Development of Solar PV Cooling System to Enhance Power Output and Efficiency Based on Phase Change Material

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Abstract. This study develops a passive cooling system for photovoltaic (PV) panels using phase change material (PCM) to enhance power output and efficiency. The novelty of this work lies in applying paraffin wax (FRW 42) with a tropical-optimized melting point (42°C) directly encapsulated on the PV back surface, specifically targeting the energy needs of green tourism in Bali. The PV cooling was tested directly in an outdoor area in Bali Selatan, and the results show a temperature reduction from 47.17°C to 42.49°C, resulting in an increase in output power by 9.83% and efficiency from 17.43% to 22.81%. This indicates the feasibility of PCM integration as a cost-effective and practical thermal management strategy for PV systems in sustainable tourism regions.

Keywords: Paraffin Wax, PCM, Solar PV, Thermal Management

1 Introduction

Bali, as a major tourist destination in Indonesia, has seen an increase in the number of tourists every year. This growth in the tourism sector has had a significant impact on energy consumption, especially in South Bali, which has the highest concentration of hotels and resorts. Data from the Bali Provincial Central Statistics Agency in 2024 shows that there are approximately 541 hotels in Bali, with around 76% of them located in the Badung region (Southern Bali). This naturally requires a very large amount of energy consumption, particularly electricity, as nearly all tourism accommodations in Bali, especially in Badung (Southern Bali), still rely on conventional electricity sourced from PLN. Electricity consumption in the southern Bali region for 2023, according to BPS data, was approximately 4,570,519 MWh, or about 71% of the total electricity consumption in the Bali region, which was 6,354,530 MWh. Based on an analysis of this data, it can be concluded that an increase in the number of tourists is directly proportional to an increase in electricity consumption (*Provinsi Bali Dalam Angka 2022,* n.d.). To address this challenge, the government and tourism industry stakeholders in Bali have begun adopting renewable energy initiatives. In this regard,

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the Bali Provincial Government has issued regulations in the form of Bali Governor Regulation No. 45 of 2019 on Clean Energy in Bali, which covers the use and/or utilization of new and renewable energy as alternative energy sources *(Pergub Bali 45 2019 Energi Bersih*, n.d.). This will be highly significant in reducing the use of conventional electricity.

Solar cells, solar panels, or solar photovoltaics (solar PV) are devices that convert sunlight into electrical energy. The effectiveness of solar panels as an electrical energy source is affected by various factors, including the type of photovoltaic material and ambient circumstances such as temperature, wind speed, and humidity. Solar panels have reduced efficiency when their surface temperature increases due to prolonged exposure to solar radiation (Bagher, 2015).

Optimizing solar panel output performance can be achieved by regulating the surface temperature of the panel. Surface cooling techniques for solar panels are often classified into two categories: active cooling, which includes water and air cooling, and passive cooling. Multiple active cooling techniques have been established, notably the implementation of Peltier cells. The integration of thermoelectric coolers (TEC) with forced airflow cooling can significantly improve the cooling efficiency of TEC, hence enhancing its performance as a cooling system (Enasel et al., 2023; Faheem et al., 2024; Kumar et al., 2015).

In addition to these active cooling methods, passive cooling methods are also being widely developed, as they offer advantages in terms of a more compact design and do not require additional energy. Passive cooling typically uses phase change material (PCM) as a medium to absorb heat from the surface of solar panels. Several studies have been conducted, such as the use of organic PCM on monocrystalline solar panels by Waqas et al. (2019), which resulted in a temperature reduction of 6–9°C and a 2% increase in solar panel efficiency. (Waqas et al., 2019) Another study using PCM was conducted by Xu et al., where it was found that PCM could reduce the temperature on the surface and bottom of the solar panel by 33.9°C, increase solar panel efficiency by 1.63%, and boost power output by 1.35 W (Xu et al., 2023). Similar findings of utilizing PCM in solar cooling PV have also been done using different types and characteristics of organic PCM. This indicates that the use of organic PCM as a passive cooler for solar PV is very promising. (Sheikh et al., 2024; Dayer et al., 2023; Naseer et al., 2019).

Despite the increasing number of studies on PCM-based passive cooling for PV systems, the majority of investigations have been restricted to laboratory or controlled environments. Only a small number of studies have focused on real outdoor tropical conditions, where high solar irradiance, fluctuating wind speeds, and elevated humidity significantly influence PV performance. This study introduces a novel approach by directly encapsulating paraffin wax FRW-42, a PCM with a melting point optimized for tropical climates, at the rear surface of PV panels. The novelty of this research is threefold: (i) the integration of PCM cooling into PV systems that are specifically designed for tourism accommodations in Bali as part of a clean energy initiative, (ii) the benchmarking of performance gains under actual tropical field conditions rather than laboratory setups, and (iii) the provision of a comparative analysis against prior PCM cooling studies. This distinctive context underscores the solution's relevance to the sustainable development of green tourism in tropical regions, in addition to its technical contribution to PV thermal management.

