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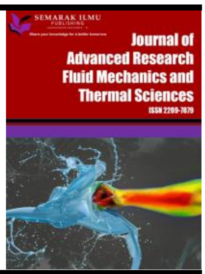

Performance Evaluation of Photovoltaic Integrated Organic Phase Change Material in a Single Container using Indoor Solar Simulator

Chia Zhi Horng[1], Mohd Afzanizam Mohd Rosli[1,*], Jayaprakash Ponnaiyan[1], Nurfarhana Salimen[1], Safarudin Ghazali Herawan[2], Faridah Hussain[3]

[1] Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[2] Industrial Engineering Department, Faculty of Engineering, Bina Nusantara University, Jakarta, 11430, Indonesia
[3] SIRIM Standards Technology Sdn. Bhd., Seksyen 15, 40200 Shah Alam, Selangor, Malaysia

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ABSTRACT

Photovoltaic panels convert sunlight, a renewable energy source, into electrical energy. The abundant irradiance will heat the photovoltaic panel, reducing the panel's efficiency. This study proposes using PCM 36 as a cooling technique to reduce the temperature of the photovoltaic panel, which is low-cost and has higher latent heat capacity. The indoor solar simulator study is performed to meet the IEC 60904-9 standard. The research process starts with validating PCM 36, sun simulator testing, validating the photovoltaic panel, and fabricating a container to place the PCM 36 at the rear side of the photovoltaic panel to cool down the temperature. The final experiments are conducted indoors, using three different irradiance levels and a one-hour photovoltaic panel operation under the sun simulator. The optimal results reveal a 31.67% reduction in temperature and a 6.83% increase in electrical efficiency at a maximum of 40 minutes, 500 W/m^2 irradiance, with a 9 mm thickness of PCM 36. Throughout this study, the efficiency of the photovoltaic system is enhanced by effectively reducing the temperature within the optimal range by incorporating phase change material.

1. Introduction

Solar energy refers to the radiant energy emitted by the sun and received by the Earth's surface. The abundant and accessible resources offered by the sun make it a highly viable candidate for extensive exploration [1]. Furthermore, solar energy accounted for thirty-eight percent of the overall clean energy supply [2]. Solar energy systems effectively utilize preheating and cooling applications and electricity generation [3]. Various technologies can be used to harness solar energy, including photovoltaic systems, photothermal systems, and photovoltaic thermal systems [4]. The photovoltaic system harnesses solar energy for various purposes, similar to other systems like flat plate solar collectors [5]. In Malaysia, the suitable climate provides opportunities to utilize solar energy in solar water heating systems and electricity generation. The country benefits from a high solar energy

* *Corresponding author.*
E-mail address: afzanizam@utem.edu.my

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radiation potential, with an average daily sunshine duration ranging from six to eight hours. This makes Malaysia conducive for harnessing solar energy effectively. However, according to Azman *et al.,* [6], the solar irradiation in Malaysia is quite low compared to other locations worldwide. At higher irradiation levels, there is a lower drop in electrical efficiency. Therefore, keeping the solar module temperature as low as possible is crucial, particularly during low irradiation intensities, such as those experienced in Malaysia [7].

Thermal regulation has started to develop by using some cooling techniques to achieve the optimum electrical efficiency of the solar photovoltaic panels and reduce their temperature. Active cooling methods for PV panels require external power or energy to operate cooling systems such as fans, nanofluid circulation, water spray, and more. On the other hand, passive cooling methods do not consume additional energy but instead dissipate heat energy to the surroundings. Examples of passive cooling methods include using phase change materials (PCM), metal fins, porous media, and more. PCMs are classified into three categories: organic, inorganic, and eutectic. A few researchers in equatorial regions who have used PCM as their cooling technique are briefly summarized in Table 1.

Table 1
Literature Review

Nature of Study	PCM	Ambient temp.	Melting Point of PCM	Latent heat of PCM	Location	Temp. Decrease	Electrical Efficiency Enhance	Reference
Experiment	RT 35	27 - 35˚C	35˚C	160 kJ/kg	Indoor, Outdoor, Malaysia	11˚C	-	Mahamudul *et al.,* [8]
Experiment	Myristic - Stearic acid	-	36.1˚C	168.3 kJ/kg	Indoor, Thailand	7.06˚C	4.226%	Homlakorn *et al.,* [9]
Experiment	Palm Wax	29 - 35˚C	52˚C	150 kJ/kg	Outdoor, Thailand	6.1˚C	5.3%	Wongwuttanasatian *et al.,* [10]
Experiment	RT 27	26 - 31˚C	27˚C	187 kJ/kg	Outdoor, Malaysia	15˚C	5.39%	Tan *et al.,* [11]
Experiment	Yellow petroleum jelly	23 - 26˚C	42 - 45˚C	196 kJ/kg	Outdoor, Indonesia	0.4 – 4.4˚C	6%	Indartono *et al.,* [12]
Experiment	A44	-	44˚C	250 kJ/kg	Indoor, Malaysia	-	3.55%	Fayaz *et al.,* [13]

In the literature review above, the melting points of the PCMs used by these previous researchers are always higher than the ambient temperature. This is due to the ability of PCMs to absorb heat energy through sensible heat until they reach their melting point. Additionally, PCM can further absorb heat energy through latent heat storage, where a phase change occurs. In an experiment conducted by Waqas and Ji [14] it was discovered that the effectiveness of PCM integration is reduced when the melting point of the PCM is more than 10˚C higher than the ambient temperature. It was concluded that a range of 3 - 6˚C higher than the ambient temperature would be suitable for optimizing the melting point of PCM.

Different designs of containers have been developed by previous researchers to conduct experiments involving photovoltaic panels with PCM, which are one single container and separated containers [15-17]. Some researchers have even delved into simulating the effects of one single container for PCM, exploring the impact of varying container sizes and dimensions on performance

[15]. Given limitations and the drive to save costs, the approach chosen in this study is to use a single container to hold the PCM at the rear side of the panel.

