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Comparative study of different phase change materials on the thermal performance of photovoltaic cells in Iraq's climate conditions

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ABSTRACT

The incident solar energy that impinges upon the photovoltaic cells undergoes a conversion process, resulting in the generation of electrical energy and conversion of absorbed energy into heat. This increase in temperature adversely affects the performance of the panel, leading to a decrease in its overall efficiency. This study examines the properties and performance of phase change materials, specifically paraffin wax, natural beeswax, and a combination of paraffin wax and beeswax, in comparison to a solar panel lacking any phase change substance. The experiment was conducted in the climatic conditions of Iraq, namely in the city of Hawija, located southwest of Kirkuk, during the summer of 2022. The prevailing environmental temperature throughout this period averaged 44 °C. The experiment involved comparing plate temperature, electrical power, and electrical efficiency. The results indicated that all the materials caused a decrease in the temperature of the board at the beginning of the experiment and for a short duration. Nevertheless, as the phase change material (PCM) undergoes melting, the dissipation of heat becomes unfeasible, resulting in a gradual increase in temperature. It was observed that there was a rise in temperature during the afternoon hours. According to the recorded data, the use of beeswax resulted in a decrease in temperature by 4 °C in comparison to the reference plate that did not incorporate phase change materials (PCM). Additionally, the efficiency of the photovoltaic (PV) system increased by 1% when compared to the PV Compared with PV (reference). The efficiency of the solar panel with beeswax ranged from 13% to 14%. According to the findings, the integration of phase-change materials with solar panels has been observed to effectively lower the temperature of the panels, hence enhancing their overall efficiency. Consequently, this approach represents a viable and advantageous choice.

1. Introduction

Photovoltaic systems are built outdoors or on roofs for maximum solar radiation. Since only 15–20% of these photons are converted into energy, the rest is absorbed as heat, raising their temperature. Each degree of temperature affects PV cell efficiency by 0.45% (Stropnik and Stritih, 2016). This heat must be dissipated in various ways to lower their temperature and keep it reasonable. The hybrid photovoltaic system phase change materials use a PV module and phase change materials to convert solar energy more efficiently than photovoltaic panels. PV converts visible and ultraviolet sun photons, while PCM uses heat. These systems are smaller than others, which is an advantage. PCM reduced panel surface temperature and increased electrical efficiency (Michael Joseph Stalin et al., 2022). Karthikeyan et al. identified the adoption of PCM-based systems based on location/climate (Velmurugan and Kumarasamy, 2021). These systems are still developing because most of the data is confusing and needs more research.

Tan et al. passively cooled solar panels using two equivalent photovoltaic panels. The plate conceals a phase change material heat storage container. The 27 °C-melting paraffin wax has 184 kJ/kg latent heat capacity. Assessment of system performance was based on container metal fin count. Panels are 45 ° from the horizon with PCM cool 15 °C more than uncooled ones (Tan et al., 2017). N. Choubineh et al. investigated how Phase change materials affected the solar panel's

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production power, performance and temperature. According to experimental findings, PCM inclusion caused a mean temperature decrease at the solar panel's rear side of roughly 4.3 °C and 3.6 °C in natural and induced convection, respectively (Choubineh et al., 2019). M. Rajvikram et al. tested reduced PV module operating temperatures with PCM and aluminium. The two panels are set side by side at 45 degrees on the platform to maximise radiation. A panel without PCM with natural ventilation is compared. Experimental results showed that PV-PCM with aluminium at the panel rear boosted panel changing efficiency by 2.4% (R. M., L. S., R. S., A. H., and D. A, 2019). Yiping Wang introduced porous media-based PV panel cooling technology for thermal management and efficiency. An active phase change cooling system using ethanol was created to cool the PV panel. Energy, average temperature, temperature distribution, and PV panel electrical performance are tested in the lab. Increasing non-condensable gas flow rates lowers PV panel temperature and boosts power. The largest temperature change is less than 5 °C. The maximum power generation improvement was 21.37 W/m^2 &19.32%, respectively (Wang et al., 2019). Zhenpeng Li. et al. added phase change material to the back surface of one module, leaving one out for comparison. The findings demonstrate that the electrical output of the PV-PCM system rose by 5.18%. In contrast, the photovoltaic temperature differential between the PV-only and PV-PCM systems might reach up to 23 °C (Li et al., 2019). S. K. Marudaipillai et al. utilized (PCM) cooling primarily to lower the temperature and boost electricity. They reported that when the outside temperature is close to 32 °C, the temperature of the PV barely increases to 38.06 °C. The temperature is lowered to 47.51 °C using the photovoltaic panel's heat sink. Compared to the reference PV panel temperature, the temperature in the PV panel falls to 36 °C in the first two hours and progressively rises to 38 °C (Marudaipillai et al., 2020).

Muhammad Hussain et al. studied the PCM layer's cooling effect through the airflow gap from the bottom. (RT18HC, RT21, RT21HC, and RT25HC) PCMs were chosen. performance indicators cell temperature, and total unit efficiency were examined. The lowest PV temperature and highest PV efficiency were obtained at 1:00 pm. Since raising the PCM layer thickness beyond 120 mm does not significantly improve system performance, it has been shown that 120 mm is the optimal thickness (Jahangir et al., 2020). Priti Singh et al. investigated thermal conductivity-optimized containers to accelerate PV-to-PCM heat transfer. Studies were done outside in Chennai, India, and compared to a reference panel for numerous seasons. The photovoltaic curves for temperature, open circuit voltage, short circuit current, current-voltage and voltage curves, power output, efficiency, and daily electricity generation were examined. The heat sink reduced the maximum PV temperature from 64.4 °C to 46.4 °C in January and from 77.1 °C to 53.8 °C in June. Electrical efficiency rose 1% in the afternoon. The daily electricity generation increased by 78 watts in February and 48 in January (Singh et al., 2020).