2 Methodology

In this research, firstly, the design of a passive cooling system using organic PCM has been developed. The design incorporates PCM encapsulation to enhance the cooling coverage of cooling in the solar PV back surface. The schematic of the design is shown in Figures 1 and 2.

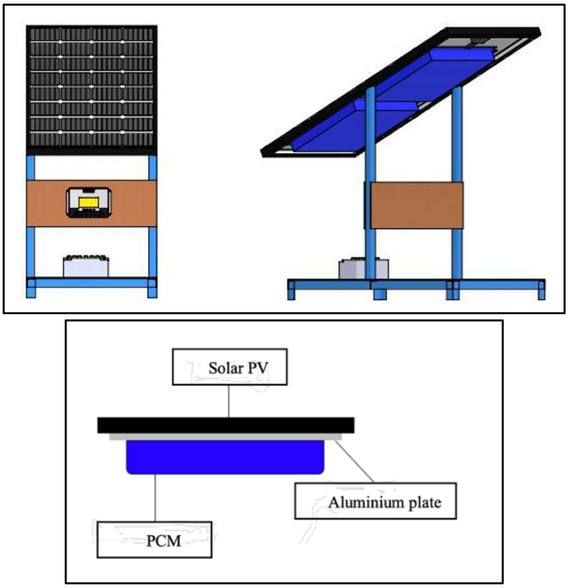

Figure 1. Schematic of Design Solar PV Cooling System using PCM

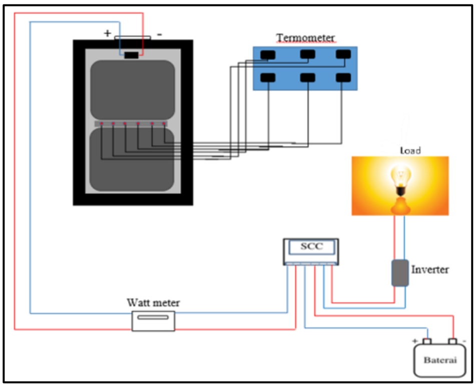

Figure 2. Schematic of Cooling System

The PCM used in this study is paraffin wax (FRW 42) with a melting point of approximately 42 °C. The PCM is encapsulated in the back surface of solar PV to maintain the surface temperature of solar PV. The size of the PCM encapsulation was 45 cm x 45 cm x 3 cm. The PCM density used in this study is 600 kg/m³. The specification details of the PCM cooling system are shown in Table 1.

Table 1. Specification of Solar PV Cooling System

No.	Component	Specification	Amount
1	PCM	Paraffin wax (FRW 42)	12 kg
2	Thermometer	Temp range -50 - 110 °C	6 pcs
3	Red wire	300/400 V	2 m
4	Black wire	300/400 V	2 m
5	Watt Meter	100 A	1 pcs
6	PCM encapsulation	50 x 50 x 3 cm^3	2 pcs

3 Result and Discussion

3.1 Result

The solar PV was tested in a clear area to optimize the solar radiation. The test was conducted with and without a cooling system between 14:00 and 16:00 (GMT+8). A digital multimeter was used to monitor the output current and voltage, a K-type thermocouple to measure the surface temperature, and an environmental meter to measure the ambient conditions, including ambient temperature and light intensity. The results of the solar PV performances without and with a cooling system are shown in Tables 2 and 3.

The power input (Pin) of the solar panel can be calculated using the formula:

$$Pin = Irad \times A \tag{1}$$

where:

Pin = Power input to solar PV (W)
$Irad$ = Light intensity (W/m²)
A = solar PV cross-sectional area (m²)

The power output (Pout) of the solar panel performance is calculated using the formula:

$$Pout = Vpv \times Ipv \tag{2}$$

where:

$Pout$ = Power output (W)
Vpv = Output solar PV voltage (V)
Ipv = Output solar PV current (A)

The efficiency of solar panels is calculated using the formula

$$\eta pv = \frac{Pout}{Pin} \times 100\% \quad (3)$$

Table 2. Solar PV Performance without Cooling System (without PCM)

