

Heat Sink-PCM Device for PV Efficiency Improvement

Carlos Armenta-Déu^{1,*}, Lizeth Mosquera²

Abstract

This paper is focused on the development of a second stage of a previous work where the PV panel efficiency is improved by using a hybrid system made up of a PCM attached to the rear side of the panel. This evolved stage incorporates a heat sink unit to improve the distribution of the heat removed from the panel; this improvement reduces the elapsed time to reach the steady state in the PCM, thus in the PV panel. A shorter time generates not only a lower operational temperature, but also a higher efficiency since the photovoltaic panel evolves in a dynamic situation due to continuous changes in solar radiation. Temperature reduction depends on solar radiation level, from barely 2.5°C, at early morning or late afternoon, where solar radiation is low, up to a maximum of 14.5°C at midday for a solar radiation level of 900 W/m². The PV panel efficiency has been improved up to 9% for the peak solar radiation at midday. Tests have proved the most effective period in PV efficiency improvement is in the range of ± 4 hours around midday based on an average solar day of 12 h. Efficiency improvement in this period is over 6.9% in the whole range. Outside this range, the efficiency improvement drops to a less of 3%. The global efficiency obtained using the hybrid heat sink-PCM system varies from 8.54% at early morning or late afternoon to 14.64% around midday. A correlation process has been developed to predict the temperature evolution of the PV panel under specific solar radiation conditions. The correlation predicts hourly values of PV panel efficiency improvement as well as global efficiency within almost 100% accuracy.

Keywords: PV panel heat removal. Hybrid heat sink-PCM device. Efficiency improvement.

INTRODUCTION

Heat removal from PV panels has been used as a method to reduce the temperature of the panel, thus improving its performance and increasing the efficiency. A general review of different methods used to this purpose is available on the literature [1]. Nevertheless, this review is mainly focused on methods based on watering front and rear side of the panel, which are not the unique solutions. A more general review is developed in a past work where authors review methods based on nanofluids, PCM system or thermoelectric devices [2–6]. Alternative methods are coupling to the rear side of the PV panel a heat exchanger through which a cooling fluid circulates [7], using specific fluids to

improve thermal conductivity and heat capacity [8], water [9] or geothermal cooling systems [10], heat sinks coupled to thermoelectric converters [11], attached PCM device with or without movable structure [12–14], beam splitters [15], hydrogels [16], heat pipes and others [17]. Air has been widely used as cooling fluid, either from HVAC systems [18] or merely from ambient combined with a PCM device [19]. The use of air as a heat exchanger is cheap and simple because of the abundance and easy access; however, due to the relative low heat capacity and thermal conductivity it is not the most appropriate system, producing a moderate to low temperature reduction [20, 21].

*Author for Correspondence

Carlos Armenta-Déu

¹Facultad de Ciencias Físicas, Dpto. Estructura de la Materia, Física Térmica y Electrónica, Universidad Complutense de Madrid, 28040 Madrid, Spain

²Facultad de Ciencias Físicas, Dpto. Estructura de la Materia, Física Térmica y Electrónica, Universidad Complutense de Madrid, 28040 Madrid, Spain

Received Date: October 11, 2021

Accepted Date: October 18, 2021

Published Date: October 22, 2021

Citation: Carlos Armenta-Déu, Lizeth Mosquera. Heat Sink-PCM Device for PV Efficiency Improvement. Journal of Thermal Engineering and Applications. 2021; 8(2): 35–48p.

In case a PCM system is used, the extracted energy from the rear side of a PV panel should be rapidly dissipated into the phase change material to avoid the creation of a thermal barrier at the PV-PCM interphase; since thermal conductivity of some PCM is poor, it is necessary to increase thermal conduction. To do so different techniques have been applied, among them we can mention the use of particle in suspension like graphite foam [22]. Another feasible solution is to insert a heat sink device into the PCM bulk that increases thermal conductivity [23]. The best advantage of this system is a more homogeneous distribution of the heat transfer provided the heat sink is properly designed.

Many configurations can be adopted in using a heat sink unit together with a PCM device [24–27]; heat sink unit can be attached to the PCM, inserted in the bulk, or filled with air [28]. The use of a hybrid heat sink-PCM system can help not only the heat removal from the PV panel but also the heat storage for thermal applications [29, 30]; therefore, it is wise to configure a heat removal system that enhances the PV panel efficiency as well as allows heat retention for thermal applications. To improve the achievement of this goal, a correct design is critical since the PCM should store thermal energy removed from the panel throughout the entire volume. If heat is not homogeneously distributed in the entire PCM volume, hot spots can appear melting the PCM in that area while adjacent zones remain in solid state. In this situation melted PCM sections play the role of heat nucleation center, absorbing energy and increasing temperature; if the melted zone is in contact with the rear side of the PV panel, both, local spot of the PV panel and melted zone of the PCM continues increasing temperature until reaching the steady state at much higher temperature than expected. To do so, an appropriate PCM must be selected as well as a correct design of the heat sink unit should be made.

THEORETICAL BASIS

Many PCM are used today for different applications [31–33]; however, not all of them are suitable for PV cooling. The use of the appropriate PCM makes the PV panel performance increasing [34–36].

It is well known that voltage and current of PV cells, thus of PV panels, evolves with temperature; while current tends to increase as temperature raises, voltage diminishes (Figure 1).

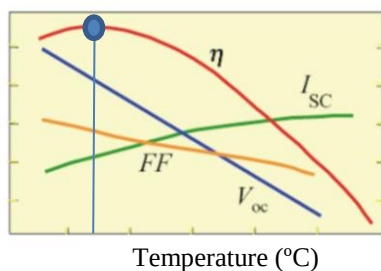


Figure 1. Evolution of characteristic parameters of a PV panel with temperature.