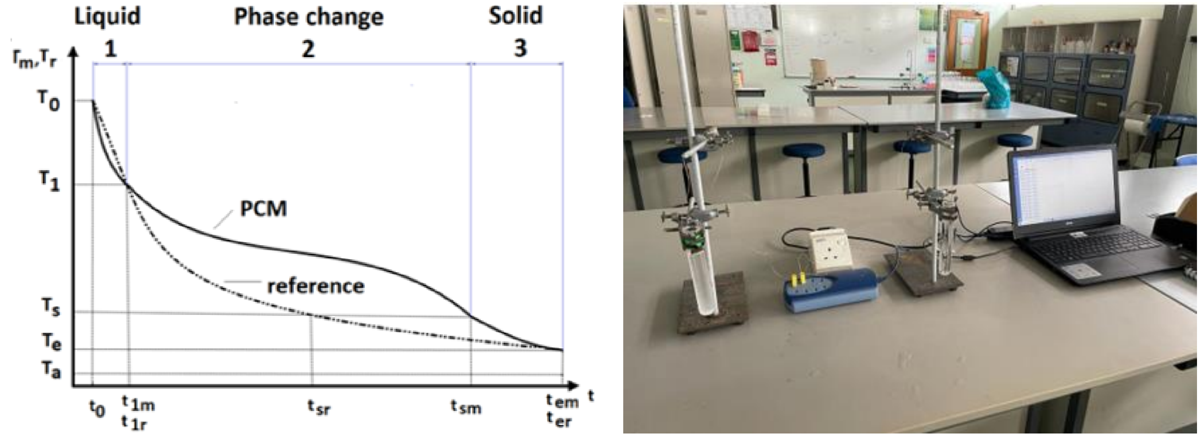
T-history method is a novel technique to validate the thermal properties of phase change materials (PCM). It has been compared to other conventional methods, such as differential scanning calorimetry (DSC), differential thermal analysis (DTA), and thermogravimetric analysis (TGA). According to a study by Gopinathan *et al.,* [18], the T-history method is more appropriate for analyzing larger samples, as it can provide a more realistic representation of PCM performance in practical applications. Due to the laboratory equipment's limitation, the T-history method has been employed in this study to validate the thermal properties of PCM, including its melting point and latent heat of fusion. This method is chosen to ensure the results are realizable and accurate in final experiments, as the PCM was purchased overseas and accompanied by a data sheet.

Based on the works of literature, there is a scarcity of research or studies regarding the utilization of PCM to improve the efficiency of solar panels in equatorial countries like Malaysia. After researching the PCM available near our country, PCM 36 was selected and purchased from China company RU Entropy, which is low cost and suited to the higher latent heat capacity requirement. PCM 36 is suitable as a cooling method for photovoltaic panels in this study as Malaysia's ambient temperature is 22˚C to 33˚C [19]. The advantages of using PCM 36 in this study are its low cost and, at the same time, higher latent heat capacity. Compared to other PCMs in previous studies, they are either low-cost or have higher latent heat capacity. However, the research gaps in this study concern the size of the solar panel and the light intensity of the sun simulator. Specifically, the current experiment does not encompass solar panels of larger dimensions, and the sun simulator's light intensity does not exceed 800 W/m2. This is noteworthy since actual irradiance levels in Malaysia can range from 1000 to 1200 W/m^2. The works in this study are separated into five stages: validation of PCM, sun simulator testing, validation of PV, fabrication of container, and final experiment. As the limitations of the solar simulator that it cannot operate in higher irradiance when exceeding 800 W/m^2, the final experiment is conducted in three different levels of irradiance, 200, 500, and 800 W/m^2, to evaluate the maximum range of PCM 36 as a cooling technique for a specific size of photovoltaic. Both conventional PV and PV-PCM are investigated for 1-hour duration, and the temperature difference and electrical performance among these two PV are collected to compare and discuss.

2. Methodology

2.1 Validation of PCM

The T-history method involves comparing the heat release behavior of the test material to that of a benchmark material in terms of sensible and latent heat. The experimental procedure involves filling test tubes with the PCM and a reference material, typically pure water, where their initial temperatures are heated and maintained above the PCM's melting temperature. The test tubes are subsequently placed vertically and cooled by the ambient temperature naturally at 24.56˚C. Temperature distribution along the time for water and PCM are recorded. T-history curve in the previous study and experiment setup is shown in Figure 1.



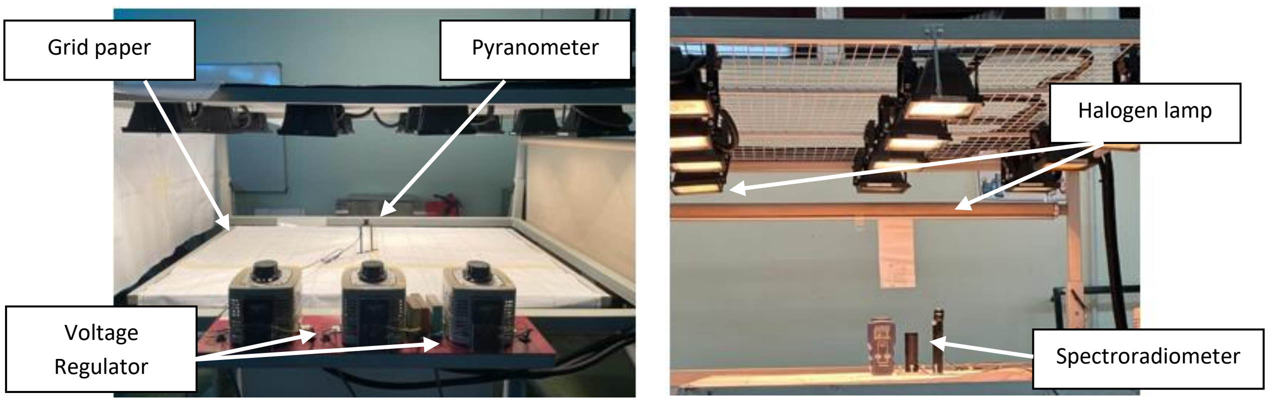
(a) (b)

Fig. 1. (a) T-history curve for PCM and Gopinathan *et al.,* [18], (b) Experimental setup

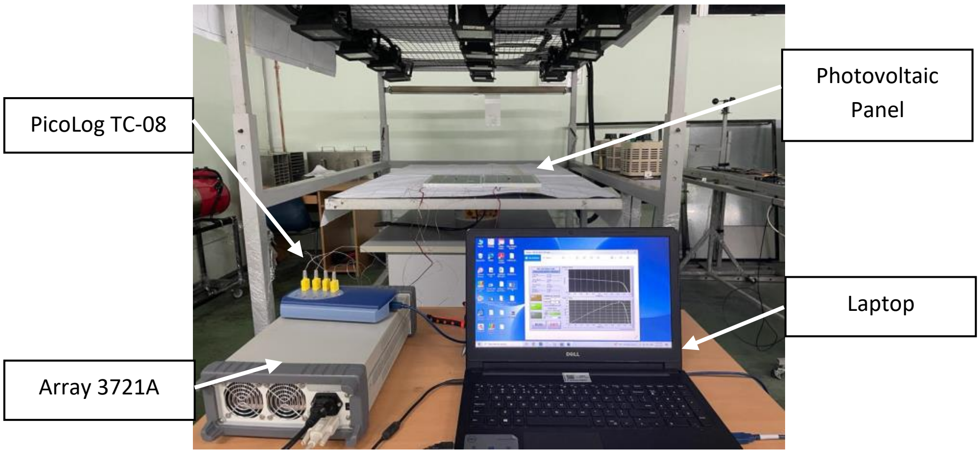
2.2 Solar Simulator Testing

Solar simulator testing is conducted in three stages, uniformity, spectral wavelength, and temporal, to ensure reliable and accurate results in the final experiment. These tests are performed at three different levels of irradiance, and the uniformity test is conducted using a pyranometer to collect the irradiance at each coordinate point on the grid paper. The spectral wavelength test is performed using a spectroradiometer to collect the wavelength of the halogen light at the center position and the wavelength of sunlight. Consequently, the natural cooling time of the PV panels is determined by collecting the temperature of PV until it reaches the initial temperature and becomes stable. The test procedures are illustrated in Figure 2 below, and the apparatus of this test is listed in Table 2 below.