The College of Engineering and Technology in India used PCM to improve photovoltaic cell energy conversion efficiency and lower solar panel temperatures to study thermal impacts. The average solar panel temperature is 45 °C, with maximum and lowest values of 55 and 38. The combined PCM solar panel temperature averages 39.6 °C, ranging from 48.6 °C to 33 °C. The highest performance is 10.3% without the PCM panel, and the electrical efficiency is 9.84%. The average PCM PV panel efficiency is 12.9%. PCM reduces PV panel temperature to 4 °C and increases efficiency by 3% (Kumar et al., 2020), fluids, phase transition materials, and porous media cool. Vaziri-Rad et al. try a porous aluminium shaving media to improve phase transition material heat conductivity. Unlike reference solar panels, hydro-PV systems have porous material and salt hydrate. Electric, thermal, and power unit efficiency were measured in July and December. PV module cooled with phase change material and porous medium decreased by 24 °C and increased energy efficiency by 4.34% over reference solar panel. Porous media accelerates phase-changer material dissolution 19–25% (Vaziri Rad et al., 2021). A study was done to see if cooling solar cells with a phase-change substance would increase their efficiency. Experiments were carried out at Batman University in 2019 starting in August, using two solar cells with a capacity of 125 W and 9 kg of calcium chloride hexahydrate as a phase-changing material at a melting temperature of 30 °C. The study's findings revealed that the surface temperature of the solar cell with the phase-changing material was 51.2 °C, while the other photovoltaic panels without the material were 53.26 °C. Voltage and current can increase by a maximum of 1.46% each (KARAKAYA and ŞEN, 2020). S. V. Chavan et al. tested three PV systems in the same environment to increase their efficiency. Using three completely symmetrical 40 W solar panels: one without alteration, one with phase change materials, fins, and PCM, and one with a photovoltaic system. Copper pipes deliver water. The second and third kinds employed white Vaseline as a phase transition substance. The experiment involved installing the panels side by side under real weather conditions. The PVT-PCM system generates 4.06% more electricity than standard PV modules (Chavan and Devaprakasam, 2021).

S. Adibbour used PCM to cool the PV and a tracer to increase their power output. Using two identical monocrystalline silicon panels, One of the two panels is a PV panel without any additions for comparison and the other is a PV board reinforced with a layer of PCM on the rear and special salts. Unlike ordinary salts, which have only one melting point, special salts can melt at their maximum over a temperature range of ten. The temperatures are measured in different places of the PCM. PV modules with PCM have a mean improved performance of 4.6% over those without PCM, with a maximum improved efficiency of 6.8% (Adibpour et al., 2021). Explored fresh water-cooled phase-change material solar panel thermal management. The PV plate, aluminium plate, and water channel formed the PCM enclosure. PCM enclosure in the rear of PV and water duct to absorb and distribute PV heat to PCM and water. Compared to PV panels without cooling, continuous water flow cooling from the collector top to bottom performed best in electrical, thermal, total, and energy gain evaluations. Reduce average temperature, increase energy generation, efficiency, and power ratio to maximise power output: 11.92%, 12.4%, 13.54%, 5.4 °C, 26.07% (Sudhakar et al., 2021). To chill solar cells, the team employed foam metallic PCM with a heat sink. Try Coconut and copper Foam. Due to its affordability, sustainability, and availability, coconut oil is a phase-changer. Maintaining laboratory temperature with copper foams with three porosities (85%, 90%, 95%) during the experiment. Inclination inhibits convective heat transport of porous liquid PCM, which hinders dissolving (85%, 90%). Nevertheless, this negative effect may prolong PV panel cooling. Maximum duration is twice as long for 85% or 90% PCM porous systems as for 95% ones (Duan, 2021).

In 2021, Arab Egypt and Benha University verified that phase-changing material and aluminium shavings cooled solar panels. The panel's back held a phase-changing substance, paraffin wax RT-42, and aluminium shavings. Sawdust reduced solar panel temperature in the study. Aluminium and phase varied by 4%, 7.4%, and 13.2%, and the generated energy was 1.85%, 3.38%, and 4.14% higher than the reference plate in December, January, and February (Sharaf et al., 2022). South Indians employ inorganic PCM to overcome organic materials' low conductivity. An aluminium sheet was coated with PCM and salt to boost thermal conductivity. Sunlight was used during a week of experiments. Monitoring cooled and uncooled solar panels with a thermal camera. Cooled PV panels improved PV energy efficiency by 7.67%. Maximum voltage improvement was 7.34% and the maximum solar panel temperature drop was 4.6 °C (Elavarasan et al., 2022) using Polyester glycol with two 40 W solar panels. Bhakre et al. used 1500 phase change materials. A metal matrix added to a phase transition material when PV is utilised yields results. Comparing PV/PCM with and without metallic matrices PEG between degrees Celsius, 1500 melts. Outside, the photovoltaic panel's thermal and electrical performance was assessed. PEG 1500 lowers photovoltaic panel temperature by 10.59% and 14.08% and boosts electrical efficiency by 5.84% and 8.87% in PV/PCM and PV/PCM metal matrix systems, respectively

(Bhakre et al., 2022). A finned container of phase change material (PCM) on the rear of PV modules passively cooled them. The novel organic eutectic of Myristic and Stearic acids is PCM. Both acids were evaluated at 60:40, 70:30, and 80:20% weight ratios. Test conditions: 900–1000 W/m^2 tungsten halogen lamps on PV module. Reference PV module performance vs. PCM cooling. Organic phase transition material improved solar module performance and temperature level. A weight ratio of 60:40% reduces temperature by 7.06 °C, boosts power by 0.454 watts, and improves module efficiency by 4.226% (Homlakorn et al., 2022).