Time	Output solar PV		Surface Temperature	Ambient		Power		Efficiency
				Temperature	Light Intensity	P_{in}	P_{out}	
Minutes	Volt	Ampere	T_{pv} (°C)	T_a (°C)	W/m^2	W	W	%
15	16.27	8.02	42	29	773.25	771.93	130.48	16.9
30	14.62	7.37	45	29	741.09	739.83	107.49	14.52
45	15.54	9.21	47.2	29	719.61	718.38	143.12	19.92
60	14.67	8.25	46.1	29	764.24	762.94	121.02	15.86
75	13.97	9.37	48.6	29	774.43	773.11	130.89	16.93
90	13.92	9.74	49.3	29	679.79	678.63	135.58	19.97
105	14.07	8.23	47	29	681.69	680.53	115.79	17.01
120	14.25	8.35	48.2	29	717.71	716.48	118.98	16.6
135	14.17	8.87	48.8	29	784.86	783.52	125.68	15.29
150	15.27	7.85	49.2	29	707.6	706.39	119.86	16.96
165	14.09	7.32	50	29	732.56	731.31	103.13	14.1
180	15.21	9.4	48.1	29	691.72	690.54	142.97	20.7
195	13.19	4.2	48	29	720.91	789.56	55.39	7.01
210	14.2	7.62	48.2	29	714.85	713.63	108.24	15.16
225	14.7	8.76	47	29	646.76	645.66	128.77	19.94
240	13.9	9.73	49.6	29	708.14	706.93	135.24	19.13
255	13.23	8.81	46.3	29	683.34	682.17	116.55	17.08
270	14.52	7.11	46	29	678.01	676.85	103.23	15.25
285	14.32	7.23	44.8	29	453.25	452.47	103.53	22.88
300	13.34	8.69	44	29	421.04	420.68	115.92	27.55
Mean	14.37	8.20	47.17	29	689.74	706.36	118.09	17.43

Table 3. Solar PV Performance with Cooling System (PCM)

Times	Output solar PV		Surface Temperature	Ambient		Power		Efficiency
				Temperature	Light Intensity	P_{in}	P_{out}	
Minutes	Volt	Ampere	T_{pv} (°C)	T_a (°C)	W/m^2	W	W	%
15	14.17	6.35	41.2	28	336.46	335.88	89.97	26.78
30	14.54	7.08	40.8	28	519.82	518.93	102.94	19.77
45	15.71	8.24	42.1	28	731.61	730.36	129.45	17.72
60	14.48	8.73	42.8	28	344.2	343.61	126.41	36.78
75	16.48	8.95	42.5	28	666.45	665.31	147.49	22.16
90	17.45	9.05	42.7	28	460.8	460.01	157.92	34.32
105	16.49	8.78	45.2	28	416.72	416.01	144.78	34.8
120	14.17	8.76	42.5	28	600.58	599.55	124.12	20.7
135	15.07	8.89	42.8	29	736.61	735.35	133.97	18.21
150	18.9	9.62	45.9	28	679.25	678.09	181.81	26.81
165	17.25	8.95	44.5	28	657.47	656.35	154.38	23.52
180	14.03	8.35	43.2	28	682.1	680.94	117.15	17.2
195	19.61	9.65	42.9	28	623.23	622.17	189.23	30.41
210	15.69	8.2	41.3	28	753.28	751.99	128.65	17.1
225	15.84	7.95	43.3	28	656.96	655.84	125.92	19.19
240	15.43	7.42	40.1	28	577.97	576.98	114.49	19.84
255	14.87	6.84	40.1	28	586.41	585.41	101.71	17.37
270	14.85	6.08	43	28	635.47	634.38	90.28	13.12
285	14.93	7.3	42.2	28	688.81	687.63	108.98	15.84
300	15.13	8.22	40.82	28	574.74	573.76	124.36	21.67
Mean	15.75	8.17	42.49	28.05	596.44	595.42	129.70	22.81

3.2 Discussion

Utilizing the data and calculations derived from the solar PV test results, the information is shown on a graph to evaluate the efficacy of the constructed cooling systems.