In this testing, the solar simulator testing is conducted by following the IEC 60904-9 international standards. In the IEC 60904-9 international standards, the light source is characterized using criteria such as spatial uniformity, spectral match, and temporal stability. The uniformity requirement stipulates that the incident light intensity at every position within the light field should not exceed ± 15% [20]. Spectral match is assessed by comparing the irradiance of halogen and real sun sources, and temporal stability is evaluated by measuring the time it takes for the system to reach a stable temperature. Halogen incandescent lamps serve as economical and convenient light sources for low-cost, compact solar simulators, making them suitable for indoor research [21].



(a) (b)



(c)

Fig. 2. (a) Uniformity test, (b) Spectral wavelength test, (c) Temporal test

Table 2
Apparatus of the solar simulator testing

Apparatus	Specifications
Solar Simulator	12*500 Watt Halogen Lamps
Pyranometer	Apogee Silicon Pyranometer
Spectroradiometer	Apogee Spectroradiometer PS300
Thermocouple	TT-K-36-SLE Omega Thermocouple Type K
Thermocouple Data Logger	PicoLog TC-08
DC Electronic Load	Array 3721A

2.3 Validation of PV

Before commencing the experiment to compare the performance of conventional PV and PV-PCM, both PV panels performed a validation under three different light intensities to collect precise data and minimize errors during the experiment. Those three different light intensities are 200 W/m^2, 500 W/m^2, and 800 W/m^2, which will also be used in the final experiments to obtain PV-PCM results in different light intensities. The specifications of PV panels are stated in Table 3 below.

Table 3
Specifications of Polycrystalline Cell PV

Specifications	Value
Dimensions	350*240*17 (mm)
Rated Maximum Power (Pmax)	10 W
Output Tolerance	±3%
Maximum Power Current (Imp)	0.58 A
Maximum Power Voltage (Vmp)	17.50 V
Short Circuit Current (Isc)	0.63 A
Open Circuit Voltage (Voc)	21.24 V
Nominal Operating Cell Temp	-40˚C to +85˚C

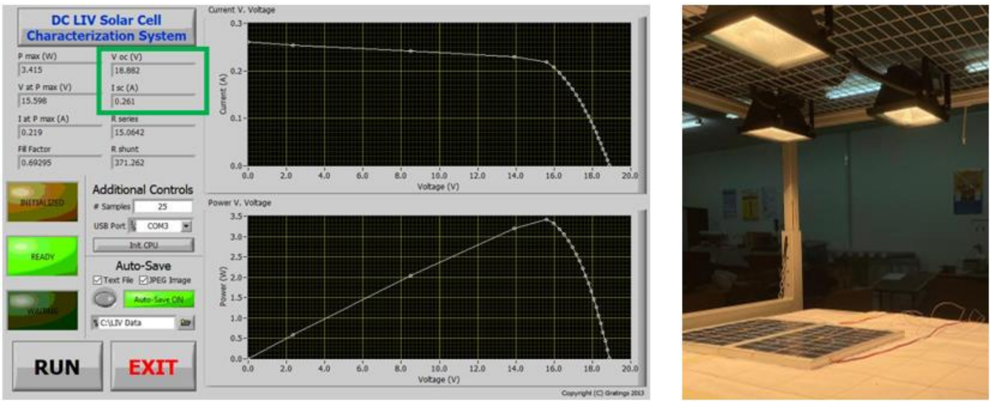
The test procedures are started by adjusting the regulator to achieve uniform distribution from halogen lamps for each light intensity in each test. Then, both PV panels accompanied by thermocouples, are placed under the halogen. Each light intensity test is conducted for 10 minutes, and data such as temperature, current, and voltage of both PV panels are collected every 3 minutes through a data acquisition system where the laptop is connected to Array 3721A and PicoLog TC-08.

The PV panels are cooled to ambient temperature to prevent the heat from accumulating in PV, affecting the results. This test procedures are repeated for 500 W/m^2, and 800 W/m^2.

An example of the collected voltage and current data and the validation process are shown in Figure 3. Eq. (1) determines the electrical power output based on the study investigated by Homlakorn *et al.,* [9].

$$P = V \times I \quad (1)$$

where P is the electrical power output of the PV panel (W), V is the open circuit voltage (V), and I is the short circuit current (A).

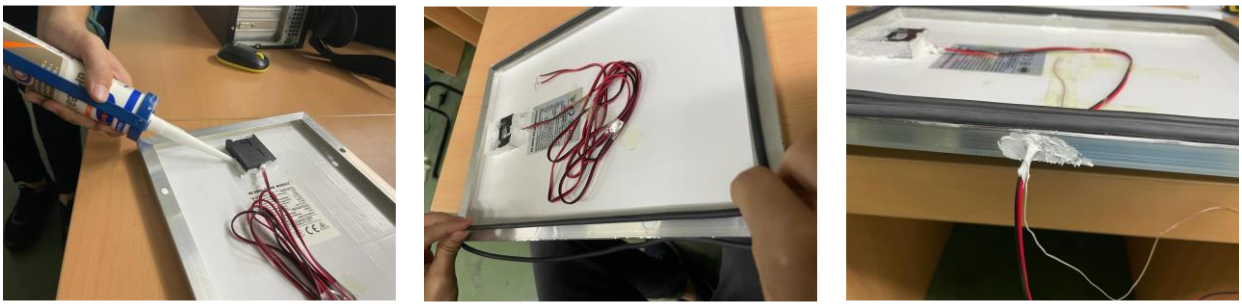


(a) (b)

Fig. 3. (a) Voltage and current collected from LIV system [18], (b) Validation process

2.4 Fabrication of Container

The container of PCM is designed and fabricated to close up PCM since there is space available at the rear side of the solar panel to fill up the PCM. Based on the study investigated by Qasim *et al.,* [22] the optimum results are obtained by fulfilling the PCM in the available space at the rear side of the PV. The work begins with wiring the thermocouple sensor at the back side of the PV panels and sealing it. Subsequently, an EPDM sponge cord has been adhered to prevent leakage between the PV panels and the aluminum plate. By calculating the ratio of the PCM quantity based on the dimensions of the PV panels, 0.8 kg of PCM is melted and poured into the rear side of the PV panel. A hole is drilled to serve as a breather, preventing the pressure from building up and allowing for the release of air during thermal expansion in the phase change of the PCM [23]. 1 mm thickness of the aluminum plate is closed tightly with PVC blinders. The process of fabrication is shown in Figure 4.



