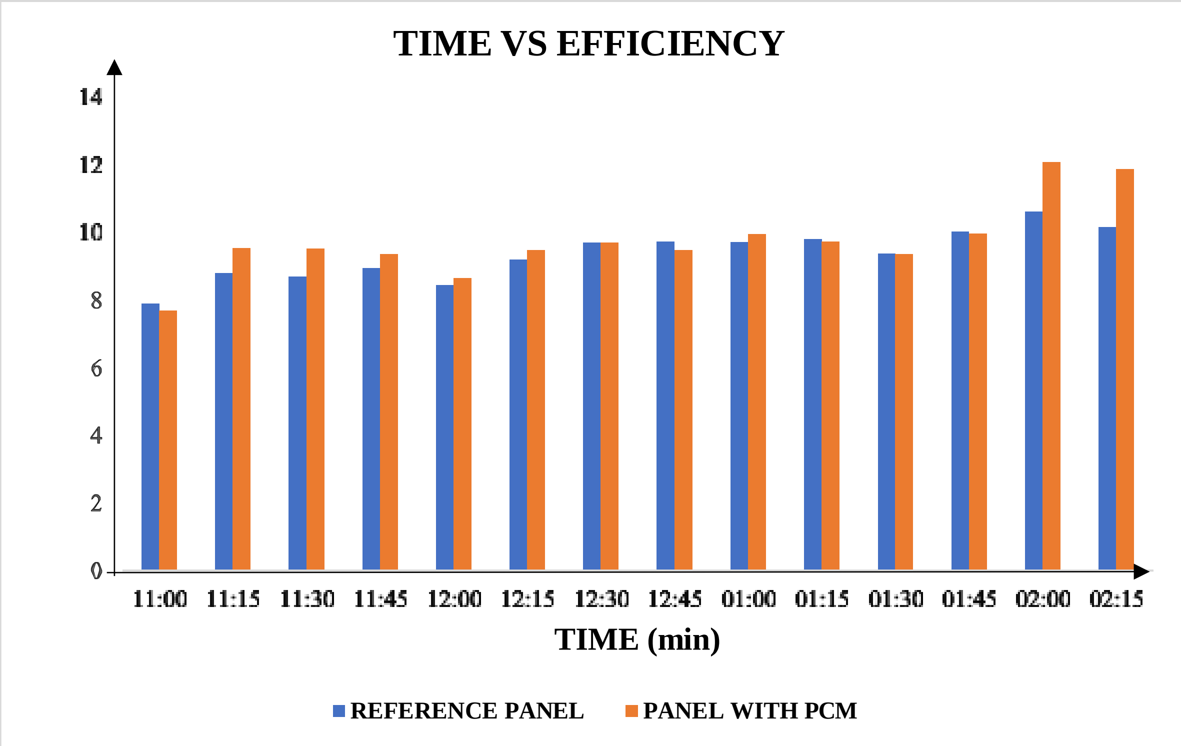


Figure 9: Time vs Efficiency (panel with PCM- reference panel)

The time vs efficiency graph (Fig 9) shows the improvement in efficiency of the PV panel when PCM is used. An overall improvement of 4.48% is observed in the PCM integrated panel.

