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Thermal analysis and efficiency enhancement of solar modified PV panels through organic PCM under climate conditions of Pakistan

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K E Y W O R D S

Solar PV Panel

Phase Change Material

Surface Temperature

Climate Conditions

Standard Test Conditions

A B S T R A C T

Passive cooling of photovoltaics (PV) using phase change materials (PCM) may be extremely effective owing to their enormous implicit specific heat. However, the low rate of heat transfer, high solar radiation, and ambient temperature drop its efficiency by 0.45%/°C. Only such a small fraction of solar irradiance is turned into electrical energy by PV cells; most of the irradiation is transformed into heat; hence, cells start operating above ambient temperature. Therefore, the exterior heat of photovoltaic panels is controlled by applying artificial cooling to enhance their efficiency. The current research aims on the significant benefits of using PCM to reduce panel surface temperature in terms of boosting energy efficiency and maintaining thermal comfort. This study demonstrates a successful design of PV controlled-temperature module using phase change materials for hot climate, especially for south Asian regions. The surface temperature of solar panels has been reduced using computational analysis and experimental study on paraffin wax. In this work, Paraffin wax used, which reduced the panel surface temperature by 5-7°C, generating a 29% increase of the modified PV panel relative efficiency compared to its standard value.

1. Introduction

As corporations, financial institutions, and nations affirm their alignment with global climate targets in 2021, net-zero and carbon-neutral promises are on the rise. The Paris Agreement signatories' environmental commitments require significant reductions in greenhouse gas emissions and energy consumption, as well as the usage of renewable power as a primary energy source. Renewable energy has environmental and economic benefits, such as the ability to generate electricity without creating greenhouse emissions and the reduction of various forms of environmental congestion. Increasing energy diversity and decreasing reliance on imported hydrocarbons. Most of the South Asian countries receive enough solar radiations where the implementation of photovoltaic technology can be useful. However, for Pakistan and any other alike, the availability of data for evidence-based decision-making is currently very limited. Pakistan has enormous solar power potential due to its abundant sunlight, which is accessible at a rate of 1000 w/m^2. The application of solar energy has the potential to aid Pakistan's distant and remote communities, particularly Sindh and

Baluchistan. With a mean per planetary solar irradiance of 19-20 MJ/m2 and an annual mean sunlight duration of 8 to 8.5 hours each day, the sun shines brightly every day. Baluchistan is well-suited to the usage of solar energy. The quantity of solar radiation energy received on a specific surface area is referred to as "insolation."[1].

As Per International Renewable Energy Agency (IRENA), renewable energy will produce 30% of the electricity needed by 2035. By 2022, about 65 percent of new power production systems will use clean, sustainable energy technologies.[2]. Many researchers have identified a variety of parameters, including irradiance, dust on photovoltaic surfaces, PV thermal efficiency, moisture, and others, as contributing to the fall in photovoltaic panels exergy efficiency. [3]. During the ten years of 2010-2020, Photovoltaics are used immensely with over 34% percent growth annually [4].

Owing to great thermal power storage, PCM recuperated photovoltaic power loss caused by high operational temperatures. Japs et al. [5] reported that phase change materials diminishes operating conditions of photovoltaic panels by 7°C on standard and introduced uniformity to the cell temperature.

Various PV cells have various patterns of performance. For instance, thin-film PV cells show a higher energy absorbency and operate superiorly in low brightness. However, crystalline silicon cells have opposed performance as they perform well at strong irradiation but underachieve at reduced incidence. Moreover, the production of a photovoltaic cell is altered by the cell temperature. With a rise in cell temperature, the power output and cell efficacy exhibit a downward trend. In this work, paraffin wax, a phase transition substance, is utilized to increase PV panel efficiency by lowering panel surface temperature [6,7,8].

The efficiency of solar panels is influenced by the amount of solar irradiance, the composition of the semiconductors, and the ambient temperature of the semiconducting cell. Solar radiation changes are unregulated. On a PV panel, most of the incident solar power is converted into heat. The temperature of the PV cell rises because of this process, lowering its efficiency and durability. As a result, making use of the leftover heat, that can reduce the temperature of the cells, is a simple approach to maximize the energy output by a PV panel. Photovoltaic and Thermal technology offers higher global energy efficiency, with values of about 65 percent, owing to the coupling of PV and heat energy produced [2]. Durez et al. [9] performed simulations using three different PCMs with different environments and suggested that when PCM is used in accordance with environment there's comprehensive results in efficiency and output power.

In the 1980s solar collectors were used in the first hybrid solar panels. Thermal collectors made of tubes were used on the backside of those panels via which fluid was warmed by the PV panel's heat. As a result, the solar cells may be cooled, increasing efficiency. This basic design had been refined and adapted to different purposes throughout the previous several years. D.G.Pena et al. [10]. developed a new design for combining photovoltaic and thermal technologies with thermal storage. A PCM tank was added to the rear of the solar panel in the new design. Heat pipes were also included in the design, to facilitate heat transfer in the PCM's deeper areas. Outcomes show that the thermal inertia of the panel was enhanced by adding PCM, resulting in lower and more uniform panel temperatures. When compared to standard thermal storage materials, PCMs can retain substantial quantities of energy across a narrower temperature range. Poor rates of thermal diffusion inside the PCM can substantially impact the charge and discharge rates that can be accomplished due to the low thermal conductivities of many PCMs.

To reduce the operating temperature, one can either use natural or induced convection to increase free cooling on the back of the panel or change the panel's architecture to absorb the surplus heat. PCMs mounted on the back of solar panels are used in the latter approach. In the process, they absorb or reject heat. When the temperature of the panels rises, the surplus heat must be absorbed until the PCM has fully melted. The solidification of the PCM should supply extra heat for the running liquid in solar thermal panels, give heat to the building, or function as an insulating material when the panel's temperature drops. The SP/PCM technology is intended to be particularly beneficial for roof-integrated panels with limited ventilation areas. P.Biwole et al. [11] conducted the CFD simulation of heat and mass transfers in a system consisting of an impure PCM located in rear of solar glass.