(a) (b) (c)

(d) (e)

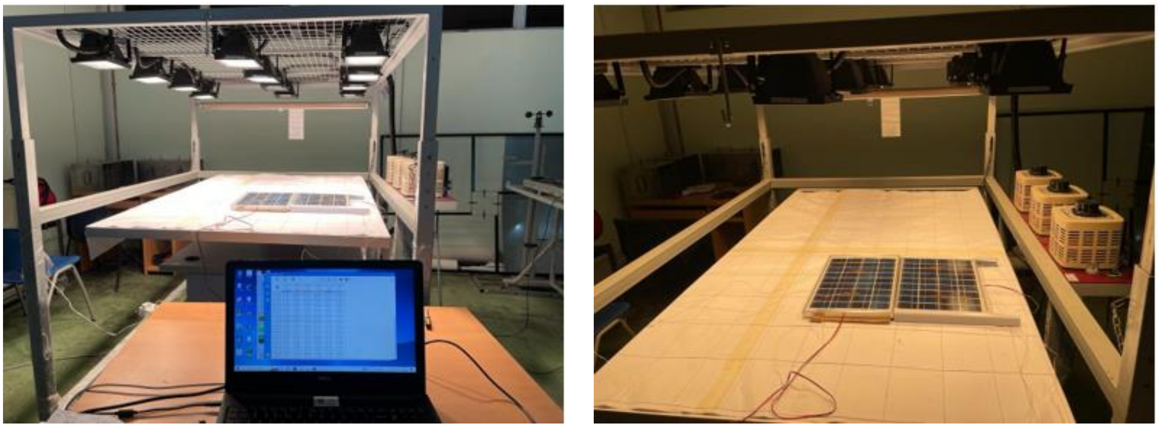
Fig. 4. The flow of the process container fabrication (a) Sealing, (b) Sticking, (c) Wiring, (d) Filling PCM, (e) Closing with PVC binders

2.5 Experiment Work

After implementing PCM into the PV panels, both conventional PV and PV-PCM are prepared for an experiment to compare their performance in terms of temperature and electricity. The experimental procedures are similar to the PV validation, where the experiment is conducted under three different light intensities, 200, 500, and 800 W/m^2, for one hour. Data is collected every 20 minutes. Electrical efficiency is determined by Eq. (2). The test procedures are illustrated in Figure 5 below.

$$\eta = \frac{P_{out}}{P_{in}} \times 100 \quad (2)$$

where P_{out} is the electrical power output from Eq. (1) and P_{in} is the product of irradiance from halogen lamps times the surface of PV, P_{in}=IA.



(a) (b)

Fig. 5. (a) Final experiment setup, (b) Position of PV located

3. Results

3.1 Validation of PCM

The T-history curve for PCM and reference in this test are obtained, as shown in Figure 6. The natural heat transfer coefficient, Biot number, specific heat of PCM in both liquid and solid state, and latent heat of fusion of the PCM are determined from the calculations based on the previous study [18,24]. The results are presented in Table 4. Based on the observations in Figure 6, it can be seen that PCM 36 starts to solidify within the temperature range of 36 to 38˚C. This confirms that the melting point of PCM 36 matches the information provided in the datasheet. Ensuring that the Biot number is less than 0.1 is crucial for the T-history method as it allows the application of the lumped capacity method. The result of the Biot number shown in Table 4 is 0.29, larger than 0.1. This indicates that the temperature distribution in the sample is not even, more complex methods will be required to analyze the problem. Several factors affect the Biot number, including the diameter of the test tube and the natural heat transfer coefficient. The previous study used a test tube diameter of 10.4 mm, and the recommended natural heat transfer coefficient is 5-6 W/m^{2}K [24]. However, using this T-history method, the latent heat of PCM is determined to be within an acceptable range, with less than a 1 percent error.

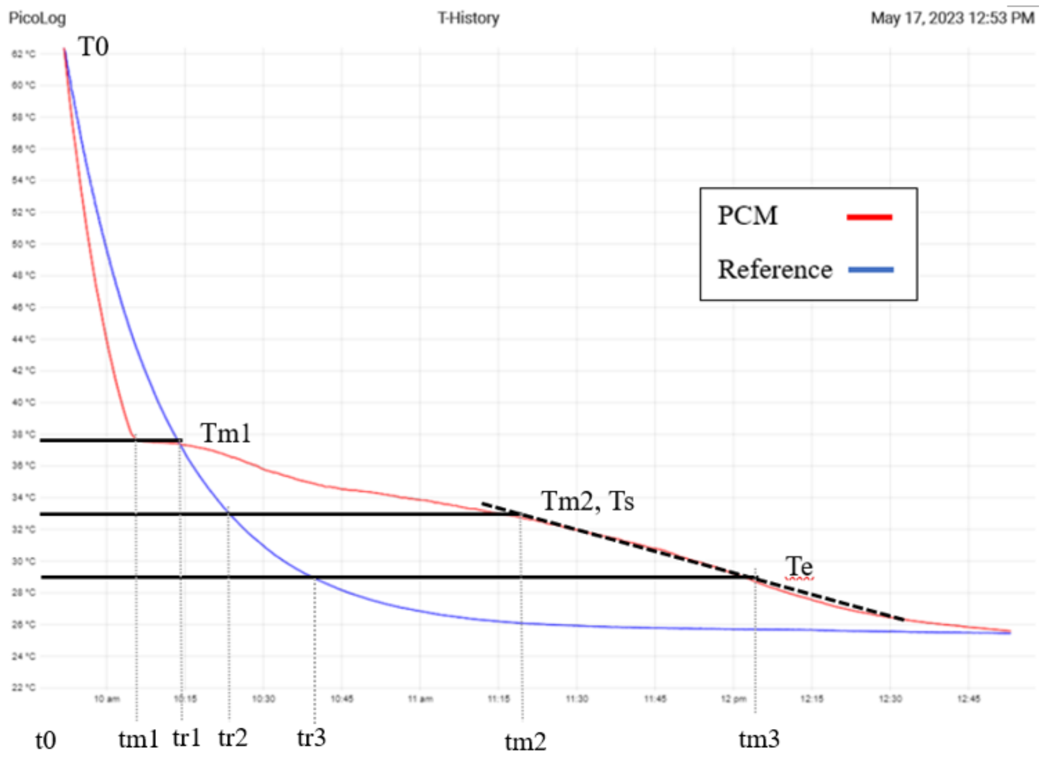


Fig. 6. T-history curve of PCM and reference material

Table 4
Results of T-history curve

Properties	Value
Natural heat transfer coefficient, h	11.92 W/m^{2}K
Biot number	0.29
Specific heat of PCM in liquid state, Cp,l	2539.94 J/kgK
Specific heat of PCM in solid state, Cp,s	12812.94 J/kgK
Latent heat of fusion of the PCM, Hm (Experimental)	217.89 J/g
Latent heat of fusion of the PCM, Hm (Manufacturer)	220 J/g
Percent error of latent heat of fusion, %	0.9591 %

3.2 Solar Simulator Testing

The results of the sun simulator testing are divided into three stages, as mentioned: uniformity, spectral, and temporal. The results to achieve uniform 200 W/m^2 irradiance are shown in Figure 7, where all the data represent the value measured on each point on grid paper. In this figure of uniformity test, the highlighted values in the grid represent the minimum and maximum values within a 10% tolerance of 200 W/m^2 irradiance. The following 500 and 800 W/m^2 are the same as the initial results. Thus, the location of PV to conduct that will result more uniformly and consistency is selected as shown in the green line.