4.2 Panel with fins

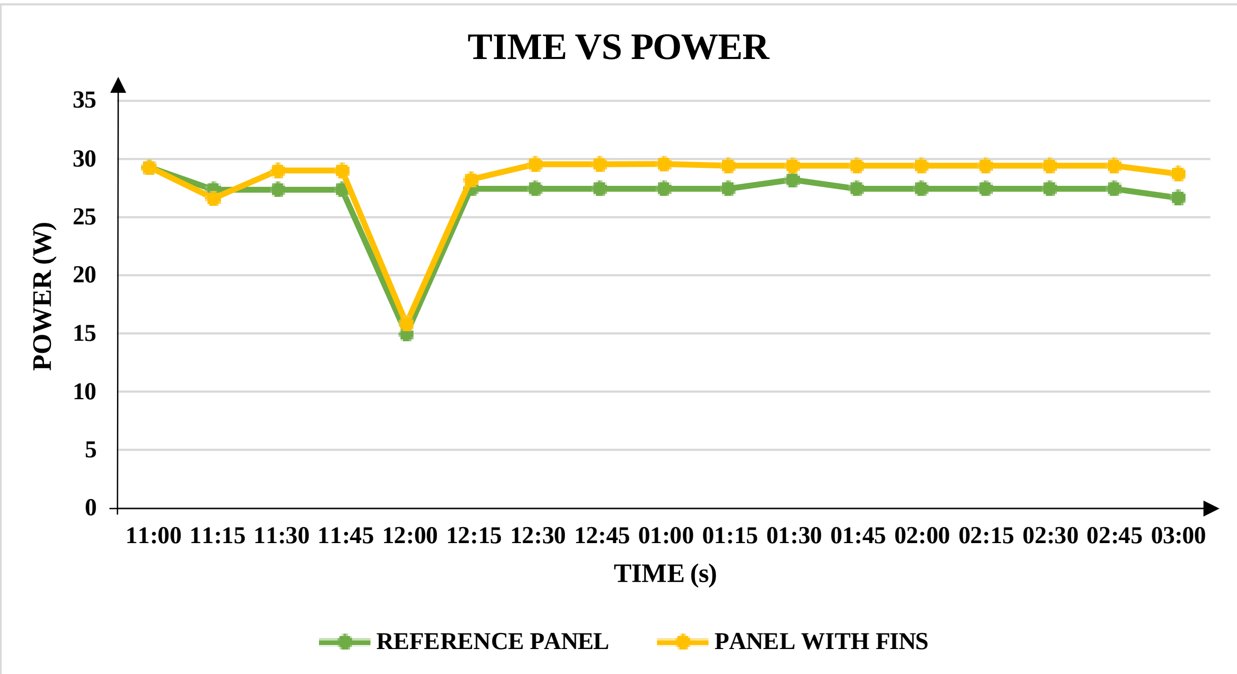


Figure 10: Time vs power graph (panel with fins vs reference panel)

Figure 10 shows that the fins integrated PV panel gives a greater enhancement in power compared to the reference panel. The maximum power of 29.55W is generated at 1.00 pm. The total increase in power output was 5.55 % compared to reference panel.

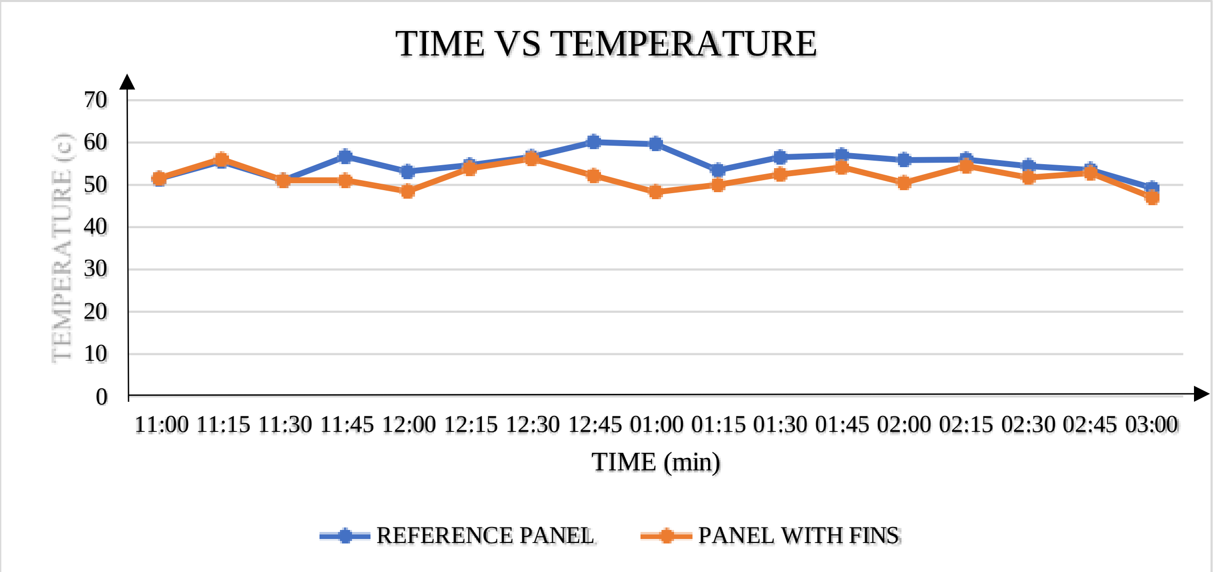


Figure 11: Time vs Temperature graph (panel with fins Vs reference panel)

Figure 11: shows that maximum temperature difference was obtained using fins compared to other three cooling methods. Fins increases the convective heat transfer by increasing the surface area. This is the reason why the integrated panel gives the best reduction in temperature. The maximum temperature difference obtained was 10.37℃ at 1.15 pm.