Muhammad Shoaib and colleagues added a heat sink to the PV module's rear to increase solar cell cooling. Phase-changing substance-filled fin-shaped cylinders. Thermal and electrical evaluation of unchanged solar modules. Heat is transferred from the solar module to the phase change material through the fins. Tests lowered the PV module temperature to 5.18 °C. Its output voltage rose 0.53 V and performance rose 2.9% over the solar cell without the new technology (Shoaib et al., 2022). The results demonstrated how the usage of an organic phase changer material reduces the temperature of the photovoltaic 7.47 °C when metal matrix sheets are not applied. It has been observed that the use of metal matrix sheets reduces the PV temperature less than the use of PCM alone and improves the electrical performance. PV performance is improved by increasing the mass of a bio-based phase changer material from 1.6 kg to 4 kg (Rahimi et al., 2023). D. Govindasamy et al. examine the issue of high operating temperatures in solar panels and propose a solution involving the utilisation of four solar panels. The initial solar panel employed a reference material, whereas the subsequent solar panels incorporated paraffin gel in combination with expanded graphite, expanded perlite, and expanded vermiculite, respectively. Comparisons were conducted by considering several electrical and energy efficiency criteria. This study examines the impact of cooling on the output and surface temperature of solar panels. The findings indicated that Unit No. 3 achieved a significant drop in surface temperature, decreasing it from 59.04 °C to 48.75 °C. Additionally, it demonstrated an improvement in electrical efficiency, increasing it from 11.97% to 14.89% during the noon hours. Moreover, there was an increase in power production, rising from 28.95 W to 36.99 W (Govindasamy and Kumar, 2023a). Zhiming found that, with no wind, 1000 W/m^2 radiation, and 7.3 °C ambient temperature, PCM can cool solar PV panels. Solar PV panel top and back temperatures drop 33.94 °C and 36.51 °C in 300 min using the PCM. PCM increased PV panel power generation efficiency by 1.63% and output power by 1.35 W. PV-PCM panels cooled from maximum temperature to room temperature in 480 min, while PV panels without PCM took 60 min (Xu et al., 2023). D. Govindasamy et al. employ PCM to lower solar photovoltaic panel temperatures and increase energy efficiency. Testing vermiculite- and perlite-paraffin gel phase transition materials on individually bonded monocrystalline solar panels. Behind the solar PV module are VP-PCM and PEP-PCM. Integrated PCM panels reduced solar cell maximum temperature, increased power generation, and improved electrical efficiency (Govindasamy and Kumar, 2023b). Shakibi et al. improved energy output with finned collectors and nanoparticle-based PCM. Thermo-PV systems. This combination improves thermal efficiency by 10–24% (Shakibi et al., 2023). Miaari et al. Using phase-change material to cool a 20 W PV module. The unit's performance and efficiency are improved by using six tiny, easy-to-assemble and dismantle phase change containers instead of one. This simplifies technological aspects. The adopted method offers many advantages over earlier ones. To adapt to weather changes, phase change materials can be easily adjusted. When the phase change material inside the container dissolves entirely, the container can be readily swapped, improving cooling and PV system efficiency throughout the day. The cooled and uncooled PV modules were measured using three temperature sensors at different positions. According to experiments, adopting proper phase change materials can lower the average PV module temperature by 10 °C and boost energy performance by 5.23% (Al Miaari and Ali, 2023).

P. Manoj Kumar et al. studied nanoscale phase transition material thermal management of solar panels. By dispersing 0.5% TiO_2 nanoparticles in paraffin, the NPCM was created. In this investigation, two similar solar PV panels were used. The second panel was integrated with NPCM behind it, while the first was merged without it. According to the study, NPCM reduced the panel's average daily surface temperature by 13 °C. The panel's daily efficiency increased by 2.1% (Manoj Kumar et al., 2021). (PV/T-PCM) efficiency increases in percentages using nanomaterials compared to the standard solar pane (Gürbüz et al., 2023a), (Gürbüz et al., 2023b). it has been found that carbon-based nanomaterials incorporated into PCM are highly effective in improving the performance of PCM. They lead to an increase in heat conductivity depending on the material resulting in improved thermal properties by up to 28 times (Olabi et al., 2021). These systems were also simulated using CFD models like Ansys FLUENT and MATLAB. Results show that phase change materials as a cooling system lower solar cell temperatures reducing losses. Efficiency boosts electricity production (Taqi Al-Najjar and Mahdi, 2022)– (Pereira et al., 2023)].

By reviewing previous studies, it is noted that no clear light has been shed on the use of phase-change materials to cool solar panels in extremely hot environments. Hence, this study aims to evaluate the effect of integrating phase-change materials with solar panels and Passive cooling under the influence of Iraqi weather conditions, which are characterized by their heat. and compare its performance with solar panels under these conditions in terms of electrical efficiency, panel temperature, and electrical output through experimental work.

2. Experimental methodology

This part describes, with a closer look, the thermal storage property of phase change materials for three compositions of phase change materials, which are beeswax, paraffin wax, and a mixture of the two, used in the thermal management of solar panels in an environment characterized by very high temperatures in the summer, and their study in external conditions and comparison between them. The experiments were carried out at Hawija, a city located in the southwestern region of Kirkuk, Iraq (35°20"12" N, 43°47"03" E), during the summer of 2022. The research spanned the entire summer season, specifically from June to August, and involved a single experiment. Every 72 h. The experiments aim to study the possibility of using phase change materials in a very hot climate and the extent of their effectiveness in this climate.

2.1. Experimental rig

This study used four solar panels from MTS, each of which has a power capacity of 50 watts and dimensions of 465 × 670 mm. Table 1 shows the overall specifications of the solar panels. The throughput of the panels was evaluated before the start of the experiments over two consecutive days for variability between them, revealing a discrepancy of less than 1%. In these experiments, a phase-change material was used, consisting of (paraffin wax, natural beeswax, and a mixture of the two in a weight ratio).

Table 1
Specifications of the solar panels used in the research.

Model Type			MTS9BB50	
Solar Cell Type			Poly158 × 52 mm	
Pm	Vmp	Imp	Voc	Isc
50 W	18.6 V	2.69 A	22.6 V	2.92 A
Max System Voltage			1000 V(IEC)	
SIZE			46.5 × 67.0 × 3.0 cm	
gravity			3.6 kg	
Productivity tolerance			0_+ 5 W	
S.T.C			1000 W/m^2,AM1.5,25 C°	
Temp. Coefficient of Pmax			- 0.35%/C°	
Operating Temperature			- 40 C°to85C°	

The cavity on the back surface of the plate, with a volume of 5 litres, was filled and sealed with a 0.8 mm thick aluminium plate to prevent any wax leakage during the melting process. The main challenge encountered during the experimental procedures was the issue of wax leakage from the container during the melting process. A sealant was used to mitigate leaks. The wax undergoes a transition from solid to liquid state when heated in a water bath, after which it is inserted into the back of the solar panel. Furthermore, a sealant has been used to effectively secure the lid, thus ensuring that no wax leaks out during the melting process.