For the spectral wavelength test, the results shown in Figure 8 indicated that the halogen lamps exhibited only an 18% difference by calculating the area from both pattern and wavelength compared to the real sun 400 W/m^2 irradiance. A previous study investigating the thermal efficiency of solar collectors under natural and artificial sunlight (halogen lamps) reported percentage differences of 3.98% and 9.91% respectively in different light fields [20].

In Figure 9, the result of the temporal test shows that 800 W/m^2 took the longest 45 minutes to cool down the PV panels naturally. It is crucial to ensure that the PV panel is cooled down to its initial temperature and maintained at a constant level to prevent heat accumulation in subsequent tests.

192	198	194	188	200	213	199
209	207	190	182	196	206	197
213	215	203	203	209	212	206
220	219	217	220	214	208	213
220	218	214	219	214	218	215
215	210	216	213	216	212	216
196	209	210	220	210	214	215
191	197	197	210	219	218	211
184	186	184	199	219	219	199

Fig. 7. Example results for each point on the grid-paper for 200W/m^2

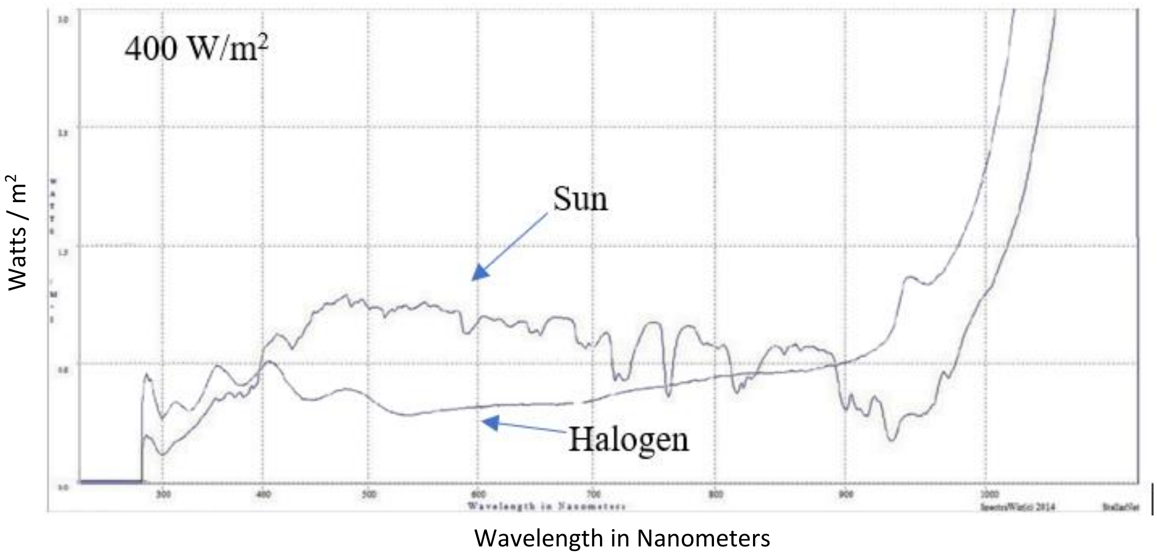


Fig. 8. Comparison wavelength and pattern of sun and halogen lamps at 400W/m^2

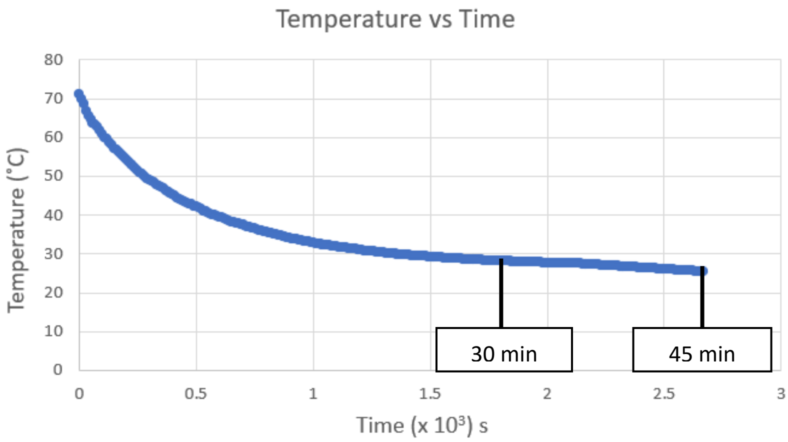


Fig. 9. Spectral irradiance variation versus time (A.Ms) on a clear sky measurement day

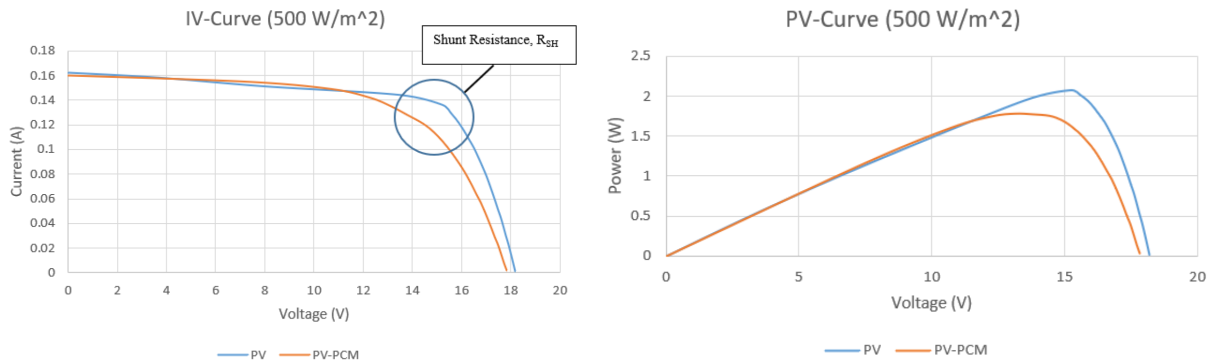
3.3 Validation of PV

The average results for the performance of both PV under three levels of irradiance are shown in Table 5 below.