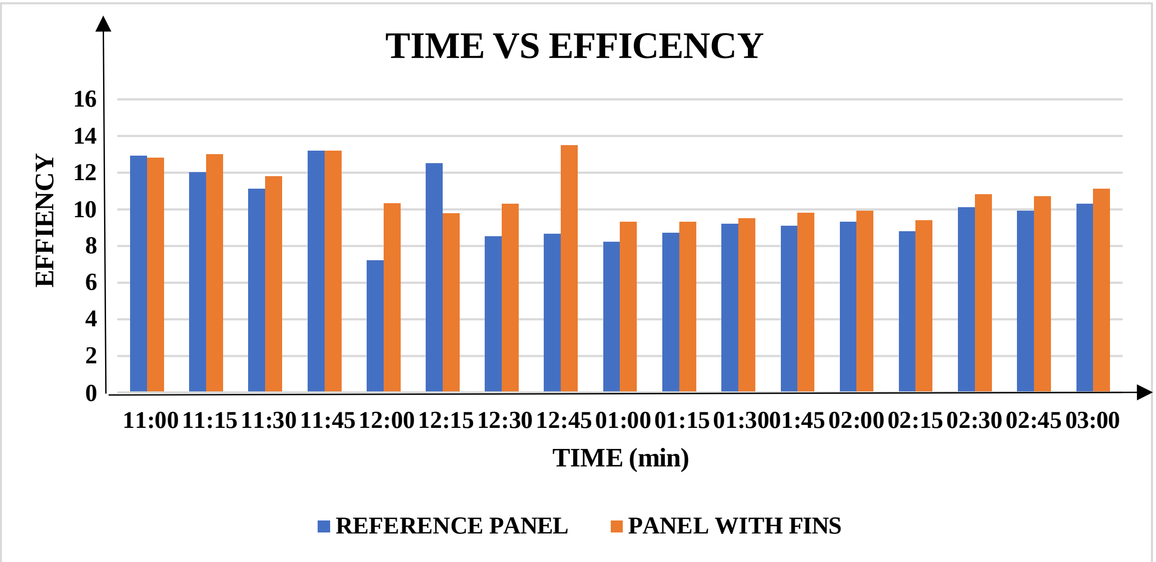


Figure 12: Time vs Efficiency graph (panel with fins Vs reference panel)

It is clear from the above graph (Figure 12) that the integration of fins into the panel has contributed positively in its efficiency and performance. In this case, maximum efficiency observed was 13.2%. Integration of fins improves the efficiency of PV panel by 8.85%.