The parameters represented in Figure 1 can be related to each other through the expression:

$$\eta = FF \frac{I_{sc} V_{oc}}{GS} \quad (1)$$

Where I_{sc} is the short circuit current, V_{oc} is the open circuit voltage, FF is the fill factor that represents how close to the ideality is the PV cell or panel, and G is the global solar radiation striking onto the PV panel surface S .

Applying dependence of V_{oc} and I_{sc} on temperature, T , equation 1 is transformed into:

$$\eta = \frac{FF}{GS} (A + BT + CT^2) \quad (2)$$

Coefficients A , B and C are given by:

$$\begin{aligned} A &= I_{SC}^o V_{OC}^o - T_R (\beta_{OC} I_{SC}^o + \alpha_{SC} V_{OC}^o) + \alpha_{SC} \beta_{OC} T_R^2 \\ B &= \beta_{OC} I_{SC}^o + \alpha_{SC} V_{OC}^o - 2T_R \alpha_{SC} \beta_{OC} \\ C &= \alpha_{SC} \beta_{OC} \end{aligned} \quad (3)$$

Super-index o accounts for the state at the reference temperature, T_R . α_{SC} and β_{OC} are the current and voltage temperature coefficients for the PV panel.

Since the temperature coefficients and reference temperature are constant, coefficients A , B and C are constant too, and can be determined for a specific panel.

Equation 2 provides a useful tool to determine the efficiency of the PV panel as a function of the operating temperature provided coefficients A , B and C are known.

Thermal performance of the PV module

Thermal performance of PV panels are influenced by ambient temperature and solar radiation. PV panel temperature depends on ambient temperature according to the relation:

$$T_{FV} = T_a + \xi P_Q \quad (4)$$

Where P_Q is the heat power dissipated to the environment and ξ is the layer thermal coefficient given by:

$$\xi = C_T / S \quad (5)$$

The coefficient C_T represents the temperature variation coefficient due to incident solar radiation, and it is expressed in $^{\circ}\text{C}/(\text{W} \cdot \text{m}^{-2})$.

Heat power dissipation, P_Q , depends on environmental conditions, especially wind speed in the nearby of the PV panel and relative humidity [37] while temperature variation coefficient, C_T , depends on structural characteristics of the PV panel and manufacturing process [38].

Since the dependence of PV panel temperature on ambient temperature can be considered linear, equation 4 can be transformed into [39]:

$$T_{FV} = T_a + G_{ef} \frac{NOCT - 20}{800} \quad (6)$$

Where G_{ef} is the effective global solar radiation onto the front surface of the PV panel and $NOCT$ is the Nominal Operating Cell Temperature.

PV panel heating reduces efficiency as shown in Figure 1; to obtain the best performance heat should be removed the quickest possible to maintain PV panel temperature near the optimum value [40], blue spot in Figure 1; if heat is not rapidly removed the panel suffers from degradation, what limits its lifespan [41].

Since the front side of the panel receives solar radiation heat must be removed from the rear side, either by conduction, convection or radiation. These two last mechanisms, in current operating conditions, can be considered negligible, therefore, only conduction is considered. Thermal transfer from PV panel to the heat sink-PCM system can be expressed as:

$$\dot{Q} = (\kappa/e) S (T_{FV} - T_a) \quad (7)$$

κ and e are the thermal transfer coefficient of the interphase layer between PV panel and environment, and the layer thickness.

In case we deal with a PCM unit attached to the rear side of the panel:

$$(\kappa/e)S(T_{FV} - T_{PCM}) = m_{PCM}c_{PCM}^s(T_{PC} - T_{PCM}^o) + m_{PCM}L_{PCM} + m_{PCM}c_{PCM}^L(T_{PCM}^f - T_{PC}) \quad (8)$$

Super-indexes s and L account for solid and liquid phase, o for initial state. Sub-index PC indicates phase change process; m is the mass of the PCM, c the specific heat, L the latent heat, and T the temperature.

Second term of equation 8 represent the absorbed heat by the PCM unit; it is assumed that the heat capacity of the heat sink unit is negligible compared to the one of the PCM.

Equation 8 considers there is a heating process in the PCM at the solid phase, first term of the right hand of equation 8, and at the liquid phase, third term, and a phase change, second term.

Taking into account that heat removal is defined by [42]:

$$\dot{Q} = G_{ef}S(1-\eta) \quad (9)$$

and combining equations 2, 8 and 9, we obtain the expression that shows the conditions for which the PCM remains in the phase change zone:

$$\begin{aligned} (\kappa/e)S(T_{FV} - T_{PCM}) &= G_{ef}S(1-\eta) = G_{ef}S \left[1 - \frac{FF}{G_{ef}S} (A + BT + CT^2) \right] = \\ &= m_{PCM}c_{PCM}^s(T_{PC} - T_{PCM}^o) + m_{PCM}L_{PCM} + m_{PCM}c_{PCM}^L(T_{PCM}^f - T_{PC}) = \\ &= m_{PCM}c_{PCM}^s(T_{PC} - T_{PCM}^o) + m_{PCM}L_{PCM} + \dot{Q}_L \end{aligned} \quad (10)$$

The term $\dot{Q}_L$ in equation 10 represents the extra heat that exceeds the PCM capacity of absorbing thermal energy from the panel maintaining at the phase change state.

Arranging equation 10 and defining extra heat per mass unit and specific heat of the PCM:

$$\dot{q}_L = \frac{\dot{Q}_L}{m_{PCM}c_{PCM}^s} = \frac{[G_{ef}S - FF(A + BT + CT^2)]}{m_{PCM}c_{PCM}^s} - (T_{PC} - T_{PCM}^o) - \frac{L_{PCM}}{c_{PCM}^s} \quad (11)$$

To fulfil the condition of maintaining the PCM below the liquid saturation point

$$\dot{q}_L \leq 0 \quad (12)$$

therefore, operating in equation 11:

$$A - \frac{m_{PCM}c_{PCM}^s}{FF} \left(\Delta T_{PCM} + \frac{L_{PCM}}{c_{PCM}^s} - \frac{G_{ef}S}{m_{PCM}c_{PCM}^s} \right) \leq (BT + CT^2) \quad (13)$$

Or:

$$(J + G_{ef}DH) \leq (D\Delta T_{PCM} + BT + CT^2) \quad (14)$$

With:

$$D = \frac{m_{PCM} c_{PCM}^s}{FF}; E = \frac{L_{PCM}}{c_{PCM}^s}; H = \frac{S}{m_{PCM} c_{PCM}^s}; J = A - DE \quad (15)$$

Where coefficients A, B, C, D, E and H are constant for a specific PV panel and PCM device.