Table 5
Average results of both PV at 200, 500 and 800 W/m^2

Level		PV 1 Test 1	PV 1 Test 2	PV 1 Test 3	Average		PV 2 Test 1	PV 2 Test 2	PV 2 Test 3	Average
200	Isc (A)	0.06	0.062	0.062	0.061	Isc (A)	0.062	0.069	0.069	0.069
	Voc (V)	19.182	18.416	18.074	18.557	Voc (V)	17.697	17.248	17.068	17.338
	Power (W)	0.749	0.721	0.703	0.724	Power (W)	0.661	0.701	0.697	0.686
	Temp. Front of PV (℃)	34.48	37.03	41.73	37.747	Temp. Front of PV (℃)	35.76	38.48	43.44	39.227
	Temp. Back of PV (℃)	34.72	37.28	42.09	38.03	Temp. Back of PV (℃)	35.45	38.03	42.83	38.77
500	Isc (A)	0.135	0.159	0.162	0.152	Isc (A)	0.153	0.157	0.16	0.157
	Voc (V)	18.604	18.965	18.197	18.589	Voc (V)	18.217	18.308	17.852	18.126
	Power (W)	1.669	2.132	2.07	1.957	Power (W)	1.638	1.811	1.775	1.741
	Temp. Front of PV (℃)	45.04	48.48	53.52	49.01	Temp. Front of PV (℃)	45.4	50.88	56.58	50.95
	Temp. Back of PV (℃)	45.88	51.59	57.63	51.70	Temp. Back of PV (℃)	43.78	49.01	54.60	49.13
800	Isc (A)	0.202	0.261	0.263	0.242	Isc (A)	0.243	0.269	0.271	0.261
	Voc (V)	19.999	18.882	17.924	18.935	Voc (V)	19.536	18.46	17.842	18.613
	Power (W)	2.71	3.415	3.225	3.117	Power (W)	2.863	3.115	3.03	3.003
	Temp. Front of PV (℃)	49.68	56.60	64.57	56.95	Temp. Front of PV (℃)	51.07	59.70	67.84	59.537
	Temp. Back of PV (℃)	50.92	59.37	67.81	59.367	Temp. Back of PV (℃)	49.46	57.49	65.45	57.467

Although the irradiance was uniformly distributed to both PV panels, the panels still have a plus or minus 3% tolerance for the output. From the table above, the properties of the PV panels have a small difference of 500 W/m^2 among the other levels of irradiance through observation. It is acceptable for both PV panel conditions to exhibit minor or slight differences during this validation, as solar panels may not be identical due to variations in electricity production caused by factors such as manufacturing differences, shading, and soiling [25]. Figure 10 shows the performance comparison between 2 identical PV panels and the shunt resistance that resulted from manufacturing defects.



(a) (b)

Fig. 10. Performance comparison between same PV panels at 500 W/m^2 (a) IV-Curve, (b) PV-Curve

3.4 Final Experiment

In the final experiment, the results for comparing conventional PV and PV-PCM are temperature differences, electrical power output, and electrical efficiency.

3.4.1 Temperature difference between PV and PV-PCM

In Table 6, the results regarding the temperature difference between conventional PV and PV-PCM at 200, 500 and 800 W/m^2 irradiance, it was observed that the medium level of irradiance, which is 500 W/m^2, showed the highest temperature reduction of 19.12˚C, followed by 16.53˚C at 200 W/m^2 and the smallest reduction is 13.11˚C at 800 W/m^2 when comparing both PV panels. The highest temperature reduction represented the performance increase of the PV panels. The temperature profiles between PV and PCM at different light intensities are shown in Figure 11.

Table 6
Temperature Difference of PV and PV-PCM

Time	PV1 = Conventional PV / PV2 = PV with PCM / Different Level Irradiance, 200, 500, 800 (W/m^2)											
min	200				500				800			
	PV 1	PV 2	ΔT	%ΔT	PV 1	PV 2	ΔT	%ΔT	PV 1	PV 2	ΔT	%ΔT
20	49.21	37.31	11.90	24.18	62.09	41.56	20.53	33.07	74.45	59.50	14.95	20.08
40	52.81	38.87	13.94	26.39	68.38	46.67	21.72	31.76	83.35	65.60	17.75	21.30
60	53.63	40.12	13.51	25.19	70.42	55.30	15.12	21.48	85.05	68.15	16.90	19.87
Average			13.11	25.25			19.12	28.77			16.53	20.42