To examine the alternative configurations of the PCM plates, a 2-D model for modeling of the CPV layers with an integrated cooling system as well as an integration of active and passive cooling systems for thermal control of concentrated photovoltaic (CPV) solar systems was developed by H.A. Nasef et al [12]. In addition, a phase change material (PCM) heat storage battery was coupled with a closed-loop water cooling system to improve system performance by employing Nano-fluid as the heat transfer fluid (HTF). When compared to traditional direct PCM-PV and water-cooling individual systems, the suggested method attained a 60% reduction in CPV average temperature.

Suhil et al. [13] performed a theoretical study based on mathematical formulations was performed, as well as an experimental test on a photovoltaic system cooled by PCM. The panels were made of paraffin graphite PCM with a thickness of 15mm and were coated with an aluminum sheet that was firmly attached to the panel frame. The results show that the system efficiency improves when the average temperature surpasses the PCM's melting point temperature. Large thicknesses are not possible due to a PCM's limited heat conductivity [14]. According to Fourier's Law, assuming one-dimensional conduction, the optimum temperature range for the use of PCM is shown in Eq. 1.

$$\frac{\dot{q}}{A} = -k\frac{\Delta T}{\partial x} \rightarrow \Delta T = \frac{q}{A}.\frac{L}{-k} \tag{1}$$

where k is the thermal conductivity (Wm/k), q is the heat flux density (W/m^2), L is the PCM thickness (m), and T is the temperature difference between the PCM and the solar panel's surface (K). As a result, determining the kind of PCM is difficult and crucial in ensuring the PV module's maximum performance. One answer is the fined systems, which are a simple, low-cost, and efficient choice. In certain papers, the optimizing of fin design, detachment, and construction material has been explored. Recently, the usage of PCM with nanoparticles to increase thermal characteristics has become more common. However, certain issues with sedimentation or deterioration were discovered [15].

Numerical simulation and finite element analysis are the two major methodologies for studying the performance of solar photovoltaic cells now. A three-dimensional numerical model of solar modules and TEG devices was developed by Kohan et al. [16]. The goal is to investigate the performance of a hybrid photovoltaic with a TEG power generating system with a thermoelectric generator mounted behind the solar panel. The model ignores the device's inherent complexity and treats it as a homogeneous medium, with the power output being treated as an internal energy sink.

Li et al.[17] Investigated the effects of light intensity on solar cell performance. The effect study on the power production performance of photovoltaic cells was obtained by examining its interaction with influencing elements. Results found that the open-circuit voltage, short-circuit current, and maximum output power of solar cells all rise as light intensity increases, according to the data. As a result, the higher the light intensity, the better the solar cell's power generating performance.

Solar panels operate at high temperatures and absorb up to 80% of the solar radiation. It is well known that PV cells captivate up to 80% of solar irradiation. On sunny days, PV panels can thus achieve very high temperatures, much above the surrounding temperatures, and a substantial part of this temperature can therefore be converted into heat. The surface temperature of a PV panel is controlled by applying artificial cooling such as fins, microchannels, and water spray to enhance the efficiency of the PV panel.

Keeping the solar radiation level constant, if the temperature of the panel is increased, then a marginal increase in the PV cell current occurs, but a marked abatement in cell voltage also occurs. As the temperature of the PV panel increases, the band gap breaks sharply this in turn, becomes the cause of some increase in photo-generation rate, and thus, PV panel current increases but, at the same time the reverse saturation current increases rapidly due to this rise in panel temperature due to which the conversion efficiency of PV panel from solar to electrical energy decreases [3,10].

Thermal management of electronics using phase change material (PCM) is viewed as a possible cooling method because of the attractive properties of PCM, such as high storage density and isothermal nature at a relatively constant melting temperature. It was first suggested in 1977 for avionics thermal control, and research has been conducted since then. Because of the PCM's poor conductivity, researchers have proposed a variety of improvement strategies, including extended surfaces of various designs, multiple PCMs, and PCM encapsulation [18,19].

M. Kabdrakhmanova et al. [20] addressed the issues related to climate factors affecting the performance of PCM-integrated buildings in subtropical regions, as well as whether PCM integration in buildings is economically and environmentally feasible. As a result, panel data regression analysis was used to assess the influence of climate-related parameters on the energy consumption of PCM integrated buildings in eight cities. Temperature-derived functions — heating and cooling degree days – had the biggest influence on energy demand, according to the findings. Energy demand was negatively impacted by wind speed, sun azimuth, and air pressure. Furthermore, employing the PCM-24 and

PCM-27 resulted in yearly energy savings of up to 12,635 kWh and a 19.9% reduction in energy use.

The melting efficiency of a paraffin/copper foam composite PCM heat storage unit with a rectangular encapsulation was quantitatively examined by S. Huang et al. [21] under the impact of varying inclination angles. According to the findings, although the metal foam ligaments had a considerable repressive influence on free convection, the composite PCM systems with various tilt degrees demonstrated a wide range of thermal behaviors and melting capacities. Natural convection was inhibited in the horizontal cases ($\theta = 0°$ and 180°) and tended to be greater in the tilted container systems, particularly in the vertical case. Furthermore, the results showed that by using a greater. With a smaller pore density metal foam and a higher Rayleigh number, the melting rate of the composite PCM system might be increased even further.

J.Cunha and P.Eames [22] investigated the possibility of using indirect thermal storage containers and systems in conjunction with various process heating and cooling networks. After a thorough investigation of PCMs with melting points ranging from 0°C to 250°C, the thermophysical characteristics of the materials with the greatest acceptable properties were reported. According to the data, organic molecules and salt hydrates were the most intriguing materials at temperatures below 100°C. Eutectic combinations with Urea tend to be the most potential PCMs in the range of 100°C to 1250°C, whereas eutectic mixtures with inorganic salts appear to be the most promising PCMs in the region of 130°C to 1250°C. A mixture of sodium and potassium melting at 170°C appears intriguing due to its low cost and low latent heat of fusion. Ramkiran et.al [23] in his research compared different colored filters to absorb the panel heat. The efficiency and power of the solar photovoltaic module were measured with and without filters, and their performance was compared and found out the magenta color has significant effect of efficiency than other colors used.