4.3 Panel with hybrid system.

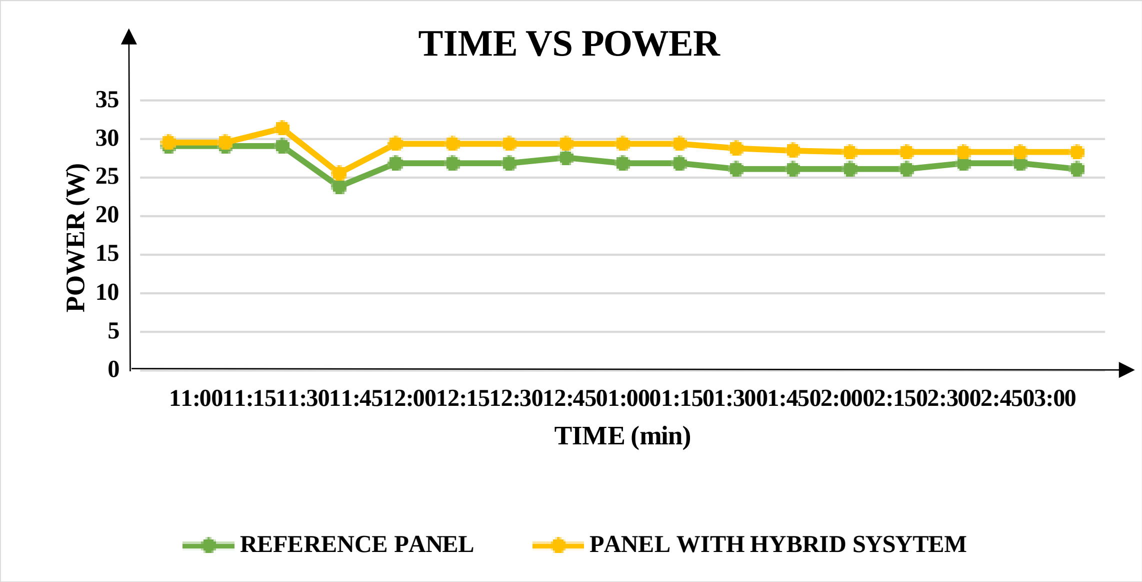


Figure13: Time vs Power graph (panel with hybrid system Vs reference panel)

Fig 13 indicates that, hybrid system shows improved power output compared to reference panel but failed to deliver the expected output. The power enhanced was 7.57%. The maximum power obtained was 31.4W at 11.30 am.

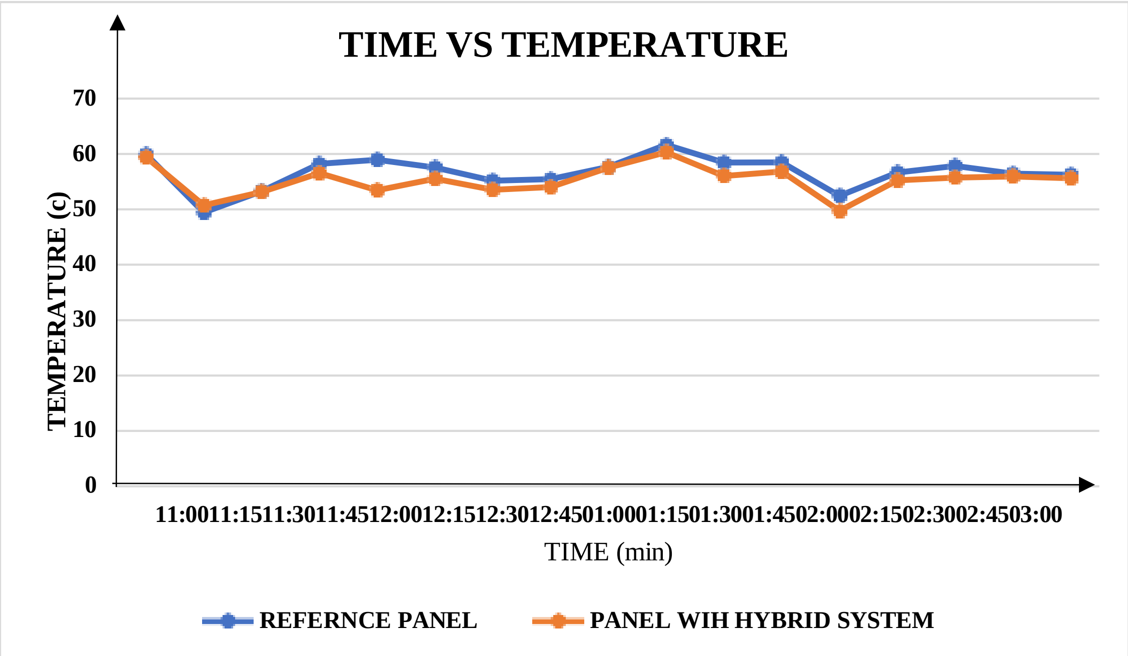


Figure 14: Time vs Power graph (panel with hybrid system Vs reference panel)

Even though the hybrid system did cool the PV panel it failed to meet the expected performance compared to other cooling techniques as shown in Figure 14. The reason for this setback is due to the decrease in convective heat transfer because of the low thermal conductivity of PCM. A maximum temperature difference of 2.7 °C is observed at 2.00 pm.