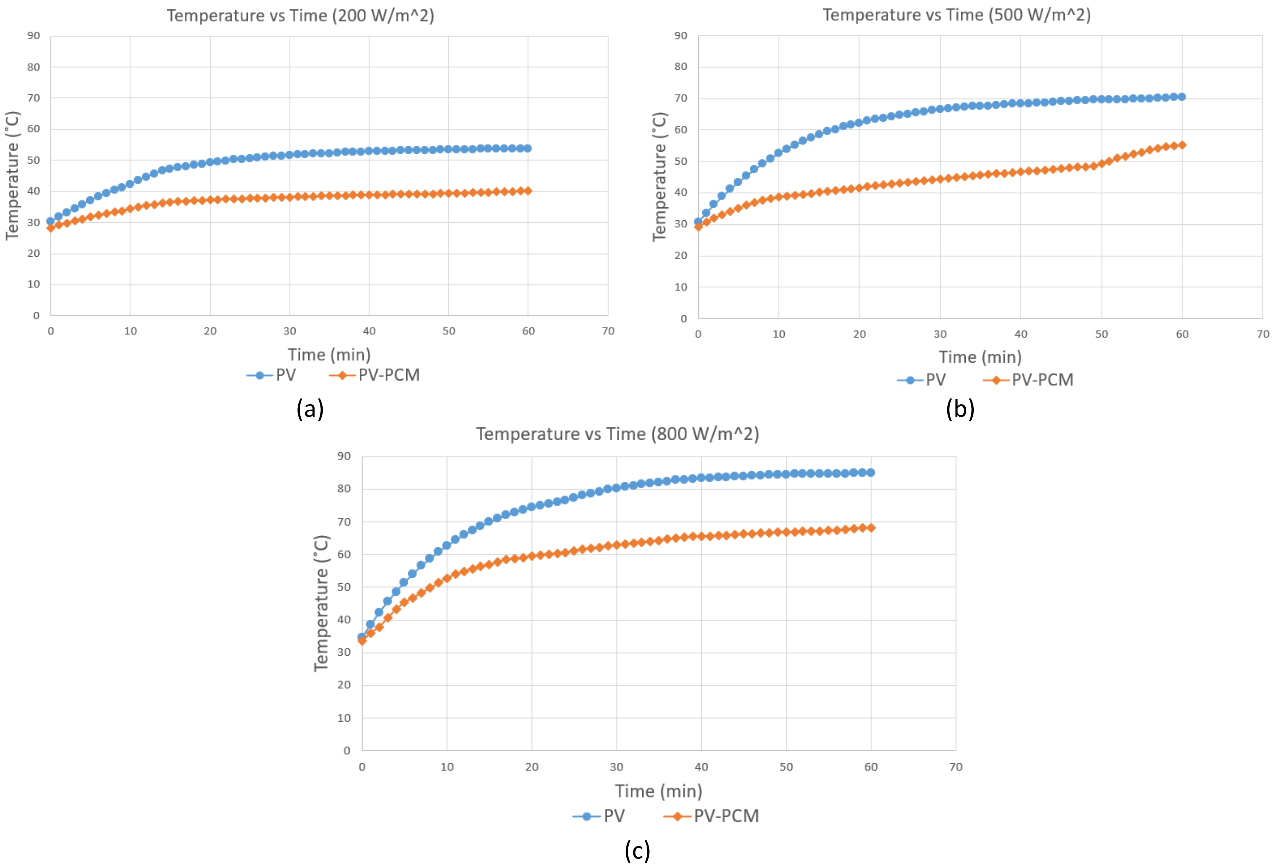


Fig. 11. Temperature difference between PV and PV-PCM (a) 200 W/m^2, (b) 500 W/m^2, (c) 800 W/m^2

3.4.2 Electrical power output and between PV and PV-PCM

In Table 7, PV 2 exhibits lower performance in terms of power output than PV 1 when comparing the electrical power output and efficiency of both PV panels at 200 W/m^2 irradiance. However, as the experiment progresses to the medium level of irradiance, which is 500 W/m^2, the performance of PV 2 improves and becomes higher than PV 1. This trend continues at 800 W/m^2. The electrical power output is increased from -2.96 % to 5.86%, corresponding with increased irradiance. The IV curves between PV and PV-PCM are presented in Figure 12.

Table 7
Electrical power output of PV and PV-PCM

Time	PV1 = Conventional PV / PV2 = PV with PCM / Different Level Irradiance, 200, 500, 800 (W/m^2)											
min	200				500				800			
	PV 1	PV 2	ΔP	%ΔP	PV 1	PV 2	ΔP	%ΔP	PV 1	PV 2	ΔP	%ΔP
20	1.14	1.10	-0.04	-3.70	2.88	2.99	0.11	3.53	4.60	4.86	0.26	5.35
40	1.13	1.11	-0.03	-2.59	2.85	3.06	0.21	6.83	4.51	4.83	0.32	6.54
60	1.15	1.12	-0.03	-2.61	2.99	3.13	0.13	4.25	4.57	4.85	0.28	5.69
Average			-0.03	-2.96			0.15	4.87			0.28	5.86

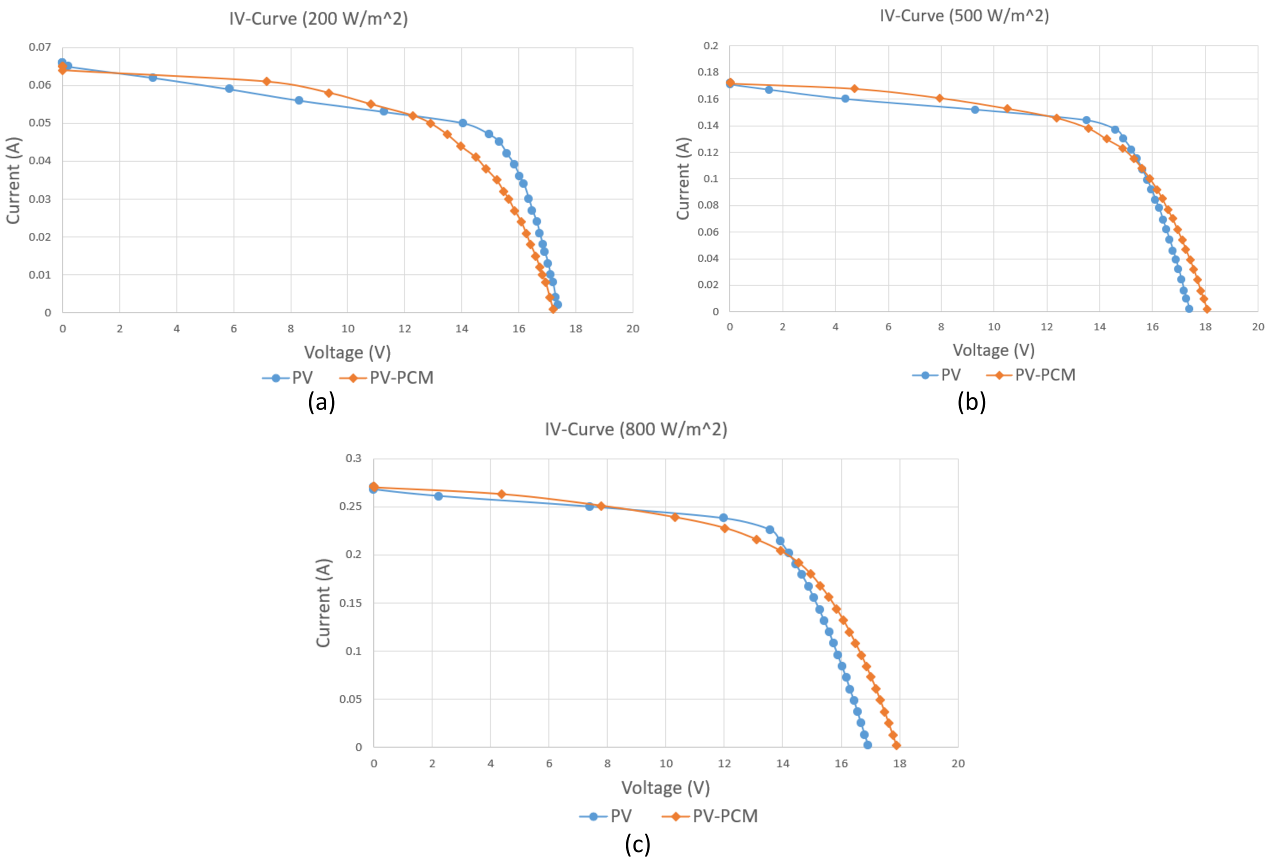


Fig. 12. IV-curve between PV and PV-PCM (a) 200 W/m^2, (b) 500 W/m^2, (c) 800 W/m^2

3.4.3 Electrical efficiency between PV and PV-PCM

In Table 8, the electrical efficiency exhibits the same results as the electrical power output. To determine the optimal range for temperature difference and electrical efficiency in this 1-hour experiment, the results indicate that the temperature reduced the most at 500 W/m^2 and the least at 800 W/m^2. As for electrical efficiency, the results showed an increased electrical efficiency from -2.96 % to 5.86 % as well as increased irradiance. Regarding the time required to achieve optimal results, it is evident that at 40 minutes, both temperature difference and electrical efficiency have increased from their initial conditions among three different light intensities. However, from 40 to 60 minutes, all the results show a decline. The IV curve between PV and PV-PCM is presented in Figure 13.