Earlier PCM was quantitatively examined the efficiency of the melting process for a PCM-based heat storage system in a horizontal cylinder with a copper metal foam under the influence of various factors. The impacts of varying cavities and pore densities, a nonequilibrium porous media model, various metal foam cases, and variable heater placements in the system on the liquid fraction and temperature were explored and compared. The results demonstrate that the copper foam-PCM unit outperforms its PCM in terms of melting time reduction by over 85 percent. The melting time is reduced by 70.5 percent and 4.7 percent, respectively, by moving the controlled temperature heater from the bottom to the side and top surface [24,25]. Ramkiran et.al [26] in his comparative study discussed the identification of suitable low-cost passive cooling techniques to reduce the operating temperature of a photovoltaic module. Passive cooling techniques (coir cooling) produced the best possible results and these techniques be used for large scale solar plants in the residential and agricultural sector.

Govindasamy and Kumar [27] conducted a study proposing the use of a paraffin jelly and expanded perlite phase change material panel. Their research demonstrated that this combination effectively reduces the maximum surface temperature of the panel while enhancing power output and efficiency when compared to other panels. Dwivedi et.al [28,29] in his research compared different cooling techniques and reported that PCM cooling is the most capable technique owing to its higher energy density per unit volume, but both air- and water-cooling methods have been used to a large extent since they can provide additional thermal energy that can be used for different purposes. Furthermore, he suggested that the rule of thumb is that the PV module’s performance can be enhanced by lowering its front surface temperature. PVT system has the highest overall efficiency as compared to other systems. Kirpichnikova et.al [30] suggested in his comparative research study that the results showed that a temperature reduction of 3.54°C is obtained for solar modules with thermal protection film compared to the one without holographic film.

The current paper focuses on the substantial benefits of improving energy efficiency and sustaining thermal comfort by utilizing the modified paraffin wax PCM to lower the panel surface temperature. This study demonstrates a successful design of a temperature-controlled PV module using phase change materials for the hot climate, especially for south Asian regions. The surface temperature of solar panels has been reduced using computational analysis and experimental study on paraffin wax. In this work, Paraffin wax was used, which reduced the panel surface temperature by 5-7^{o}C, generating a 29% increase of the modified PV panel relative efficiency compared to its standard value. To the best of author(s) knowledge, there is no such paper published those covers sustaining thermal comforts using modified PCM paraffin wax under different climatic conditions for the northwestern region of Pakistan and South Asian countries.

Table 1

Selected studies on cooling of PV modules

Authors	Highlights	Technology
Kasaeian A., Khanjari Y., Golzari S., Mahian O and Wongwises S [31]	Thermal efficiency ranges from 15% to 31% while electrical efficiency ranges from 12% to 12.4%.	Hybrid solar Photovoltaic/Thermal system cooled by forced air circulation
Hachem F., Abdulhay B., Ramadan M., El Hage H., El Rab M.G. and Khaled M [32]	Pure and Combined PCM increased electrical efficiency by an average of 5.8%.	PCM based
Abrahamyan Y.A., Serago V.I., Aroutiounian V.M., Stafeev V.I., Karamian G.G., Martoyan G.A. and Mouradyan A.A [33]	Efficiency increased by 40–69% of reference value	Water immersion cooling technology
Ntsaluba S., Zhu B. and Xia X [34]	7.82% increased extracted energy, where thermal efficiency decreased between 5.54% and 7.34% using connecting pipes.	Hybrid PV/T
This work	Efficiency increased by 29% relative to the standard PV panel	PCM based

2. Design, Construction of Proposed PCM

Organic PCM offers greater benefits than inorganic PCM because it is chemically stable, noncorrosive, has a smaller volume change during the phase transition, and is devoid of nucleation agents and undercooling phenomena. The main disadvantage of organic PCM is its low thermal conductivity, which limits heat storage and releases rates during phase transitions. Integration of nanomaterials such as carbon nanotubes and exfoliated graphite nanoplatelets in the compound is one possible solution to this problem, albeit this may lower total latent heat and lead to excessive supercooling. Organic PCMs have a lower density than eutectic PCMs, which results in a compound with a single melting temperature. However, because of their newness, data on their thermal and physical qualities are currently scarce. The primary goal of hybrid solar technology is to utilize the solar energy captured by the PV panel but not converted into electricity. A technique for heat storage in a solar panel using paraffinic organic type PCMs is suggested in this novel design. In this model 100-watt, EVA-encapsulated PV panels were tested having the latitude angle: 33.7ºN, 72.8ºE.

Table 2 lists the thermal characteristics of organic materials identified in the literature, as well as the PCM specifications that may match the research's needs.

Table 2

Comparison of Organic PCM [35,36]

Material	Thermal cond. $(\frac{W}{m.K})$	Specific heat $(\frac{kJ}{kg.K})$	Density $(\frac{kg}{m3})$	Temp. °C		Melting heat $(\frac{kJ}{kg})$
				Ts	TL	
Paraffin wax	0.212	2.8	880	56	58	173.6
RT41	0.2	2	802	37.5	42.9	141.7
P116	0.21	2.1	830	50	50	190
N-eicosane	0.1505	17.3 at T = 38 °C	785	36.5		237.4
RT47	0.2	2.0	880 for solid and 770 for liquid		48	160

The different types of RT PCM have been analyzed initially based on their melting point and heat storage capacity as shown in Fig. 1. In this research, German Rubitherm RT47 PCM was used for the modification of the PV panels, as shown in table 3. As in a phase change process, the temperature is nearly constant, thus an almost constant PV surface temperature could be maintained for the required duration.