The initial solar panel was kept in its original condition as a reference panel, to serve as a basis for comparative analysis without any modifications or augmentations. A phase change material, specifically paraffin wax, was used on the back of the second solar panel. The literature indicates that about 10% of the volume is allocated to accommodate the melt volume. The third plate underwent a similar procedure, where a phase change material, specifically natural beeswax, was introduced after the wax had been strained and filtered. In the fourth panel, a mixture of paraffin wax is incorporated. The process involved blending natural beeswax with paraffin wax at a 2:1 ratio by weight.

The experimental setup included the use of Type K thermocouples. The Type K thermocouples were calibrated to an accuracy of ± 0.1%. Thermocouples are installed, two on the front and two on the back of the solar panels. In addition, a double is installed in the wax middle and another on the aluminium cover. All couplers were connected to a data logger. The data logger used to record temperature data was a JK500 multi-channel type with 32 channels. All devices and tools used are described in Section 2.3.

The panels are arranged side by side on an iron platform. The platform consists of metal rods placed at different angles, with one side designed to be adjustable in order to adjust the tilt angle of the solar module. The stand was placed in the south-facing direction and its inclination was set to a horizontal angle of 30°. This configuration was chosen to optimize the reception of the highest possible amount of annual solar radiation at the specific location of the site, as illustrated in the photo of this cooling setup and the schematic diagram in Fig. 1 & 2.

Measurement of complete meteorological variables, such as wind speed, radiation intensity, and environmental temperature, was performed using the Davis weather system. The variables that were measured during the experiment included the temperature of the plate, the temperature of the phase change material (PCM), and the temperature at the back of the enclosure. The measurement of electrical output is conducted manually at hourly intervals from eight in the morning to five in the afternoon. Utilizing a multi-meter possessing a precision level of ± 0.1%. The measurements conducted included the determination of the output current and voltage. A 50-watt light bulb was employed as the electrical load. Furthermore, the parameters that were measured encompassed the environmental temperature, incident solar radiation, temperature of the photovoltaic module, and temperature of the PCM box.

From a literature review, the melting point range of 15–90 °C is a critical characteristic of phase change materials (PCM) when considering their suitability for solar heating and convection stabilization purposes. Natural beeswax and paraffin wax were used, as beeswax is a natural material with stable properties. In addition, it is an environmentally friendly material, and its melting point is approximately suitable. Table 2 presents the specifications of the wax used in the conducted experiment.

2.2. Preparing PCM panels

The available paraffin wax was purchased from local markets, which

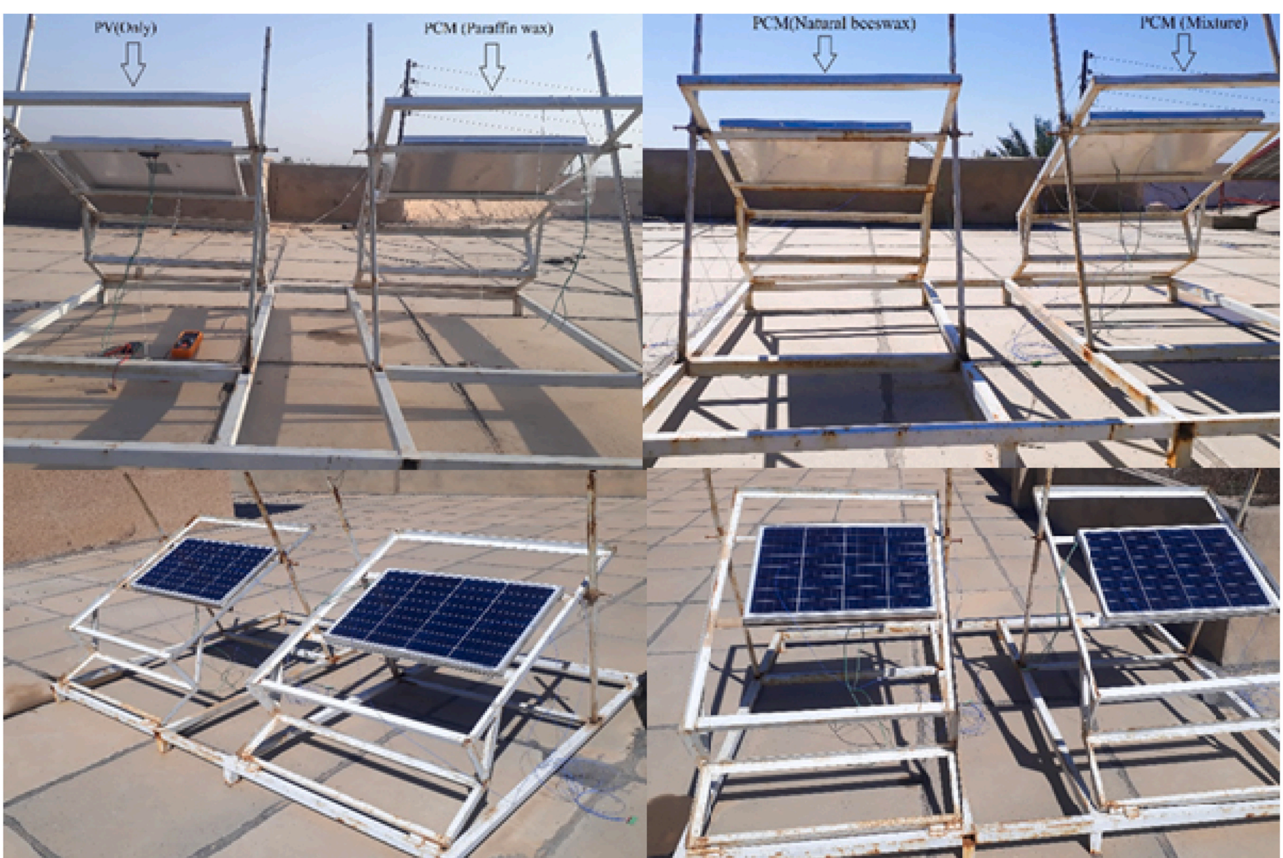

Fig. 1. Pictures of the experience.