Equation 14 shows the condition to maintain the PCM operating within the phase change state. Since the PV panel temperature increases with solar radiation the two terms on both sides of the inequality increase; therefore, to verify the PCM device operates at the right conditions, the following equation must be fulfilled:

$$m_{PCM} \geq K \left(A + G_{ef} \frac{S}{FF} - BT - CT^2 \right) \quad (16)$$

With

$$K = \frac{FF}{L_{PCM} + c_{PCM}^s \Delta T_{PCM}} \quad (17)$$

which is also constant for the specific defined system.

Equation 16 imposes the minimum mass of the PCM device to fulfil the condition of operating at the phase change state.

EXPERIMENTAL TESTS

Characterization tests of the PV panel

Solar radiation has been simulated using a solar lamp whose radiation spectrum matches the solar one, within 94% in the visible range and 91% in the infrared. To reproduce real conditions a simulation process for the solar radiation, using the PVGYS software, has been developed [43]. Figure 2 shows the graph representation of the simulated solar radiation.

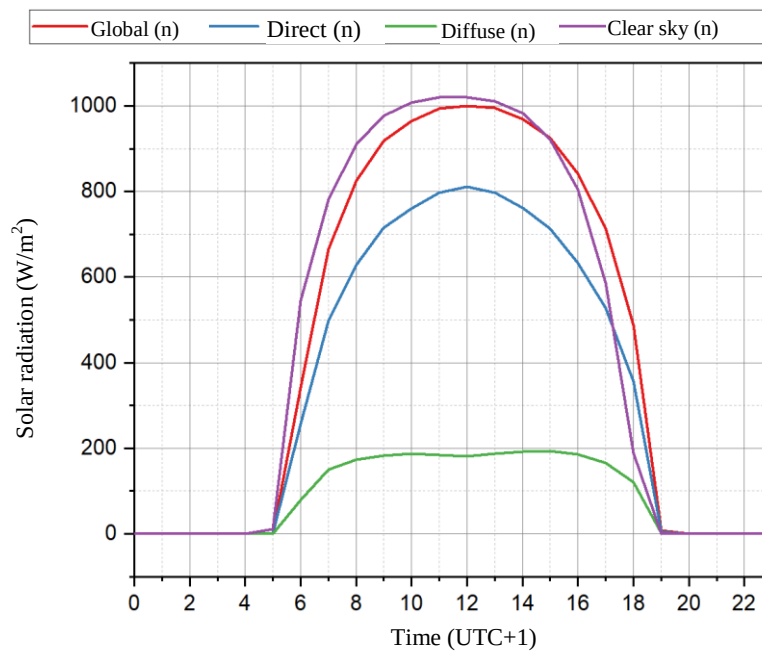


Figure 2. Simulated solar radiation.

To analyze the evolution of the PV panel temperature with solar time we have extracted from Figure 2 the solar radiation values corresponding to specific hourly intervals. Table 1 shows the simulated solar radiation distribution for a typical solar day starting at 6 am and ending at 6 pm. A twelve hours solar day length has been considered since it represents the yearly average value.

Table 1. Solar radiation distribution for daily hourly intervals.

Starting hour	Ending hour	Starting hour	Ending hour	Solar radiation (W/m^2)
06:00	07:00	12:00	13:00	351.9 ± 34.9
07:00	08:00	13:00	14:00	592.2 ± 56.0
08:00	09:00	14:00	15:00	712.6 ± 65.7
09:00	10:00	15:00	16:00	793.3 ± 68.4
10:00	11:00	16:00	17:00	866.5 ± 65.0
11:00	12:00	17:00	18:00	908.3 ± 63.2
12:00				940.8 ± 66.1

Experimental tests have been run on a PV panel whose main characteristics are described in Table 2.

Table 2. Characteristics of the tested PV panel.

Parameter	Value
Power (P_{FV})	10 Wp
Open circuit voltage (V_{OC})	21.2 V
Maximum voltage (V_{PM})	17.6 V
Short circuit current (I_{SC})	0.61 A
Maximum current (I_{PM})	0.57 A
Power coefficient (γ_P)	$-(0.50 \pm 0.05) \text{ } ^\circ\text{C}^{-1}$
Voltage coefficient (β_{OC})	$-(90 \pm 5) \text{ mV} ^\circ\text{C}^{-1}$
Current coefficient (α_{SC})	$-(0.065 \pm 0.015) \text{ } ^\circ\text{C}^{-1}$
NOCT	$(47 \pm 2) ^\circ\text{C}$

Since the required amount of PCM, according to equation 16, depends on both, solar radiation level and PV panel temperature, we have developed a characterization test of the PV panel to establish the temperature evolution with solar radiation level. The results of this process are represented in Figure 3.