Table 3

Rubitherm RT47 PCM Properties [37]

Commercial Name	RT47
PCM Category	Organic
Melting Point (ºC)	46
Latent Heat (kJ/kg)	160
Density (kg/m^3)	880 for solid and 770 for liquid
Thermal Conductivity (W/m-k)	0.2
Specific Heat Capacity (kJ/kg-)	2.0
Quantity (kg)	0.5

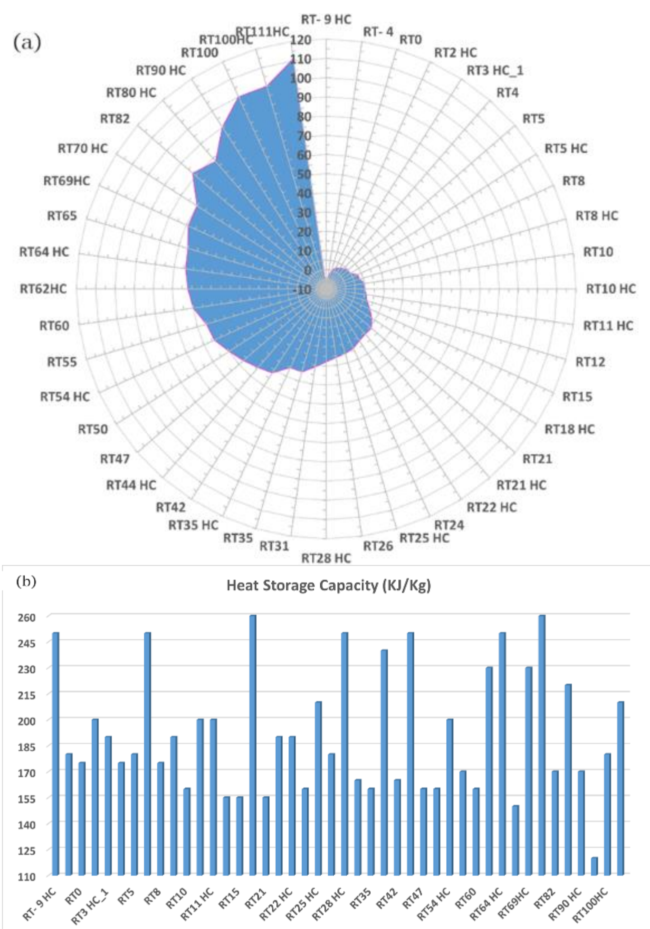

Fig. 1. RT PCM Comparison (a) Melting Point, (b) Heat Storage Capacity

3. Experimental Setup

100-watt EVA-encapsulated PV panels were tested at 33.7◦N and 72.8◦E latitude angle at summer season northern Punjab province of Pakistan. Table 4 shows the electrical properties of the PV panels considered for the research. Modified PV panels are of the same specifications as the housing on the back provided for the Phase change material. The phase change material used is Paraffin Wax. Two-thirds of the housing is filled with paraffin wax. Additionally, copper pipes are provided in PCM housing to provide a path for air cooling of PCM. The Capital cost for Modified panel is 7500 which is almost 1500 Pkr more than the standard solar panel.

Table 4

Electrical Properties of PV Panel

Maximum Power	100W
Open Circuit Voltage	21.25V
Max Power Voltage	1000VDC
Power Tolerance	3%
Short Circuit Current	6.03A
Max Power Current	5.71A
Max Sense fuse rating	10A
Dimensions	1200x540x35mm
Weight	8.3 Kg

Fig. 2 (a) and (b) shows the experimental setup and modified PV panels with adjustable inclination angles and two-thirds filled with Paraffin Wax PCM. To provide active cooling for the PCM during the day, a 30W blower is mounted on the frame.

To measure the operating temperature of the PV cells, four standard calibrated K-type thermocouples and a solar power meter (TM-207) were installed. K-type thermocouples were used because of their reliability, accuracy, and their extensive temperature range.

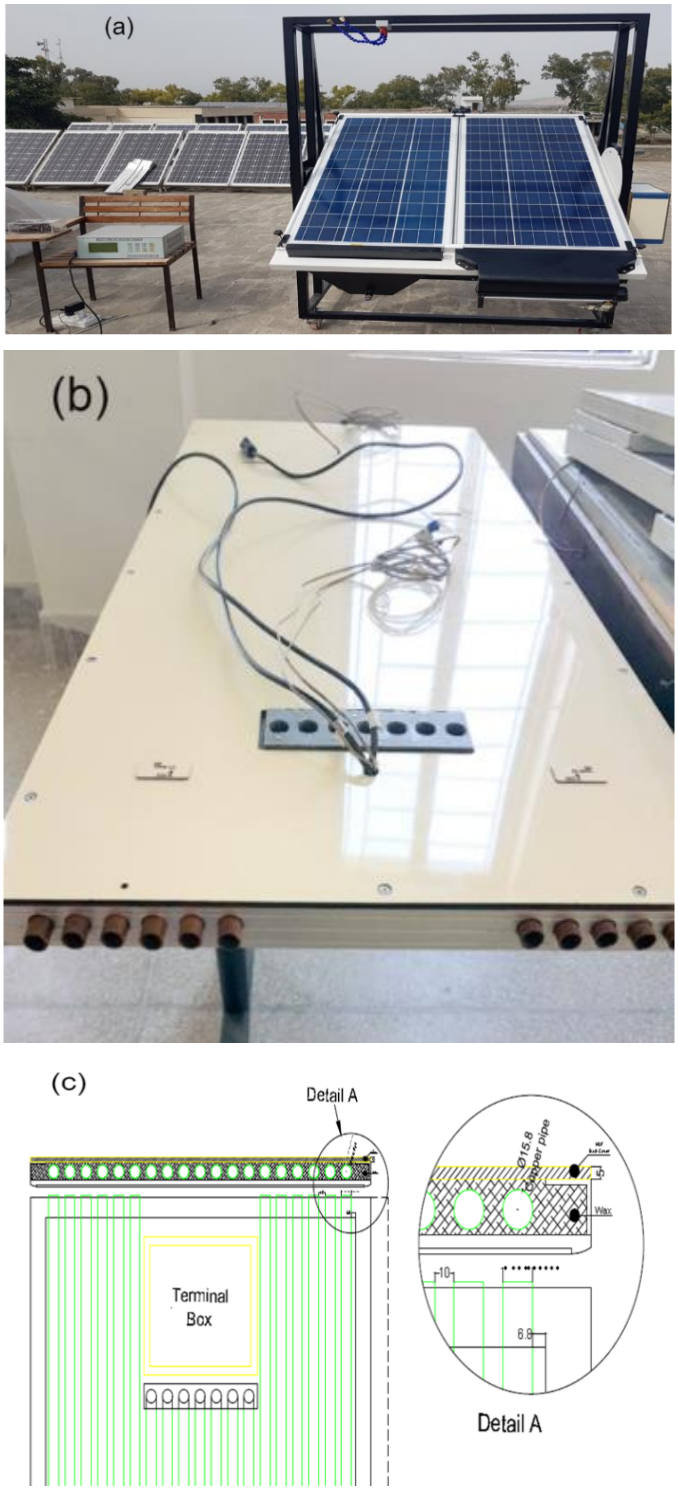

Fig. 2. (a) Experimental Setup, (b) shows the experimental setup and modified PV panels, and (c) Schematic diagram of the modified PV panel

