Acta Scientific COMPUTER SCIENCES

Volume 7 Issue 2 May 2025

Research Article

Optimization of Energy Efficiency of a Solar Powered PV Cooling System with PCM Storage Tank

Adebayo Adeniyi D[1]* and Emu Chuks[2]

[1]*Department of Electrical and Electronic Engineering, Federal University Otuoke, Nigeria*

[2]*Department of Electrical and Electronic Engineering, Niger Delta University, Nigeria*

***Corresponding Author:** Adebayo Adeniyi D, Department of Electrical and Electronic Engineering, Federal University Otuoke, Nigeria.

Received: February 06, 2025

Published: April 25, 2025

Abstract

Phase Change Materials (PCMs) have gained significant attention for their potential in various applications, particularly in storing solar thermal energy as latent heat. This capability of PCMs addresses the intermittent nature of solar energy, making them a crucial component in solar thermal systems. These systems are broadly classified into active and passive categories. In active solar thermal systems, solar collectors convert solar energy into thermal energy, which is then stored in insulated tanks filled with PCMs. Additionally, PCMs can be integrated beneath photovoltaic panels to regulate their temperature and store thermal energy for subsequent cooling and heating applications. The thermal efficiency of PCM-insulated tanks is comparable to that of solar collectors, enhancing the overall system efficiency. Passive solar systems, on the other hand, utilize building components such as windows, walls, and floors to capture solar energy. PCMs can be embedded in walls for passive heating, thermal insulation, and cooling, exploiting their low thermal conductivity and high heat storage capacity.

Keywords: Phase Change Materials (PCMs); Photovoltaic (PV)

Introduction

The rapid depletion of fossil fuels and the resulting environmental impacts, such as global warming, air pollution, and harmful greenhouse gas emissions, have made it clear that we must transition to cleaner, more sustainable energy sources. Among the various renewable energy options, solar power stands out as one of the most promising. The sun provides an almost limitless supply of energy, and harnessing this power through photovoltaic (PV) systems allows us to generate electricity without contributing to the environmental damage caused by traditional fossil fuels. At the core of a solar PV system are photovoltaic cells, which convert sunlight directly into electricity. These cells, typically made of semiconductor materials like silicon, are vital components of solar panels. However, one major challenge with PV cells is that they do not convert all the solar radiation they absorb into electricity; in fact, a large portion of that energy is turned into heat, which raises the temperature of the cells. Unfortunately, as the temperature of PV cells rises, their efficiency in converting sunlight into electricity decreases. This presents a significant obstacle to optimizing solar power systems [3]. Reducing the temperature of PV cells has become a critical focus in solar energy research and development. Various cooling techniques, including both active and passive methods, have been explored to maintain optimal PV cell temperatures and improve overall system efficiency. One of the most innovative approaches to this issue is the use of Phase Change Materials (PCMs). PCMs absorb excess heat when the PV cells become too warm, storing it and preventing the temperature from rising too high. This not only increases the efficiency of the PV system but also helps to extend the lifespan of the solar panels by reducing thermal stress. In this project, we explore the potential of integrating PCM-based cooling systems with solar PV panels. We look at how this method can optimize energy efficiency and reduce thermal losses, leading to improved power output and better sustainability. By addressing the issue of heat in solar panels, we take an important step toward making solar power even more viable as a clean energy source for the future. Solar energy, in many ways, represents a path forward—a path toward a cleaner, more sustainable world. The combination of scientific ingenuity and practical applications like PCM cooling systems can help unlock the full potential of solar power, making it more efficient, accessible, and reliable for generations to come [2].

Materials

- Glass cover
- PV Cells
- EVA Sheets
- Tedlar
- PCM
- PCM plates/tubes

Glass cover

The transparent shield keeps the photovoltaic cells safe from outdoor factors such as dirt, precipitation, and impact, while enabling sunlight to filter through efficiently. It is constructed from strong, light-transmitting glass.

PV cells

Photovoltaic cells serve as the essential elements that transform sunlight into electrical energy. Constructed from semiconductor substances, they play a vital role in creating electrical power and generating heat that can be controlled and retained with the help of phase change materials.

EVA sheets (EVA-PV-EVA)

These layers consist of Ethylene Vinyl Acetate that envelop the photovoltaic cells. They offer structural reinforcement and heat stability, which helps maintain the durability and performance of the photovoltaic module.