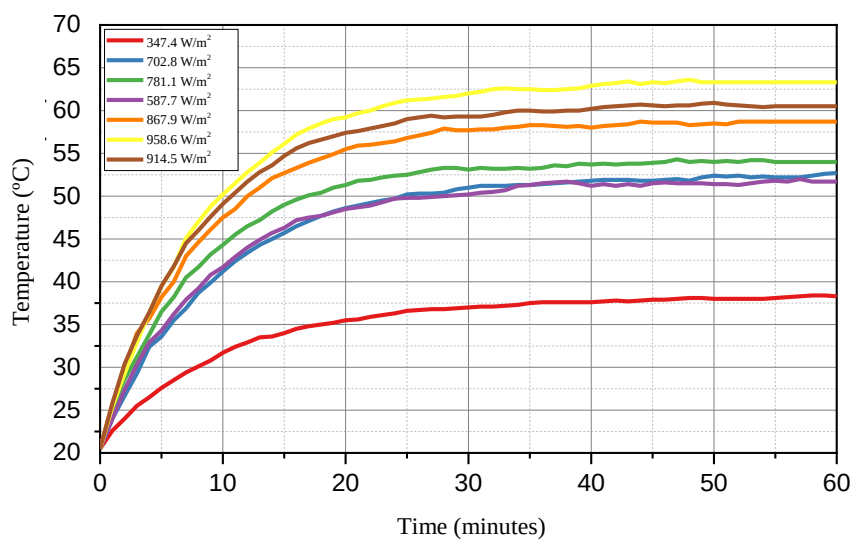


Figure 3. Temperature evolution of the PV panel with solar radiation level.

It can be observed that steady state temperature of the PV panel increases with solar radiation. To establish the relation between the two parameters we have developed a correlation process, obtaining the following expression:

$$T_{FV} = 0.0365G_{ef} + 31.289 \quad (R^2 = 0.970) \quad (18)$$

Correlation indicates the dependence of temperature of the PV panel on solar radiation is linear within high accuracy.

Combining equations 16 and 18 and grouping terms:

$$m_{PCM} \geq a + bG_{ef} + cG_{ef}^2 \quad (19)$$

With:

$$\begin{aligned} a &= K(A - 31.289B - 979.002C) \\ b &= K\left(\frac{S}{FF} - 0.0375B + 1.173C\right) \\ c &= K(0.0014C) \end{aligned} \quad (20)$$

Equation 19 provides a useful tool to determine the minimum required amount of PCM to maintain it within the phase change zone as a function of the solar radiation.

Once this equation is obtained, we are in position to calculate the required amount of PCM for our testing model. Using values for the parameters involved in equation 19, a mass of 2840 g is obtained.

To select the appropriate PCM, two factors are important, first the temperature of phase change of the PCM that should match the operational temperature of the PV panel, and second the available space considering the frame of the PV panel. Using the dimensions of the tested panel, 417x264x30 mm (LxWxH), the density of the PCM should be:

$$\rho = \frac{m}{(L)(W)(H)} = \frac{2.840}{(0.417)(0.264)(0.030)} = 860 \text{ kg} / \text{m}^3 \quad (21)$$

That matches perfectly with the paraffin wax. Since this PCM operates in the range of 40° C to 70° C depending on the organic composition, it is a very suitable PCM for PV panel cooling. In our case, we choose an intermediate organic composition with a phase change temperature within the range of 47° C to 54.4° C.

Efficiency of the PV panel for the different solar radiation level is obtained from equation 1; the results of the characterization tests are given in Table 3.

Table 3. Efficiency of the PV panel for different solar radiation level.

Solar radiation (W/m ²)	Efficiency (%)
347.4	7.02
587.7	5.56
702.8	5.90
781.1	5.75
867.9	5.75
914.5	5.69
958.6	5.91

We observe the efficiency remains almost constant except for the lowest value of the solar radiation. Since this solar radiation corresponds to early morning or late afternoon, see Table 1, where collected energy is very low, we can discard this value and average the PV panel efficiency, resulting a value of 5.76%.

The low value of the efficiency is due to the effects of temperature; in effect, the optimum point of the PV panel is 25°C [43]; therefore, the greater the deviation, the lower the efficiency. Because the operating temperature of the PV panel during characterization tests is in the range of 51.7°C to 65.1°C, averaging the PV panel temperature within the mentioned range, we obtain a working temperature of 60.9°C, meaning a deviation of 35.9°C from optimum value.

To validate the results from the characterization process we have applied the following expression that reflects the efficiency loss for specific operating conditions:

$$\Delta\eta = \gamma_p \left(\overline{T}_{op} - T_{NOCT} \right) \frac{G_{max}}{\overline{G}_{ef}} \quad (22)$$

Applying values from our test:

$$\Delta\eta = (0.5)(60.9 - 47) \frac{1000}{802} = 8.67\% \quad (22)$$

Adding this value to the average efficiency obtained in the test, it results:

$$\eta = \eta_{av} + \Delta\eta = 5.76 + 8.67 = 14.44\% \quad (23)$$

Which is in good agreement with the reference value, 15%, provided by the manufacturer.

Heat sink-PCM device tests

A second group of experimental tests are developed to determine the influence of the hybrid heat sink-PCM device on the PV panel performance. To do so, a finned flat comb-shaped heat sink was designed to fit the rear side of the PV panel with fins height matching the thickness of the PV panel frame. A methacrylate layer was glued to the edge of the PV panel frame and the inner empty space was filled up with liquid paraffin wax. T-type thermocouples, with an accuracy of $\pm 0.5^\circ\text{C}$, are used to measure the PV panel temperature, the bulk of the paraffin wax and the heat sink. Thermocouples are connected to a data acquisition system that records temperature continuously. Output voltage and current from the PV panel are measured using a DC power analyzer that records values every second with accuracy of 1 mV and 1 mA.

Tests are run under same solar radiation level than in the previous test obtaining the time evolution of the system temperature for the different solar radiation level. Figure 4 shows the results of the experimental test.

It can be observed that PV panel temperature has been reduced from an average value of 60.9°C to 49.3°C, a reduction of 11.6°C. Translating this value to efficiency improvement (equation 21), we have:

$$\Delta\eta = (0.5)(11.6) \frac{1000}{802} = 7.23\% \quad (24)$$

Adding this efficiency improvement to the value obtained for PV panel only, the current efficiency is: $\eta = 5.76 + 7.23 = 12.99\%$. This result improves the efficiency increase obtained in a previous work [44] where efficiency using only a PCM device was 8.61%. Table 4 resumes the comparative analysis of the PV panel efficiency for the different configurations.