Temperature and humidity were continuously monitored with the TM-184 precision meter, with transmitters and signal conditioners. Current-voltage measurements of a PV module are key methods for analyzing the performance of a crystalline solar module. Therefore, a solar module analyzer was used for tracing the IV curve of the PV module by connecting the analyzer cable with the PV module manually during the day, after each hour. The solar module analyzer of type PROVA 210 has a high resolution (1 mV and 1 mA) and displays a range of DC of 0-12 A and a DC voltage of 0-60 V. This module provides IV curves, Power curves, open-circuit voltage, short current, and maximum voltage. The PROVA 210 can also be used for establishing the optimum solar panel inclination, helping with the maintenance of the solar panel, and the identification of the solar power system requirement. Table 5 displays the list of components used for the experimentation and their specification.

The output power of the PV module was measured with the sola module analyzer (PROVA 210). The obtained result showed that the output power is different at different tilt angles due to the increase or decrease of solar irradiance. In addition, the output power varies linearly with the increasing irradiance. The theoretical comparison between the different tilt angles is based on the well-established solar geometry equations and the minimization of the solar incidence angle. It is worth noting that the PV module received higher irradiance at a lower incidence angle and therefore more power was produced at a lower incidence angle.

4. Results and Discussion

A solar panel experiment was conducted on the roof of the Mechanical Engineering building at UET Taxila, nestled in the scenic surroundings of Taxila, Pakistan which is 32Kms from Islamabad (Capital of Pakistan). Fig. 3 shows the hourly average measured values of the wind velocity and ambient temperature for the considered duration.

Table 5

Setup components and Specifications

Components	Specifications
Thermocouple	K-type, 0 to 200°C extension wire, –270 to 1260°C grade wire, ± 2.2°C or 75% standard, ± 1.1°C or 0.4% error
Pyranometer	3½ digits, 2000 readings, 2000 W/m2, 634BTU / (ft2xh) range, 0.1 W/m2, 0.1 BTU/ (ft2xh) resolution, Accuracy: Typically, within +/- 10W/m2 [+/-3 BTU/ (ft2xh)] or +/- 5% whichever is greater in sunlight. Temperature included error +/- 0.38 W/m2 / °C [+/-0.12 BTU/ (ft2xh)] / °C] deviation from 25°C, Cosine corrected angular accuracy, < +/-3% per year drift, 0.25s sampling time, 5C~40°C blown 80% RH operating temperature and humidity, 9V battery power supply.
Temperature Humidity meter (TM-184)	Temperature: -20.0°C~60.0°C/-4.0°F~140.0°F, Humidity: 1%~99%, Operating temperature and humidity: -20°C~+60°C, Humidity accuracy: ±1.0%RH (15%RH~90%RH), ±2.5%RH (90%RH), Temperature accuracy: ±0.5°C/±1.0°F (0°C~40.0°C /32°F~104°F); other ±2.0°C /3.6°F, 1s sampling time, 30000 data sets capacity, 0.1% RH, 0.1°C, 0.1°F resolution, 9V battery NEDA 1604 IEC 6F22 or JIS 006P (only data logger use), or AC to DC Adapter. (9V/300 mA).
Solar Module Analyzer (PROVA-210)	Resolution:1 mV and 1 mA, 60 V, 12A, Prova-210 PV Analyzer, Data logging memory size: 99 records, Kelvin clips 12A max

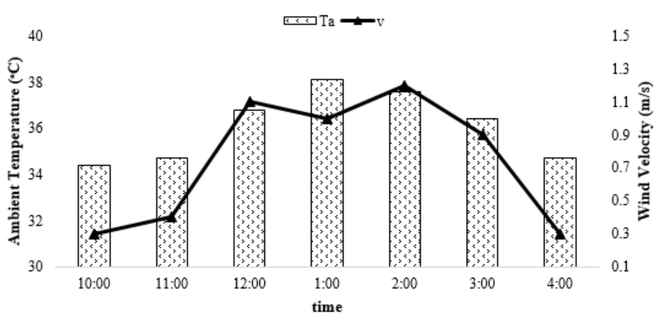

Fig. 1. Variation of ambient temperature and wind velocity throughout the experimentation

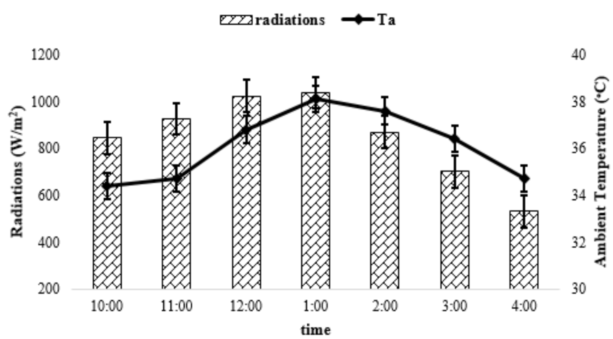

Fig. 2. Variation of average values of irradiance and ambient temperature

It was observed that the ambient temperature was maximum at 1:00 pm and was about 38.1°C. Whereas, the wind velocity was maximum at 2:00 pm. Both ambient temperature and wind velocities were minimum at 10:00 am and 4:00 pm. It was also observed that the percentage increase in ambient temperature and wind velocity from minimum to maximum values was 3.6% and 1%, respectively.