Fig. 2. **PCM system components with solar panel.**

Table 2
Specifications of PCM used in the research.

Specifications	Beeswax	paraffin wax
Freezing and melting of wax	65 ℃	56 °C
latent heat	229 J/kg	229 J/kg
density at the melting point	878 kg / m3	868 kg / m3

is white paraffin manufactured by Histo-Line Laboratories, its melting point is 56 degrees Celsius, in a granulated form, packed in a plastic container weighing 2 kg per unit, as in Fig. 3.

Preparation of raw natural beeswax, which was extracted from honey bee hives and was melted in a water bath, then filtered by placing it in a galvanized iron cylinder, then pressing it with a piston to enter through a fine wire mesh that removes all the plankton carried by the wax, as it emerges from the filtration with a consistency similar to that of cooking oil, where the required quantity has been collected, as in Fig. 3.

Four solar panels with a capacity of 50 watts were used, as mentioned, with dimensions of 465 × 670×30 mm. The height of the cavity in the back surface was 30 mm. The wax was melted in a water bath until it became liquid. The cavity was filled, leaving 10% space for solidification. The fusion was left. Until it freezes, then a sealant is applied to seal the aluminium lid. Once the aluminium lid is tightened tightly, the previous process is repeated for the two plates of beeswax and paraffin wax. As for the plate in which the mixture is placed first, the weight of the wax packed in each of the two previous plates is measured, and a mixture is placed. Of beeswax and paraffin wax with a weight ratio of 2 beeswax to 1 paraffin wax. Table 2 shows the specifications of the wax used in this study.

2.3. Instruments and measurement devices

The devices and tools used in the experiment include 50-watt polycrystalline solar panel shown in Fig. 4a from MTS Company. Thermocable type K temperature gauge senses temperatures from − 75–250 °C shown in Fig. 4b has been installed at selected points to measure and collect the temperature data using 32-channel multichannel JK500 type data logger shown in Fig. 4c. The weather core system shown in Fig. 4d has been used to measures the intensity of solar radiation, wind speed, ambient temperature, and other weather variables. It measures these variables throughout the day and stored so that it can transferred to the computer. Pure paraffin wax shown in Fig. 4e with melting and freezing point of 56 °C has been mixed with Pure natural beeswax shown in Fig. 4f with melting and freezing point of 65 °C to prepare the PCM used in this study.

2.4. Mathematical equations for assessment of PV module

Solar cell efficiency refers to the quantitative measure of the electrical output generated by a solar cell in relation to the amount of incoming energy it receives in the form of sunshine. The percentage of solar energy that is converted to electrical power is referred to as the efficiency of the conversion of energy (η) of a solar cell. The calculation involves the division of the highest possible electricity production by the product of the solar radiation intensity and the area.

$$\eta = \frac{P}{E \times A} \times 100 \tag{1}$$

The power output of the solar cell can be calculated by the multiplication of the cell's current as well as its voltage.

$$P = V \times I \tag{2}$$

$$FF = \frac{\text{Imp} \times Vmp}{Isc \times Voc} \tag{3}$$

The quantification of a photovoltaic cell's efficiency relies on the ratio of converted electrical energy to the total incident power. The measure in question is formally and specifically defined as:

$$P_{\max} = V_{OC} \times I_{SC} \times FF \tag{4}$$

$$\eta = \frac{P_{\max}}{P_{inc}} \tag{5}$$

3. Analysis of the results

3.1. Solar radiation and the surrounding temperature

On a very hot summer day in July, ambient temperatures and solar radiation were measured from 8:00 am to 5:00 pm. It was found that the temperature rises continuously as solar radiation intensity increases, peaking at 3 o′clock in the evening with a temperature of 43.5 °C and solar radiation values ranging from 300 to 956 W/m2. The peak of the solar radiation intensity was at 1 o′clock in the afternoon. As depicted in Fig 5.

Fig. 3. Preparing PCM panels.

3.2. solar panel temperature

The temperatures were compared between the reference PV without PCM and the three PV containing different types of phase-changing materials in these extremely hot summer climates. Fig. 6 shows that the temperature of the panel without a PCM steadily rises as solar radiation intensity rises until it reaches its maximum at 1:00 pm when the radiation intensity reaches its maximum. The increase in wind speed, which also enhances the heat exchange between the solar panel and the surroundings, caused temperatures to start to drop. It steadily drops as the amount of radiation falls; the solar panel's temperature ranges from 38.65° to 69.4°C, with an average daily temperature of 54.7 °C. Temperatures were lower when paraffin wax was used in solar panels; they varied from (37.8–69.9)°C until 2:00 PM. The wax melts completely because it cannot absorb any more heat. Then the temperature of the panel begins to rise, and the rise continues compared to the reference panel, even after a slight decrease in the intensity of solar radiation and a decrease in the temperature of the surrounding environment. As the wax begins to freeze, it releases heat that increases the temperature of the panel. This process continued until the test's conclusion and the average daily temperature of the solar panel was (54.21 °C). As for the solar panel that contains a mixture of paraffin wax and natural beeswax, The solar panel's temperature varied. (37.65–67.65) °C the temperatures were lower than the PV without phase change material 8 °C at 11:00 am with the increase in temperature this difference started to decrease at 1:00 pm it started to rise until the end of the experiment where the wax was completely melted. As the wax cannot absorb more heat, the same scenario is repeated and the panel heats up, as the temperature increase to 2.9 °C at the end of the test was higher than the reference panel, and the average daily temperature of the solar panel was (53.62 °C). As for the solar panel containing natural beeswax, the temperature ranged between (37.5–62.3) degrees Celsius, and the panel temperature was 10.8 °C lower than the PV without phase change material at 11:00 am, and the temperature difference continued up to 2: 00 p.m. when the temperature was equal between the two solar panels, as the wax melted completely because it could not absorb more heat. Then the temperature of the plate begins to rise after 3:00 pm, and the rise continues compared to the reference plate even after the decrease in the intensity of solar radiation and the temperature of the surrounding environment decreases slightly as the wax begins to freeze, releasing heat that increases the temperature of the plate, and this process continues until the end of the experiment when the temperature rises to 2 °C at the end of the test is higher than that of the reference panel, and the average daily temperature of the solar panel (51.66 °C).