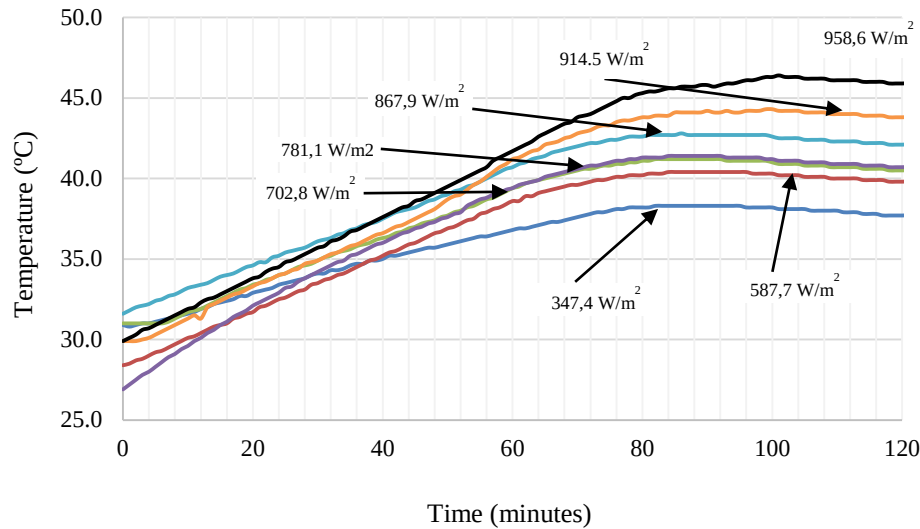


Figure 4. Evolution of the PV panel with the attached heat sink-PCM device.

Table 4. Comparative results of average PV panel efficiency for different configurations.

Configuration	Efficiency (%)
PV panel	5.76
PV+PCM	8.61
PCM-heat sink-PCM	12.99

It can be noticed that the use of a heat sink-PCM device improves the efficiency by 7.23%, while the use of a simple PCM device only improves the efficiency by 2.85%; this means the insertion of a heat sink increases the PV panel efficiency 2.5 times respect to the use of the PCM device alone. The efficiency increase obtained with the new system also improves the referenced increases of the PV panel efficiency using only a PCM device, which is the range of 2.8% to 4.3% [45, 46], coupled PCM and thermoelectric (TEG) devices that increases the efficiency by 1.38% [47], or even the efficiency improvement of advanced systems like PCM with TES unit, which increase the efficiency up to 6.5% [48].

To a more detail analysis of the developed study of the PV panel efficiency improvement, a comparison is made for every solar radiation level; the results of this comparison are presented in Figure 5. The analysis of the results from Figure 5 shows the influence of using a heat sink-PCM device for low solar radiation level (347.4 W/m^2) is of minor significance, since the reduction of temperature is only 2.5°C , which barely influences the efficiency of the PV panel. Applying equation 21 we obtain an efficiency improvement of 1.6%. In the case of medium to high solar radiation level (702.8 W/m^2), the influence of the PCM reveals more important, especially when combined with the heat sink device; in this case the reduction of temperature is of 11°C , what results in an efficiency improvement of 6.9%, near the above mentioned value of 7.23%. In the third case, for a solar radiation value of 914.5 W/m^2 , the influence of the heat sink-PCM device is the greatest, with a temperature reduction of 14.5°C that means an efficiency increase of 9.0% [49].

To allow a daily hourly prediction of the efficiency improvement of a PV panel equipped with a heat sink-PCM device, we have correlated temperature reduction and efficiency improvement to solar radiation, obtaining the following mathematical functions:

a) *Temperature reduction*

$$\Delta T = 12.329 \ln G_{ef} - 69.669 \quad (R^2 = 0.9995) \quad (25)$$

b) Efficiency improvement

$$\Delta\eta = 7.6199 \ln G_{ef} - 42.995 \quad (R^2 = 0.9998) \quad (26)$$

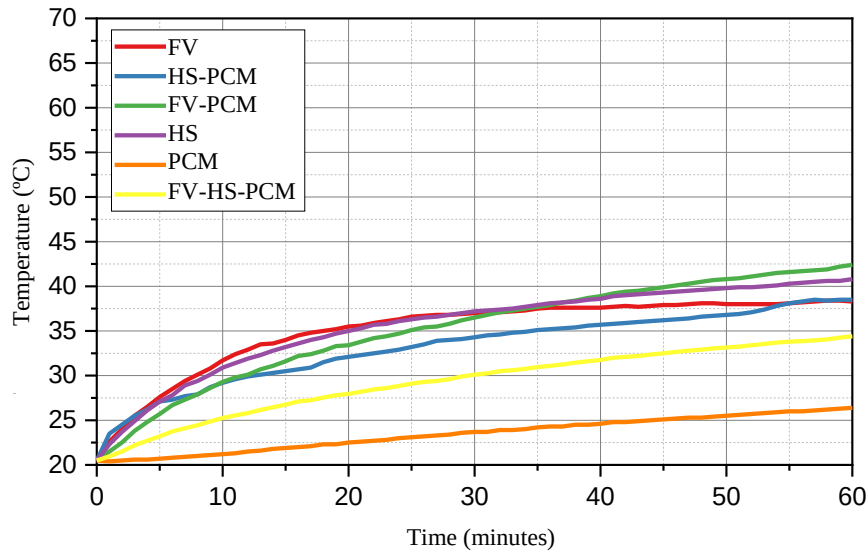


Figure 5. (a) Temperature evolution of different PV panel configurations (solar radiation level: 347.4 W/m²) FV: Photovoltaic panel; HS: Heat Sink; PCM: Phase Change Material.