Fig. 4 shows the average global irradiance measured on a PV panel surface. The solar radiation value was maximum at 1:00 pm and was about 1100 W/m^2. At 4:00 pm, the solar radiation value was 500 W/m^2, showing that as the day progresses, the sun angle changes and the irradiance on the PV panel surface lowers. At the time peak value of solar radiation and ambient temperature, the fluctuation was minimum, showing a constant behavior. However, the fluctuation was maximum at 10:00 am and 4:00 pm.

4.1 Variation of the Surface Temperature of Standard and Modified PV Panels

PV panels are generally made of silicon. Several steps including crystal growing, wafering, solar cell production, and solar panel assembly are required to build them. When photons of solar light strike a PV panel, they excite the energy carrier's presence in it, and electron-hole pairs are generated on the panel surface. For silicon, the bandgap was 1.7 eV. The solar spectrum contains radiation of different intensities and frequencies, therefore only the radiation which has an energy of 1.7ev are absorbed by the PV panel, and the remaining radiations produce thermalization effects in the PV panel. Due to the thermalization on the panel surface, the surplus of solar radiation heats the PV panel, making its temperature rise. The average solar panel operating temperature lies between 60°C and 65°C, which was very high. Because of this temperature rise, the efficiency of the PV panel decreases.

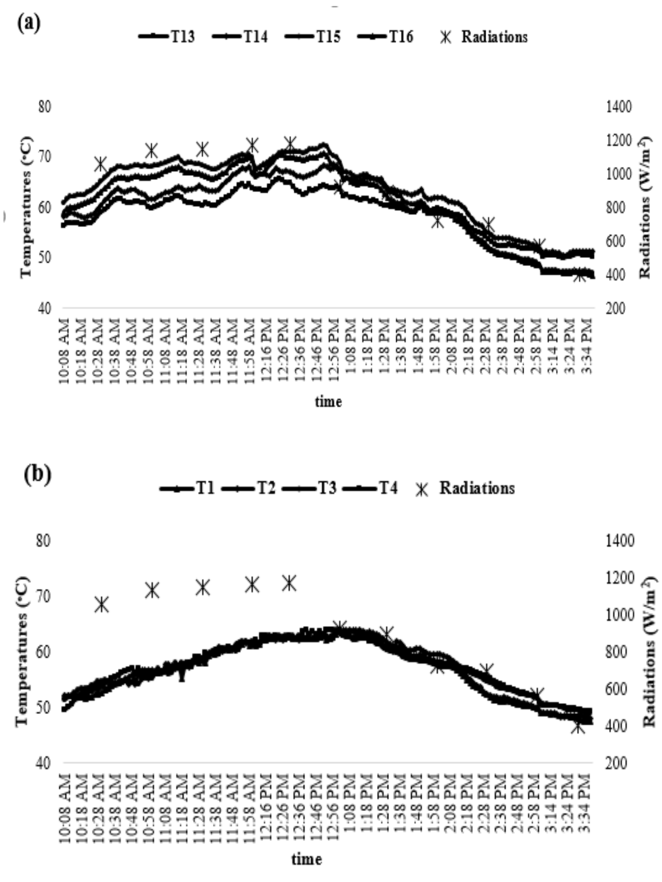

Fig. 3. PV panel surface temperature variations for different radiations (a) Standard panel (b) Modified panel

Fig. 5 shows the daily variations of the surface temperature of both standard and modified PV panels. For the temperature distribution of the standard PV panel in Fig. 5(a), it can be observed that at 1:00 pm, when the maximum solar radiations strike the PV panel, the temperature T13 was the highest, around 71°C, while the other temperatures T14, T15, and T16 were between 65°C and 67°C. This can be explained by the fact that the thermocouple of this temperature T13 was placed at the center of the panel and there was no shading at this location. For the modified PV panel shown in Fig. 5(b), the maximum surface temperature was measured around 63°C at the peak solar radiations time. The surface temperature appears to be between 5°C and 7°C lower on the modified PV panel than on the standard PV panel. This shows clearly that the PCM had successfully absorbed heat from the PV panel.

4.2 Variation of Output Power

Fig. 6 shows the output power variation of both the standard and modified PV panels for different solar radiations.

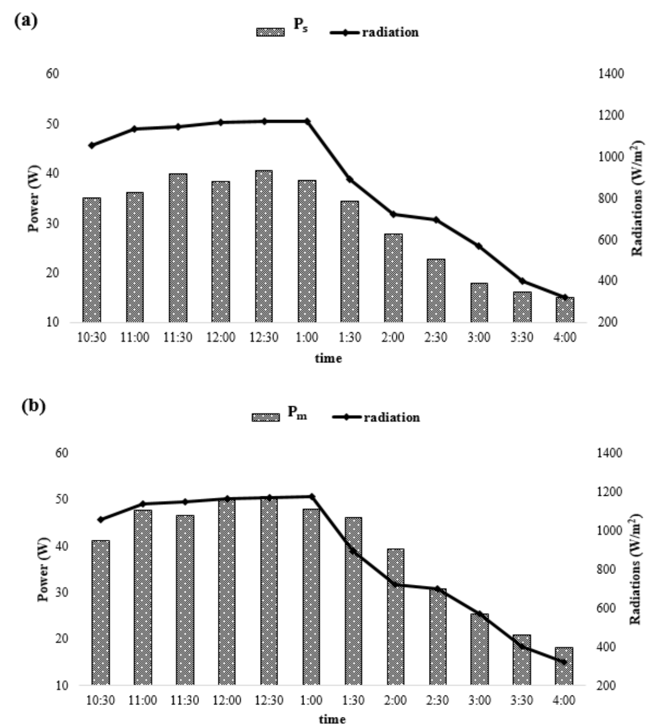

Fig. 4. Variation of the output power of PV panels at different radiations (a) Standard panel (b) Modified panel

It can be observed that when solar radiation is at its maximum (at 1:00 pm) the power of the standard PV panel is slightly lower than at 12:30 pm. At 1:00 pm, radiation is high but thermalization effects are more dominating while at 12:30 pm, radiations are also high but thermalization effects are lower than that at 1:00 pm. At 12:30 pm, the output power of the standard and modified PV panels are 40 Watt and 50 Watts, respectively. This shows again that the PCM works well and reduces the surface temperature of the modified PV panel and hence enhances the output power.