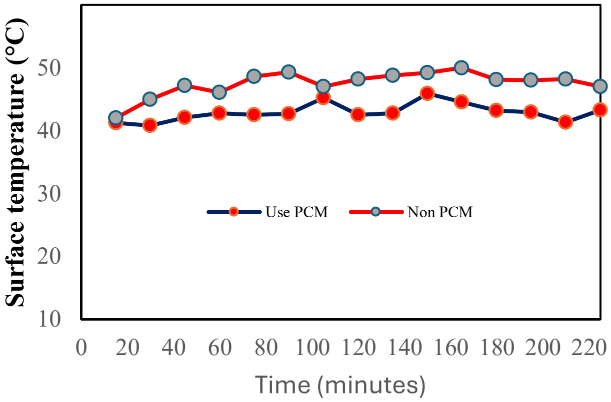

Figure 3. Surface Temperature of Solar PV

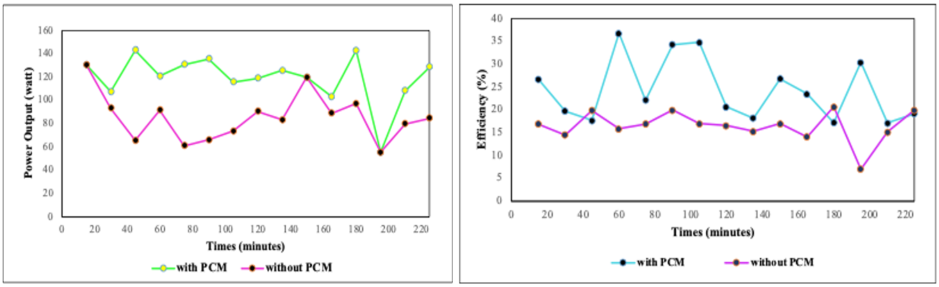

Figure 4. Power Output and Efficiency of Solar PV

Figure 3 illustrates that the surface temperature of solar panels using phase change materials (PCM) is lower than that of panels lacking PCM. The surface temperature achieved through the utilization of PCM attains a minimum of 40.1°C, with an average surface temperature of 42.49°C. In contrast, the surface temperature without PCM attains a minimum of 42°C and an average of 47.17°C, which is considerably higher than that of the panel with PCM. This indicates that PCM operates efficiently, extracting heat from the solar panel’s surface and thereby maintaining the surface temperature within the ideal range of below 50°C.

Figure 4 illustrates the average output power generated with and without the use of PCM. The average output power in the PCM test was 129.70 watts. The average in the test without PCM was 118.09 watts. The average output power without PCM was inferior to that with PCM. This is attributable to the rise in the solar panel's surface temperature, which has reached 47.17°C. Figure 4.4 illustrates that the average efficiency achieved in the test utilizing PCM was 22.81%, whereas the test conducted without PCM resulted in an average of 17.43%. This results from the substantial power output generated by the surface cooling of the solar panel utilizing phase change materials (PCMs). Comparisons to previous work using PCM passive cooling methods are shown in Table 4.

Table 4. Comparison of Passive Cooling Methods using PCM for Solar PV

Study	PCM	ΔT Reduction (°C)	Efficiency Gain (%)	Remarks
Waqas et al. (2019)	Organic PCM	6–9	2.0	Indoor controlled test
Xu et al. (2023)	Paraffin	33.9	1.63	Lab-scale PCM
This study (2025)	Paraffin wax (FRW-42)	4.68	5.38	Outdoor tropical field

Table 4 presents a comparison of the comparative efficacy of PCM-based PV cooling systems from prior research and the current study. Waqas et al. (2019) reported a temperature decrease of 6–9°C and a slight efficiency enhancement of approximately 2% during indoor controlled experiments utilizing organic phase change materials (PCM). Xu et al. (2023) achieved a temperature reduction of 33.9°C, accompanied by only a 1.63% increase in efficiency, as their research was conducted on a laboratory-scale photovoltaic system utilizing a paraffin-based phase change material. In contrast, the present study demonstrates a unique balance between thermal regulation and efficiency improvement. Although the average temperature reduction (4.68°C) is smaller than the values reported in laboratory studies, the efficiency gain (+5.38%) is significantly higher. This outcome is attributed to the use of paraffin wax FRW-42, which has a melting point tailored to tropical operating conditions. More importantly, the experiments were conducted under real outdoor tropical field conditions that closely represent actual PV deployment scenarios. The use of PCM, especially paraffin-based, as a solar panel cooler has several limitations. The PCM cooling performance is influenced by the melting temperature of paraffin (42°C), which may limit effectiveness under lower irradiance conditions. Prolonged exposure can also lead to thermal saturation, which reduces the long-term cooling capability. Furthermore, encapsulation adds weight and may complicate installation for large-scale PV arrays.

4 Conclusion

The investigation into the performance of PV solar panels indicates that a passive cooling system utilizing PCM (paraffin wax FRW-42) can operate effectively. The implementation of PCM can improve the efficiency of solar PV. The mean surface temperature of the solar PV is approximately 42.49°C, significantly lower than the surface temperature without PCM, which is approximately 47.17°C. The power output of solar PV increases by about 9.83%, from 118.09 watts without PCM to 129.70 watts with the PCM cooling system. The solar PV efficiency using a PCM cooling system is also higher than that without a PCM cooling system. The efficiency using PCM is approximately 22.81%, and without PCM, it is 17.43%.

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