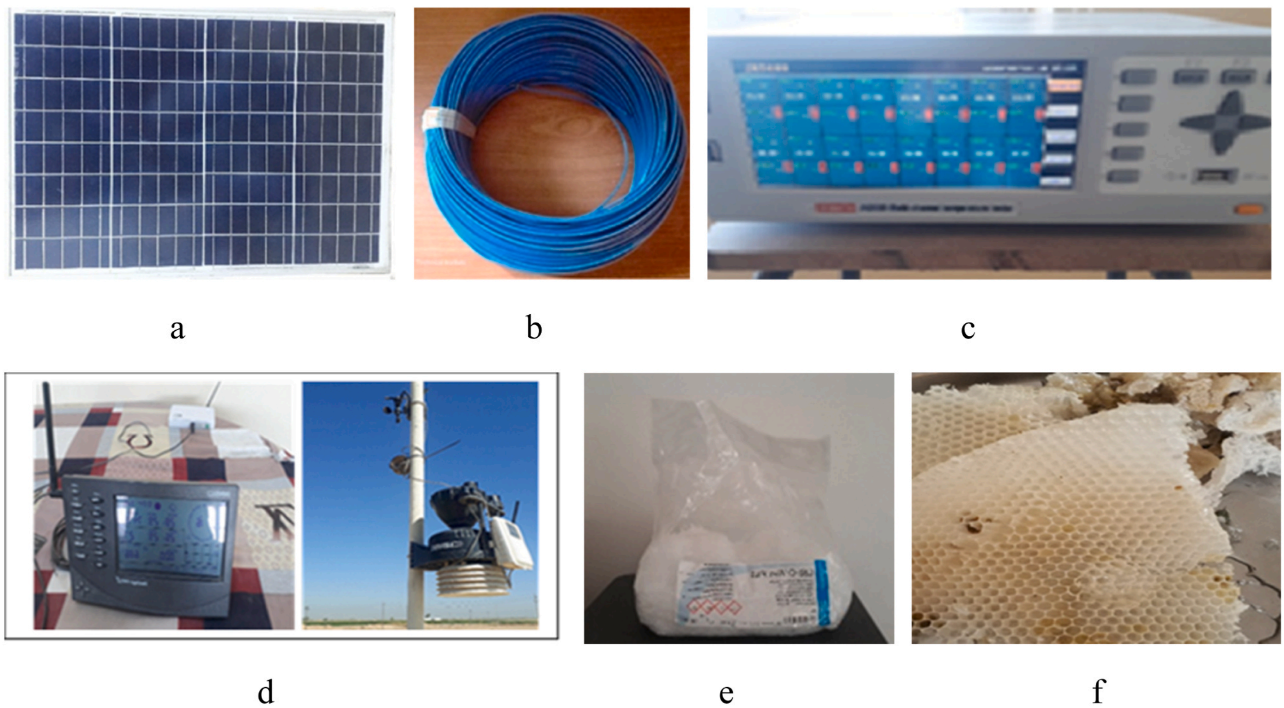

Fig. 4. Instruments and measurement devices.

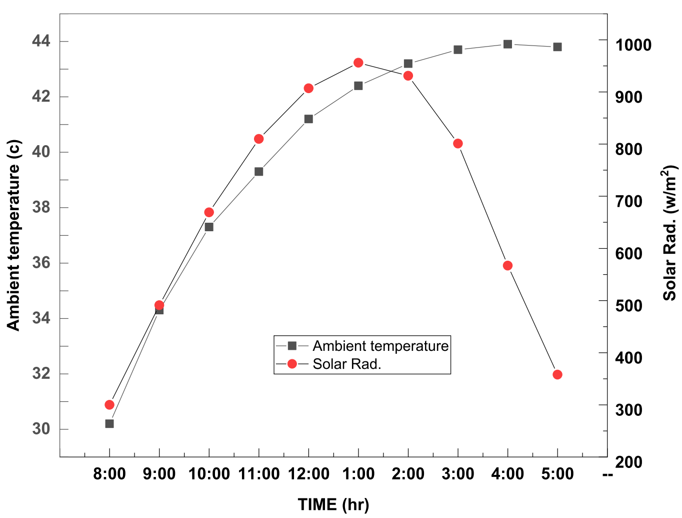

Fig. 5. shows the amount of solar energy and the ambient temperature over time for July 7, 2022.

3.3. Generated power

The energy produced from the panels, whether by increase or decrease, indicates the extent of the increase and decrease in efficiency under the same conditions, as noted in Fig. 7. In the diagram. It is evident that as sun radiation grows, so does electric power and reaches its peak at 1:00 pm with the peak of the solar radiation in all the cooled plates by using the phase-changing materials and the solar panel without PCM. At the end of the experiment, it was noted that the electrical output decreased for the three plates cooled with phase-changing materials in different proportions. This is attributed to the high temperature of the panels, as honeybee wax was able to maintain a somewhat low temperature compared to the remaining two panels for a limited period, where the daily rate of the generated power was (28.9, 28.8, 29.5, 28.9), PV $_{ONLY}$, PV $_{paraffin}$, PV $_{beeswax}$, PV $_{mixture}$ respectively. It is worth noting

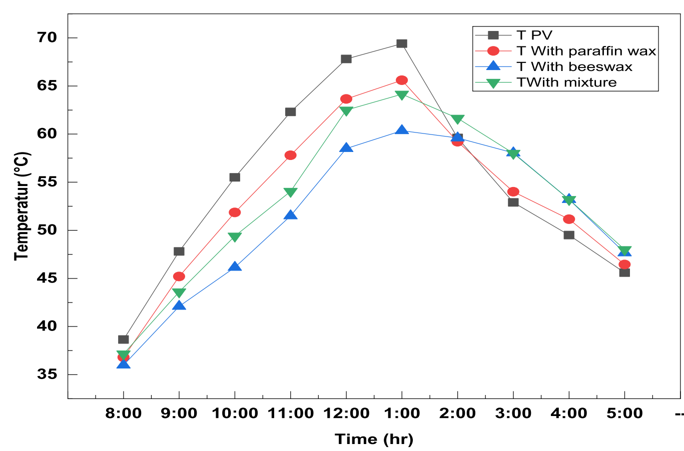

Fig. 6. Comparison of the temperature of solar panels with time for the day 7/7/2022.

an increase in the current values and a decrease in the voltage values in the afternoon hours due to the high temperatures of the solar panels, as shown in Figs. 8 and 9.