4.3 Power Comparison and Percentage Increase In Power

Fig. 7 shows the output power variation of both standard and modified PV panels and the percentage increase in power from the modified panel for different solar radiations. At 10:30 am the output power of the standard and modified panels was 35W and 41W, respectively, and the percentage increase of power was 6%. Similarly, at 12:00 pm, 1:30 pm, and 2:00 pm, the percentage increase in power was maximum. This shows that the PCM works efficiently from 11:00 pm to 2:00 pm. As the day progresses, the percentage increase of power decreases due to the decreasing solar radiation value and due to the PCM starting to cool down.

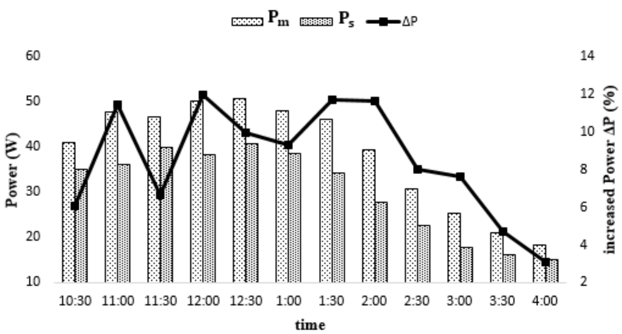

Fig. 5. Power comparison of both solar panels and percentage increase in output power

4.4 Variation of Efficiency

A PV panel efficiency is usually very low due to thermalization effects and is dependent on many factors such as the ambient temperature, wind velocity, relative humidity, and incoming solar radiation. The panel will show a higher efficiency when the combination of these factors is optimum. Fig. 8 shows the variation of efficiency for both standard and modified PV panels at different solar radiations throughout the day. It can be seen that at 10:30 am, the efficiency of the standard PV panel is around 6% while for the modified PV panel, it is almost 7%, showing a 16.7 % efficiency increase. Similarly, at 1:30 pm the efficiencies of both standard and modified PV panels are about 6.2% and 9.1%, respectively, showing an efficiency increase of around 46.8%. It is thus noted that the average efficiency of the standard PV panel is almost 6.5% and 8.5% for the standard and modified panels, respectively, generating a 29% increase the efficiency. Altogether, this clearly shows that the PCM works efficiently.

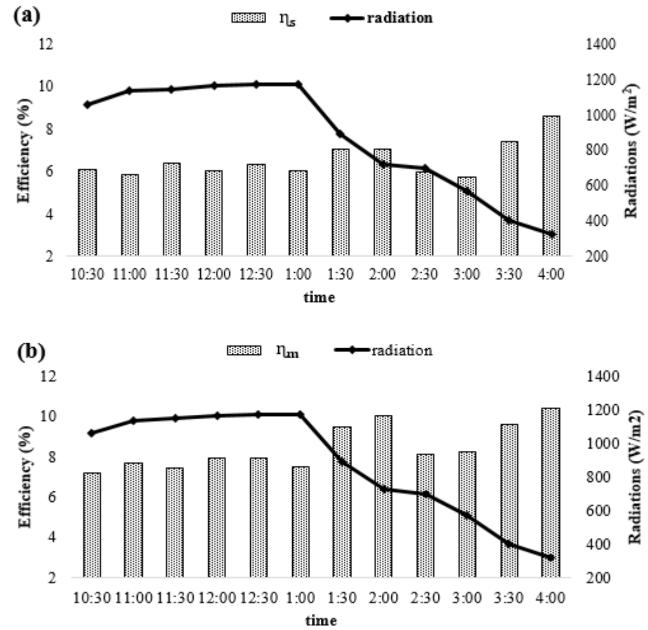

Fig. 6. Variation of Efficiency of the solar panels for different solar radiations (a) Standard panel (b) Modified panel

4.5 Efficiency Comparison of Both Standard and Modified Solar Panels

Fig. 9 shows the efficiencies of both standard and modified solar panels throughout the day. The efficiency of the modified solar panel is always higher than that of the standard solar. It can be also noticed that at 10:00 am when solar radiations are not too high, the efficiency value of the standard and modified solar panels are 6% and 7% respectively. At 2:00 pm, the efficiency of modified PV panels has shown a remarkable 43% of improvement due to the melting of the PCM.

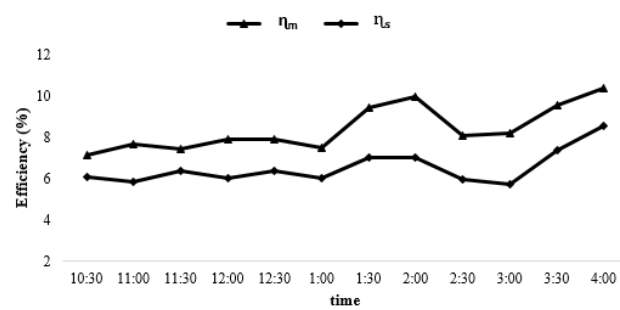

Fig. 7. Comparison of efficiencies of standard and modified PV panels

4.6 Exceptional Hot Day Data

During the experiment, one exceptionally hot day occurred on 20th April when the ambient temperature reached 47°C. During that day, the PCM used in this research work did not perform as expected. The system worked well until 2:00 pm and kept the panel cool. However, due to the high rise of the ambient temperature and the panel surface temperature around 70°C, the PCM temperature itself rose so much that it could not absorb more heat from the panel and worked as an insulation layer. Hence, the efficiency and power of the modified PV panel were this time best for the standard PV panel. This shows that the use of RT47 PCM also has temperature limitations. Fig. 10 shows the variation of average surface temperature for both PV panels during this exceptionally hot day. Between 10:00 am and 2:00 pm, the average temperature of the modified PV panel appeared lower than that of the standard PV panel. However, after 2:00 pm the temperature of the PCM (paraffin wax) did not cool down rapidly, and reverse effects occurred. This appears clearly as a drawback of using paraffin wax.