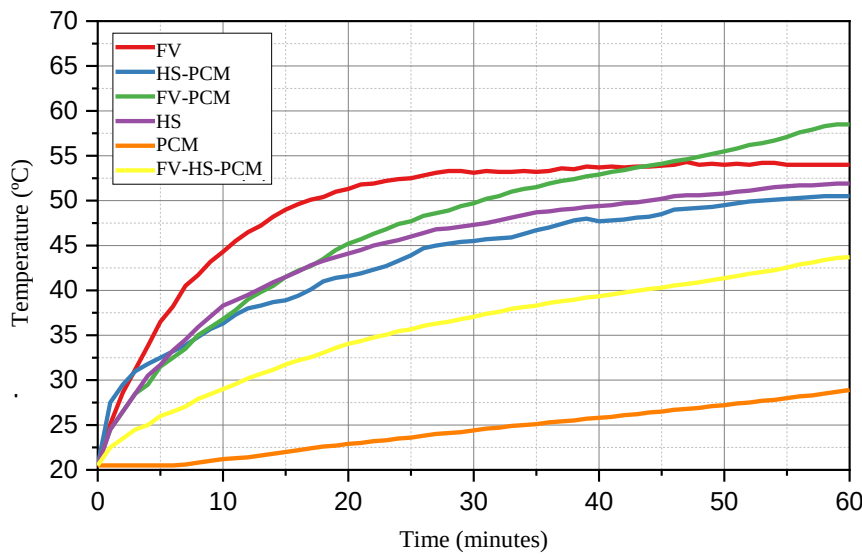


Figure 5. (b) Temperature evolution of different PV panel configurations (solar radiation level: 702.8 W/m²) FV: Photovoltaic panel; HS: Heat Sink; PCM: Phase Change Material.

Equations 25 and 26 show the efficiency and temperature reduction improvement depends linearly on temperature reduction; in effect, correlating both parameters it results:

$$\Delta\eta = 0.6179\Delta T + 0.0659 \quad (R^2 = 0.9999) \quad (27)$$

Equation 26 provides a useful tool to predict the increase of the PV panel efficiency as a function of the solar radiation. If we combine equation 26 with values from Table 1, we can obtain the daily hourly efficiency improvement of the PV panel.

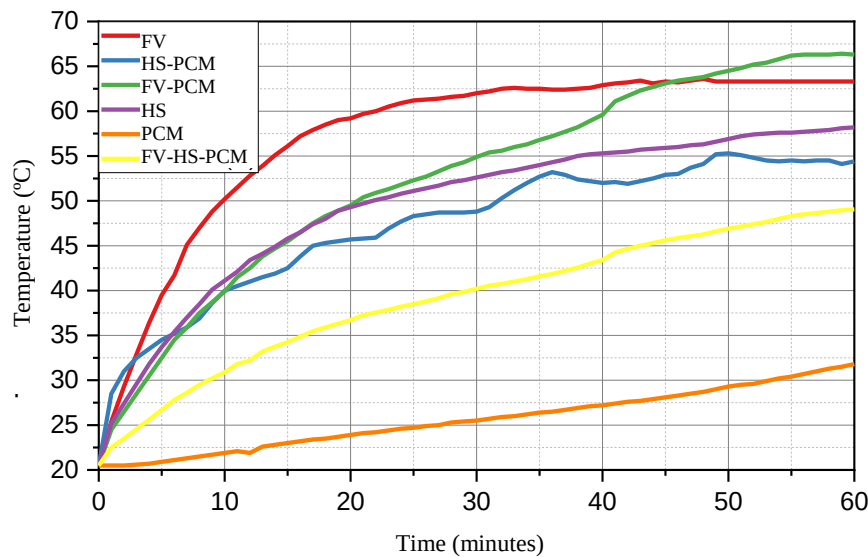


Figure 5. (c) Temperature evolution of different PV panel configurations (solar radiation level:914.5 W/m²) FV: Photovoltaic panel; HS: Heat Sink; PCM: Phase Change Material.

CONCLUSIONS

A heat sink-PCM hybrid system has been built using paraffin wax as heat storage to collect heat removed from the PV panel. The hybrid system reduces the PV panel temperature and increases its efficiency.

Efficiency improvement depends on temperature reduction. The proposed system reduces the temperature of the PV panel proportionally to the solar radiation level. The effects of temperature reduction are significant in the range of ± 4 hours around midday in an average solar day of 12 hours; therefore, it represents 2/3 of the solar day length where the PV panel efficiency is significantly improved.

The efficiency of the heat sink-PCM hybrid system has been increased by a maximum of 9% for high solar radiation level, with an average improvement of 7.23%. As a result of this improvement, the PV panel efficiency has raised to 13% for an average operating temperature of 42° C. The efficiency improvement is high, above 6.9% in the aforementioned time range, dropping to a less of 3% outside this range.

The average efficiency using the heat-sink-PCM device is close to the reference value of 15% provided for the manufacturer, but for a higher working temperature; converting the efficiency obtained in the proposed prototype to the standard temperature of 25° C the efficiency is of 16.4%, even higher than the reference value; therefore, the insertion of a heat sink-PCM device represents an effective improvement in the PV performance.

A mathematical function has been developed to relate the efficiency improvement to the solar radiation level, providing a useful tools to predict daily hourly efficiency of a PV panel equipped with a heat sink-PCM device. The prediction is of high accuracy, near 100%, what ensures the reliability of the predicted values.