3.4. Electrical efficiency

Electricity, which may be described as the produced electrical power divided by the intensity of solar radiation per unit area, is created when sunlight strikes solar panels, which convert it into electricity. The efficiency is based on the solar panel's maximum productivity based on its temperature. The following equation can be used to compute it:

$$\eta_{ele} = \frac{P_{\max}}{E \times A} \tag{6}$$

E: Solar radiation is measured in watts per square meter.

A: The area of the solar panel is measured in square meters.

Fig. 10 shows that the efficiency rises with the rise in radiation and

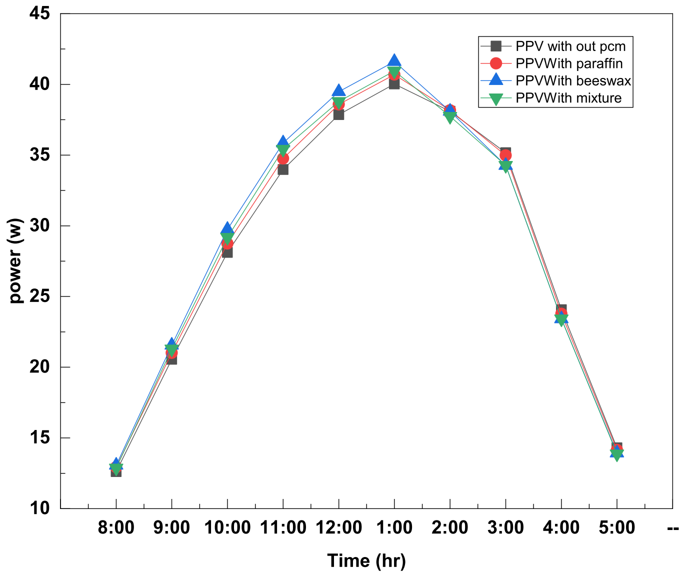

Fig. 7. The power generated over time for day 7/7/2022.

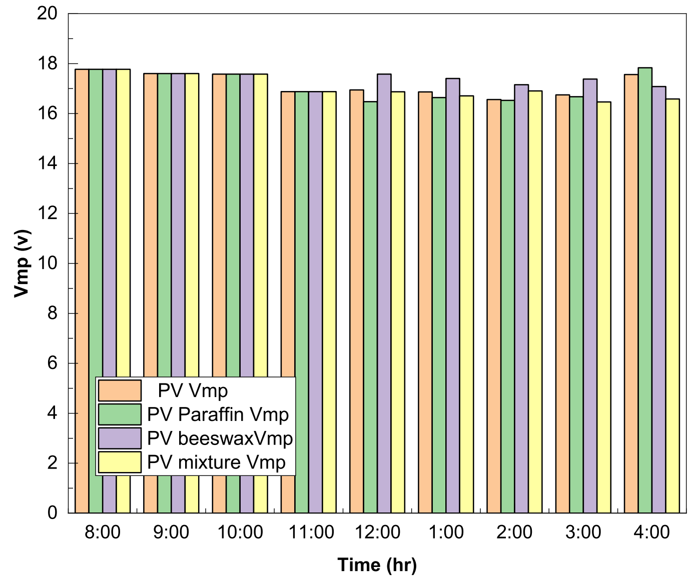

Fig. 9. Open circuit voltage over time for day 7/7/2022.

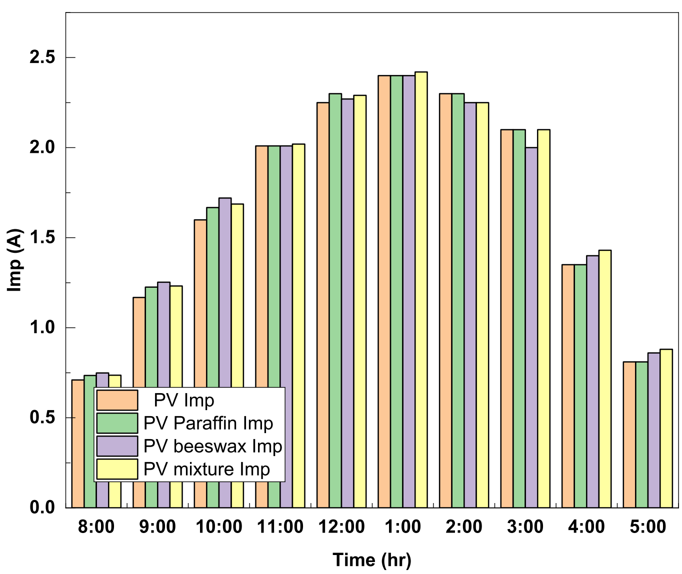

Fig. 8. Open circuit current over time for day 7/7/2022.