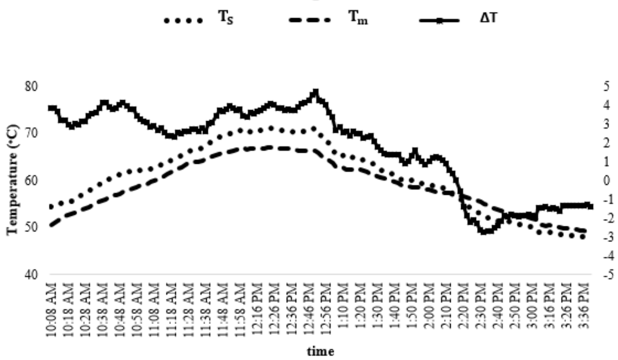

Fig. 8. Variation of the temperature of standard and modified PV panels during an extremely hot day

Fig. 11 shows the power of the standard and modified PV panels at 47ºC. At 10:30 am, the power difference between the standard and the modified PV panels was small i.e., 3W. Thereafter, the difference increased, and at noon the difference was reported around 18W, as the PCM started to absorb heat. The temperature raised highly until 1:00 pm, the power curve shows a decreasing trend afternoon and at 2:00 pm, the reverse effects started. The power of the modified PV panel became lower than that of the standard PV panel; this phenomenon continued until 4:00 pm. As explained earlier, the too high ambient temperature made the PCM temperature raise too high, which made it inefficient.

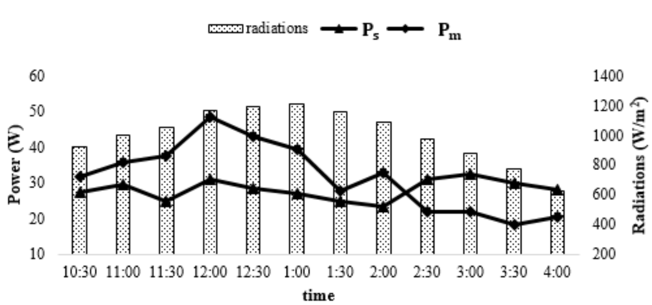

Fig. 9. Variation in Power of standard and modified PV panels during an extremely hot day

Fig. 12 shows the efficiency of both panels during the extremely hot day when the ambient temperature was raised to 47°C. As expected, the efficiency of the modified PV panel increased from 10:30 am to 2:00 pm, and then decreased until the end of the day, noting that efficiency was slightly regained a 2 pm and 4 pm. In comparison, the efficiency of the standard PV panel decreased until 2:00 pm but increased highly thereafter. At noon the efficiencies of the modified and standard PV panels were about 7.8% and 4.8% respectively, while at 3:00 pm the efficiencies were about 4.1% and 6.2% respectively.

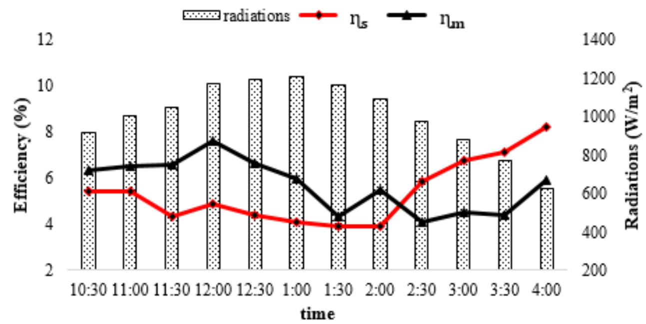

Fig. 10. Variation of Efficiency of standard and modified PV panels during an extremely hot day

4.7 Active Cooling

As the PCM did not work efficiently under extremely hot conditions after some time during the day, a 30W blower was placed at the bottom of the PV panel when the PCM started failing, passing air through the copper tubes and thus reducing the PCM temperature. Fig. 13 shows that under such conditions, the PCM worked as intended without a blower until 2:15 pm, and then, active cooling from the blower was generated to maintain the PCM efficiency. Results show that by using this approach, the average temperature of the modified PV panel always remained lower than that of the standard PV panel.

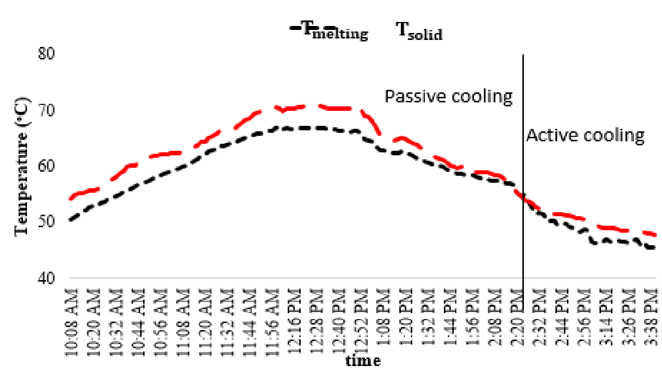

Fig. 11. Variation in temperature after active cooling in standard and modified PV panels

5. Conclusion

As solar radiation strikes a PV panel surface, its surface temperature rises rapidly, and the output power and efficiency of the PV panel decrease drastically. To manage this issue, different techniques can be used to reduce the PV panels' surface. PCM, which can absorb heat and act as a heat sink in any heating system, is being used in many applications to thermally manage heating issues. Paraffin wax has been used as PCM in this study as the surface temperature of the PV panel lies between 25 and 65°C, and the melting temperature of paraffin wax is around 46°C. When the surface temperature of the PV panel is raised, the PCM reduces the surface temperature by absorbing heat and enhancing the output power and efficiency of the panel. The surface temperature of the modified PV panel was shown to be reduced by 5 to 7°C compared to the surface temperature of a standard PV panel, and the output power of the modified PV panel increased by about 7 to 8W. The efficiency of the modified PV panel increased by about 29% when compared to the standard PV panel efficiency value. Performance of the solar panels in tropical conditions can be increased by placing them at locations where they receive maximum sunlight in the day and using some storage devices like batteries etc. to store energy. This study can further be enhanced by replacing the paraffin wax with some more suitable phase change material having high melting point or by increasing the number of copper tubes inserted in phase change material so that more heat loss occurs by natural convection.

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