REFERENCES

1. Someshwar S. Bhakre, Pravin D.Sawarkar, Vilas R.Kalamkar (2021) Performance evaluation of PV panel surfaces exposed to hydraulic cooling – A review, Solar Energy Volume 224, Pages 1193-1209

2. Akbar Maleki, Arman Haghighi, Mamdouh El Haj Assad, Ibrahim Mahariq, Mohammad Alhuyi Nazari (2020) A review on the approaches employed for cooling PV cells, *Solar Energy*, Volume 209, Pages 170-185
3. Abdulhammed K.Hamzat, Ahmet Z.Sahin, Mayowa I.Omisanya, Luai M.Alhems (2021) Advances in PV and PVT cooling technologies: A review, *Sustainable Energy Technologies and Assessments*, Volume 47, 101360
4. Shrey Verma, Subhashree Mohapatra, Subhankar Chowdhury, Gaurav Dwivedi (2021) Cooling techniques of the PV module: A review, *Materials Today, Proceedings*, Volume 38, Part 1, Pages 253-258
5. Akbar Maleki, Arman Haghighi, Mamdouh El Haj Assad, Ibrahim Mahariq, Mohammad Alhuyi Nazari (2020) A review on the approaches employed for cooling PV cells, *Solar Energy*, Volume 209, Pages 170-185
6. Challa Babu, P. Ponnambalam (2017) The role of thermoelectric generators in the hybrid PV/T systems: A review, *Energy Conversion and Management*, Volume 151, Pages 368-385
7. Mohamed Fterich, Houssam Chouikhi, Sadoth Sandoval-Torres, Hatem Bentaher, Ahmed Elloumi, Aref Maalej (2021) Numerical simulation and experimental characterization of the heat transfer in a PV/T air collector prototype, *Case Studies in Thermal Engineering*, Volume 27, 101209
8. Fazlay Rubbi, Khairul Habib, R.Saidur, Navid Aslfattahi, Syed Mohd Yahya, Likhan Dasa (2020) Performance optimization of a hybrid PV/T solar system using, Soybean oil/MXene nanofluids as A new class of heat transfer fluids, *Solar Energy*, Volume 208, Pages 124-138
9. Nasrin Abdollahi, Masoud Rahimi (2020) Potential of water natural circulation coupled with nano-enhanced PCM for PV module cooling, *Renewable Energy*, Volume 147, Part 1, Pages 302-309
10. Nabil A.S.Elminshawy, A.M.I.Mohamed, K.Morad, Y.Elhenawy, Abdulrahman A.Alrobaian (2019) Performance of PV panel coupled with geothermal air cooling system subjected to hot climatic, *Applied Thermal Engineering*, Volume 148, Pages 1-9
11. Rouhollah Salehi, Ahmad Jahanbakhshi, Mahmood Reza Golzarian, Mehdi Khojastehpour (2021) Evaluation of solar panel cooling systems using anodized heat sink equipped with thermoelectric module through the parameters of temperature, power and efficiency, *Energy Conversion and Management: X*, Volume 11, 100102
12. Adeel Waqas, Jie Ji (2017) Thermal management of conventional PV panel using PCM with movable shutters – A numerical study, *Solar Energy*, Volume 158, Pages 797-807
13. Rok Stropnik, Uroš Stritih (2016) Increasing the efficiency of PV panel with the use of PCM, *Renewable Energy*, Volume 97, Pages 671-679
14. Sajan Preet (2021) A review on the outlook of thermal management of photovoltaic panel using phase change material, *Energy and Climate Change*, Volume 2, 100033
15. Sushil Kumar, Robin Thakur, Arvind Singhy, R.K.Tripathi, Muneesh Sethi (2021) A review of heat removal mechanism in concentrated PVT systems using beam splitter, Available online 8 July 2021
16. Saber Abdo, Hind Saidani-Scott, Jorge Benedic, M.A.Abdelrahman (2020) Hydrogels beads for cooling solar panels: Experimental study, *Renewable Energy*, Volume 153, June 2020, Pages 777-786
17. S. Sargunanathan, A. Elango, S. Tharves Mohideen (2016) Performance enhancement of solar photovoltaic cells using effective cooling methods: A review, *Renewable and Sustainable Energy Reviews*, Volume 64, October 2016, Pages 382-393
18. Wassim Salameh, Cathy Castelain, Jalal Faraj, Rabih Murr, Hicham El Hage, Mahmoud Khaled (2021) Improving the efficiency of photovoltaic panels using air exhausted from HVAC systems: Thermal modelling and parametric analysis, *Case Studies in Thermal Engineering*, Volume 25, June 2021, 100940
19. Lijie Xu, Jie Ji, Jingyong Cai, Wei Ke, Xinyi Tian, Bendong Yu, Jun Wang (2021) A hybrid PV thermal (water or air) wall system integrated with double air channel and phase change material:

- A continuous full-day seasonal experimental research, *Renewable Energy*, Volume 173, Pages 596-613
20. Alen Rida, Determinación de la mejora del rendimiento en un panel fotovoltaico (Determination of the efficiency improvement in a photovoltaic panel), Master Thesis, Complutense University of Madrid (2012)
 21. Jan Wajs, Aleksandra Golabek, Roksana Bochniak, Dariusz Mikielewicz (2020) Air-cooled photovoltaic roof tile as an example of the BIPVT system – An experimental study on the energy and exergy performance, *Energy*, Volume 197, 117255
 22. Chunrong Zhao, Michael Opolot, Ming Liu, Frank Bruno, Simone Mancin, Kamel Hooman (2021) Phase change behaviour study of PCM tanks partially filled with graphite foam, *Applied Thermal Engineering*, Volume 196, 117313
 23. Zaiguo Fu, Xiaotian Liang, Yang Li, Lingtong Li, Qunzhi Zhu (2021) Performance improvement of a PVT system using a multilayer structural heat exchanger with PCMs, *Renewable Energy*, Volume 169, Pages 308-317
 24. T.Wongwuttanasatian, T.Sarikarin, A.Suksri (2020) Performance enhancement of a photovoltaic module by passive cooling using phase change material in a finned container heat sink, *Solar Energy*, Volume 195, Pages 47-53
 25. Preeti Singh, Sourav Khanna, Sanjeev Newar, Vashi Sharma, K. Srinivas Reddy, Tapas K. Mallick, Victor Becerra, Jovana Radulovic, David Hutchinson, Rinat Khusainov (2020) Solar Photovoltaic Panels with Finned Phase Change Material Heat Sinks, *Energies*, Volume 13, Issue 10, 2558
 26. Idris Al Siyabi, Sourav Khanna, Tapas Mallick, Senthilarasu Sundaram (2018) Multiple Phase Change Material (PCM) Configuration for PCM-Based Heat Sinks—An Experimental Study, *Energies*, Volume 11, Issue 7, 1629
 27. Abhishek Saxena, Nitin Agarwal, Brian Norton (2021) Design and performance characteristics of an innovative heat sink structure with phase change material for cooling of photovoltaic system, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, Taylor and Francis online, <https://doi.org/10.1080/15567036.2021.1968545> (Accessed on 07/10/2021)
 28. Rasool Kalbasi (2021) Introducing a novel heat sink comprising PCM and air - Adapted to electronic device thermal management, *International Journal of Heat and Mass Transfer*, Volume 169, 120914
 29. Maria C.Browne, Brian Norton, Sarah J. McCormack (2016) Heat retention of a photovoltaic/thermal collector with PCM, *Solar Energy*, Volume 133, Pages 533-548
 30. S.Rahmanian, H.Rahmanian-Koushkaki, P.Omidvar, A.Shahsavari (2021) Nanofluid-PCM heat sink for building integrated concentrated photovoltaic with thermal energy storage and recovery capability, *Sustainable Energy Technologies and Assessments*, Volume 46, 101223
 31. M. Kenisarin and K. Mahkamov (2007) Solar energy storage using phase change materials, *Renewable and Sustainable Energy Reviews*, Volume 11, Issue 9, Pages 1913–1965
 32. M. M. A. Khan, R. Saidur, F. A. Al-Sulaiman (2017) A review for phase change materials (PCMs) in solar absorption refrigeration systems, *Renewable and Sustainable Energy Reviews*, Volume 76, Issue 9, Pages 105–137
 33. Shuai Zhang, Daili Feng, Lei Shi, Li Wang, Yingai Jin, Limei Tian, Ziyuan Li, Guoyong Wang, Lei Zhao, Yuying Yan (2020) A review of phase change heat transfer in shape-stabilized phase change materials (ss-PCMs) based on porous supports for thermal energy storage, *Renewable and Sustainable Energy Reviews*, Volume 135, Issue, August 2020, 110127
 34. Akshayveer, A. P. Singh, A. Kumar, O. P. Singh (2020) Effect of natural convection and thermal storage system on the electrical and thermal performance of a hybrid PV-T/PCM systems, *Materials Today Proceedings*, Volume 39, Part 5, Pages 1899-1904
 35. M. Tao, L. Zhenpeng, Z. Jiaxin (2019) Photovoltaic panel integrated with phase change materials (PV-PCM): technology overview and materials selection, *Renewable and Sustainable Energy Reviews*, Volume. 116, Issue December 2019, 109406

-
36. A. Waqas, J. Jie (2018) Effectiveness of Phase Change Material for Cooling of Photovoltaic Panel for Hot Climate, *Journal of Solar Energy Engineering*, Trans. ASME, Vol. 140, Issue 4, Pages 1–19
 37. A. McEvoy, T. Markvart, L. Castañer, *Practical Handbook of Photovoltaics*, 2nd ed.: Fundamentals and Applications, Ed. Academic Press (2011), ISBN: 9780123859341
 38. Sarah Kurtz, Analysis of Photovoltaic System Energy Performance Evaluation Method, Technical Report, NREL/TP-5200-60628, National Renewable Energy Laboratory (NREL), November 2013
 39. Antonio Luque, Steven Hegedus, *Handbook of Photovoltaic Science and Engineering*, Ed. John Wiley and Sons Ltd., 2003
 40. A. Karafil (2016) Temperature and Solar Radiation Effects on Photovoltaic Panel Power, *Journal of New Results Sci.*, Volume 5, Issue 12, Pages 48-58
 41. S. Dubey, J. N. Sarvaiya, B. Seshadri (2013) Temperature dependent photovoltaic (PV) efficiency and its effect on PV production in the world - A review, *Energy Procedia*, Volume 33, Pages 311–321
 42. C. Armenta-Déu (2021) Analysis of the performance of a PV-PCM system in variable solar radiation conditions, *Journal of Alternate Energy Sources and Technology*, Volume 12, Issue 1, Pages 1-20
 43. EU SCIENCE HUB, JRC Photovoltaic Geographical Information System (PVGIS) - European Commission. https://re.jrc.ec.europa.eu/pvg_tools/es/tools.html (accessed March, 08, 2021)
 44. How hot do solar panels get?. Effect of temperature on PV panel efficiency, Greentumble, Solar Energy, March 12, 2018, <https://greentumble.com/effect-of-temperature-on-solar-panel-efficiency/> (Accessed, October 08, 2021)
 45. Lizeth Mosquera, Thermodynamic photovoltaic panels: Stage II: Improvement of the design to increase thermal efficiency in heat removal, Master Thesis, Complutense University of Madrid (2021)
 46. K.Senthil Kumar, S.Revanth, D.Sanjeev, P.Sabesh Kumar, P.Surya (2021) Experimental investigation of improving the energy conversion efficiency of PV cell by in integrating with PCM, Volume 37, Part 2, Pages 712-716
 47. K.Senthil Kumar, H.Ashwin Kumar, P.Gowtham, S.Hari Selva Kumar, R.Hari Sudhan (2021) Experimental analysis and increasing the energy efficiency of PV cell with nano-PCM (calcium carbonate, silicon carbide, copper), Volume 37, Part 2, Pages 1221-1225
 48. Milad Naderi, Behrooz M.Ziapour, Mohammad Yousefi Gendeshmin (2021) Improvement of photocells by the integration of phase change materials and thermoelectric generators (PV-PCM-TEG) and study on the ability to generate electricity around the clock, *Journal of Energy Storage*, Volume 36, 102384
 49. N.Souares, J.J.Costa, A.R.Gaspar, T.Matias, P.N.Simões, L.Durães (2020) Can movable PCM-filled TES units be used to improve the performance of PV panels? Overview and experimental case-study, *Energy and Buildings*, Volume 210, 109743