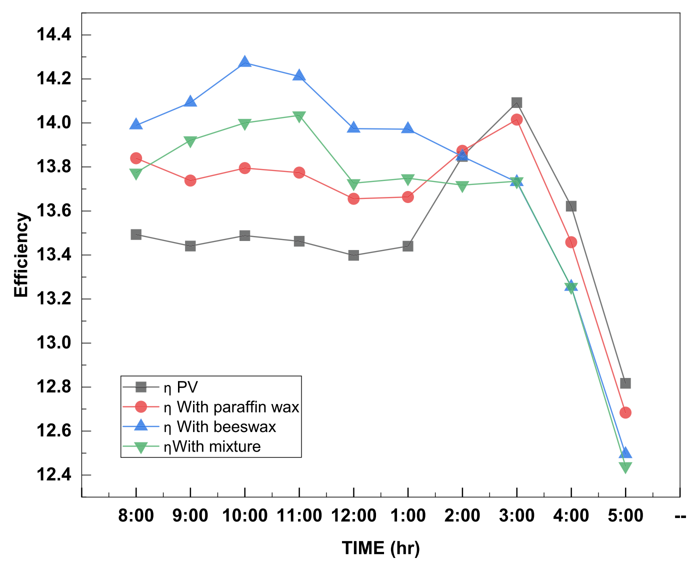

Fig. 10. Electrical efficiency with time for day 7/7/2022.

decreases with the rise in radiation because, with the rise in solar radiation, the heat also rises. With the rise in the temperature of the panel, the electrical efficiency decreases. From the first hours, the solar panel's efficiency increased, and it kept increasing until 11:30 AM. The solar panel's back was coated with paraffin wax. When it reaches a point where it can no longer absorb further heat, this causes a rise in plate temperature and a fall in efficiency, with the peak efficiency being (14.1%) at 9:00 am, as for the solar panel, which has been incorporated a mixture of wax in the back. It is noted that the efficiency increased from the beginning of the experiment to 11:00 am. It decreased more sharply between 11:30 am and 2:00 pm. It rose slightly at 3:00 pm, where it was observed that the wind speed activity decreased due to the high temperature of the solar panel and the decrease in solar radiation until the end of the experiment. The highest efficiency recorded was (14.22%) at 10: 00 am. The solar panel has natural beeswax on the back. It is noted that the efficiency increased from the beginning of the experiment until it reached the highest value at 10:00 in the morning. It decreased until two in the evening until it became equal to the reference panel. It decreased due to the high heat of the solar panels and the solar radiation decreasedd until the experiment's end. The highest efficiency (14.5%) was recorded at 10:00 am.

Though there is no study conducted under the same conditions as this study, some results of similar studies are listed in Table 3 for comparison. Acceptable agreement is observed for the obtained results taking into consideration the variation in the experimental setup and environmental conditions.

4. Conclusion

In this research work, the performance of phase change material incorporation in the rear of the photovoltaic panel was investigated through the use of four solar panels, one of which was left as a reference plate. The phase change material was incorporated into the remaining three panels, which were as follows: a plate in which paraffin wax was incorporated, a plate in which paraffin wax was incorporated beeswax, and a panel in which a waxy mixture of honey bees and paraffin wax was mixed in a ratio of 2–1, respectively, and compared to a solar panel without phase change material (reference) under the real conditions of

Table 3
Comparison of the obtained results with recent studies.

Ref.	Experimental setup	Obtained results
(Tan et al., 2017)	Efficiency Gains of Photovoltaic System Using Latent Heat Thermal Energy Storage,	passively cooled solar panels using two equivalent photovoltaic panels. The plate conceals a phase change material heat storage container. The 27 °C-melting paraffin wax has 184 kJ/kg latent heat capacity. Assessment of system performance was based on container metal fin count. Panels are 45 ° from the horizon. PV panels with PCM cool 15 °C more than uncooled ones, the trial found
(Choubineh et al., 2019)	An experimental study of the effect of using phase-change materials on the performance of an air-cooled photovoltaic system	investigated how Phase-change materials affected the solar panel's production power performance and temperature. According to experimental findings, PCM inclusion caused a mean temperature decrease at the solar panel's rear side of roughly 4.3 °C and 3.6 °C in natural and induced convection, respectively
(R. M., L. S., R. S., A. H., and D. A, 2019)	Experimental investigation on the abasement of operating temperature in solar photovoltaic panels using PCM and aluminium	tested reduced PV module operating temperatures with PCM and aluminium. The two panels are set side by side at 45 degrees on the platform to maximise radiation. A panel without PCM with natural ventilation is compared. Experimental results showed that PV-PCM with aluminium at the panel rear boosted panel charging efficiency by 2.4%
(Kumar et al., 2020)	Experimental investigation of improving the energy conversion efficiency of PV cells by integrating with PCM	PCM has been used to improve photovoltaic cell energy conversion efficiency and lower solar panel temperatures to study thermal impacts. The average solar panel temperature is 45 °C, with maximum and lowest values of 55 and 38. The combined PCM solar panel temperature averages 39.6 °C, ranging from 48.6 °C to 33 °C. The highest performance is 10.3% without the PCM panel, and electrical efficiency is 9.84%. The average PCM PV panel efficiency is 12.9%. PCM reduces PV panel temperature to 4 °C and increases efficiency by 3%
(Shoaib et al., 2022)	Thermal management of solar photovoltaic modules by using drilled cylindrical rods integrated with phase change materials	Heat sink at the back of the PV module to increase solar cell cooling. Phase change material filled in fin-shaped cylinders. The comparison was made with a panel without a phase changer. Heat is transferred from the solar module to the phase change material through the fins. Reduced the temperature of the PV module to 5.18 °C. The output voltage increased by 0.53 V and the performance increased by 2.9% compared to the solar cell without it

the Iraqi atmosphere, which is characterized by high temperatures. The temperature of the panel was studied and extracted Energy and electrical efficiency. The results also showed that paraffin wax slightly reduced the temperature of solar panels, as the average temperature difference of the solar panel compared to the reference solar panel was one degree Celsius. In the second case, in which the wax mixture was used, it had a greater effect in reducing the average temperature of the solar panel compared to the reference panel, slightly more than the first case, which was 2 degrees Celsius. As for the third case, the use of beeswax was better than the previous cases, as it reduced the average temperature of the solar panels compared to the reference panel by four degrees Celsius. Regarding electrical generation, the average daily electrical output was 28, 28.5, 31, and 28.7 watts for the reference plate, paraffin, beeswax, and PV mixture, as the effect on the electrical efficiency of beeswax improved by 1% the efficiency ranged between 13% and 14%. As for the other two types, the improvement was very slight. Beeswax showed better performance under the weather conditions in the study area, Iraq, which is evident from the study.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.egyr.2023.11.022.

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