Table 8
Electrical efficiency of PV and PV-PCM

Time	PV1 = Conventional PV / PV2 = PV with PCM / Different Level Irradiance, 200, 500, 800 (W/m^2)											
min	200				500				800			
	PV 1	PV 2	ΔEff	%ΔEff	PV 1	PV 2	ΔEff	%ΔEff	PV 1	PV 2	ΔEff	%ΔEff
20	6.76	6.52	-0.24	-3.70	6.86	7.11	0.25	3.53	6.84	7.23	0.39	5.35
40	6.75	6.58	-0.17	-2.59	6.79	7.28	0.50	6.83	6.71	7.18	0.47	6.54
60	6.83	6.66	-0.17	-2.61	7.12	7.44	0.32	4.25	6.80	7.21	0.41	5.69
Average			-0.20	-2.96			0.36	4.87			0.42	5.86

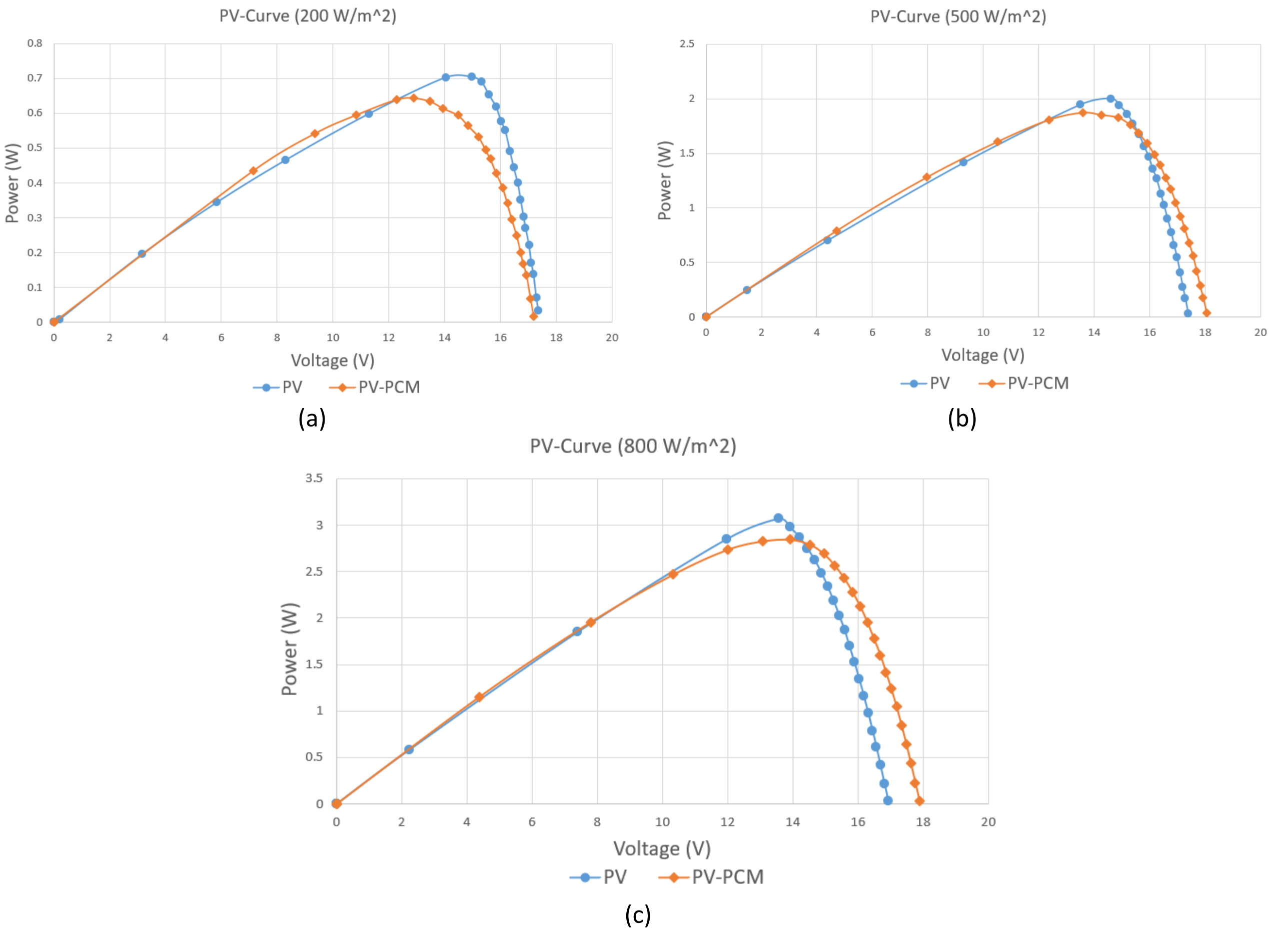


Fig. 13. PV-curve between PV and PV-PCM (a) 200 W/m^2, (b) 500 W/m^2, (c) 800 W/m^2

The optimum results indicate that the temperature of PV-PCM is reduced highest at 500 W/m^2 and smallest at 800 W/m^2. Regarding the time of this experiment, it is evident that at 40 minutes, both temperature difference and electrical efficiency have increased from their initial conditions. Therefore, the optimum range for temperature reduction is 19.12˚C, and electrical efficiency increased by 6.83 % in PV-PCM at a maximum of 40 minutes and 500 W/m^2 irradiance throughout this 1-hour experiment.

4. Conclusions

The performance of photovoltaic integrated with organic PCM 36 was evaluated in this study. The experimental procedures started with the validation of PCM 36. It was found that the latent heat of PCM 36 is validated through T-history method resulting in a 0.9591 percent error in latent heat comparison. In solar simulator testing, the results are acceptable to provide more accurate data. The validation of photovoltaic resulted in the smallest differences between the same photovoltaic panels at 500 W/m^2 in the validation of panels. In designing the single container, the thickness of the PCM 36 used to give the optimum results for the performance in this study is 9 mm, which is in the range of effective thickness to absorb heat based on the previous study [26]. In the final experiment, PCM 36 is implemented at the rear side of the panels for performance analysis. This study evaluates the performance of conventional photovoltaic panels and photovoltaic with PCM 36 based on temperature reduction and electrical efficiency. PCM 36 in this study resulted in the highest temperature reduction, 19.12˚C, and the highest electrical efficiency increase of 6.83 % at the maximum range of 500 W/m^2 and 40 minutes.

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