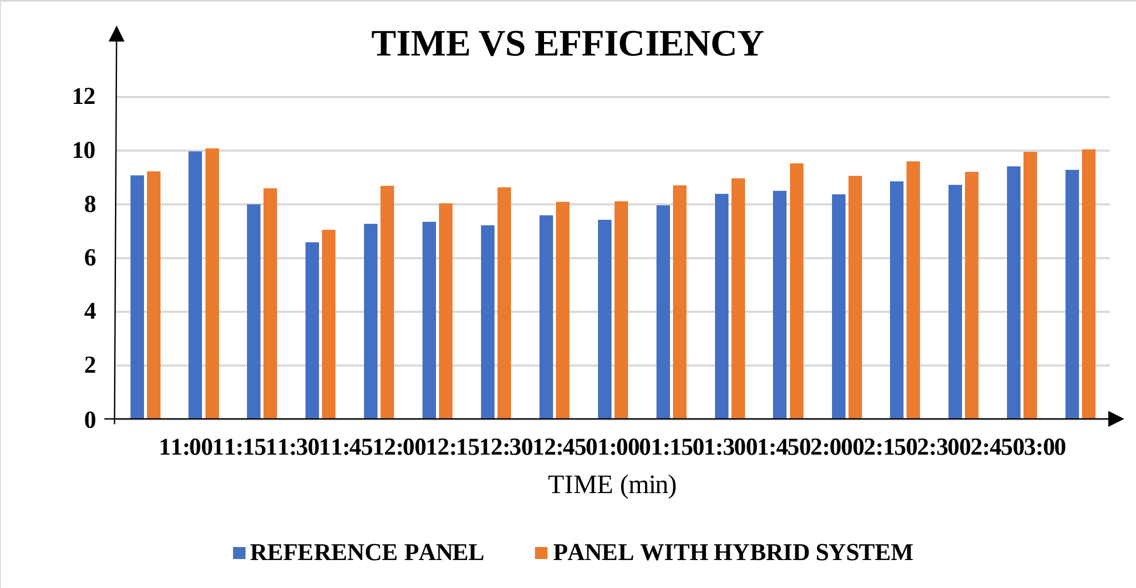


Figure 15: Time vs Efficiency graph (panel with hybrid system Vs reference panel)

It is clear from the above graph (Fig 15) that the integration of hybrid fins-PCM system into the panel has contributed positively in its efficiency and performance. In this case, maximum efficiency observed was 10.1. Integration of hybrid fins-PCM system improves the efficiency of PV panel by 7.8%.

5. CONCLUSIONS

- This study investigated the effectiveness of three passive cooling systems—fin-cooled, hybrid (fin + PCM), and PCM-only in improving the performance of photovoltaic (PV) panels. The results showed that integrating any of these cooling methods led to a significant reduction in panel temperature, which in turn boosted power output, improved efficiency, and extended the operational lifespan of the panels.

- Of the systems tested, the fin-cooled setup proved to be the most effective, achieving the greatest temperature reduction of about 10.37°C. This improvement had a substantial impact on panel performance. In comparison, the hybrid system reduced the temperature by 5.5°C, while the PCM system resulted in a 4.4°C reduction, making them less effective. Although the PCM system is capable of absorbing heat during its phase change, its performance drops once the material has fully transitioned. The hybrid system, which combined fins and PCM, did not perform as expected due to the low thermal conductivity of the PCM and possible issues with its integration with the fins, which led to reduced heat transfer and diminished cooling efficiency.

- The study also highlighted the role of thermal cycling—heating during the day and cooling at night—in causing long-term degradation of PV panels and reducing their efficiency. By using passive cooling methods, this temperature variation could be minimized, helping to extend the lifespan of the panels.

- In conclusion, the findings strongly support the use of fin-based passive cooling as an effective and cost-efficient solution for improving PV panel performance. However, it is important to note that these results are specific to the equipment and conditions used in this study, including the type of PV panel, the PCM OM 35, and the experimental setup with digital voltmeter, ammeter, and rheostat. As such, the results may vary under different conditions, but they provide a solid foundation for further research and the adoption of passive cooling technologies in the photovoltaic industry.

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