Tedlar

This substance serves as the rear layer of photovoltaic modules. It shields against environmental deterioration, humidity, and ultraviolet rays, improving the longevity of the photovoltaic cells.

PCM

Paraffin wax serves as the phase change material. It takes in and retains surplus heat generated by the photovoltaic cells, helping to sustain ideal working temperatures and enhance efficiency by emitting the accumulated heat when necessary.

Plates of PCM tank

- **Copper Tube Plate:** Features copper tubes that are packed with PCM. The excellent thermal conductivity of copper guarantees optimal heat transfer.
- **Insulated Plate:** Constructed using insulating substances such as glass wool, this plate reduces heat loss and keeps thermal energy stored in the PCM tank for future use.

Together, these materials increase the effectiveness and longevity of the PV solar panel system by improving thermal management thanks to the incorporation of PCM storage.

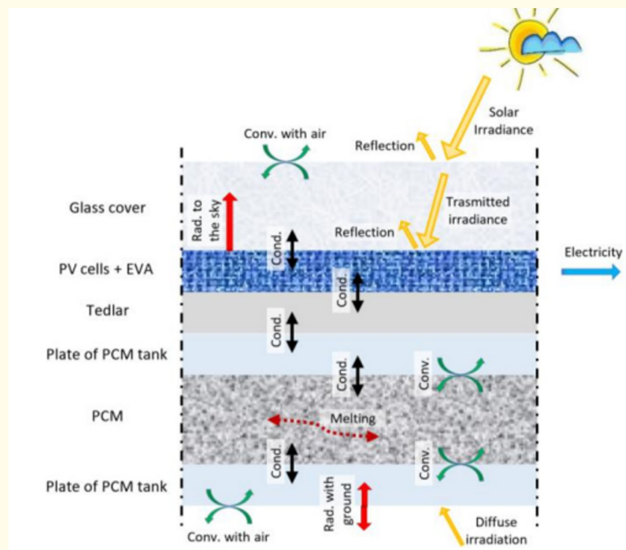

Figure 1

Types of PCM

The RT classification of phase change materials includes organic compounds engineered to absorb and release substantial amounts of heat during their transition from solid to liquid forms. These materials keep their temperature nearly stable while melting and freezing, which makes them ideal for a wide range of uses in different temperature settings (Solanki., *et al*. 2007) [1]. Thanks to their high purity and tailored compositions, these materials possess considerable latent heat capacity within small temperature ranges. Furthermore, they are chemically stable and can last indefinitely. The RT phase change materials offered by Rubitherm are designed for temperatures between roughly -10°C and 90°C (14°F to 194°F). For specific temperature needs outside of this spectrum, it is possible to create custom phase change materials. High-capacity RT options, like Rubitherm RT 5 HC, are available for particular temperatures. These materials exhibit a latent heat capacity that is 25-30% greater than that of regular RT materials and feature a more restricted melting temperature range, making them well-suited for applications with space limitations (Tonui and Tripanagnostopoulous, 2007) [2].

Product	Melting area	Heat storage capacity	
RT - 9 HC	-9°C	250 kJ/kg	PDF
RT - 4	-4°C	180 kJ/kg	PDF
RT 0	0°C	175 kJ/kg	PDF
RT 2 HC	2°C	200 kJ/kg	PDF
RT 3 HC_1	3°C	190 kJ/kg	PDF
RT 4	4°C	175 kJ/kg	PDF
RT 5	5°C	180 kJ/kg	PDF
RT 5 HC	5°C	250 kJ/kg	PDF
RT 8	8°C	175 kJ/kg	PDF
RT 8 HC	8°C	190 kJ/kg	PDF
RT 10	10°C	165 kJ/kg	PDF
RT 10 HC	10°C	200 kJ/kg	PDF
RT 11 HC	11°C	200 kJ/kg	PDF
RT 12	12°C	160 kJ/kg	PDF
RT 15	15°C	150 kJ/kg	PDF
RT18	18°C	150 kJ/kg	PDF
RT 18 HC	18°C	260 kJ/kg	PDF
RT 21	21°C	165 kJ/kg	PDF
RT 21 HC	21°C	190 kJ/kg	PDF
RT 22 HC	22°C	190 kJ/kg	PDF
RT 24 HC	24°C	200 kJ/kg	PDF
RT25	25°C	180 kJ/kg	PDF
RT 25 HC	25°C	230 kJ/kg	PDF
RT 28 HC	28°C	250 kJ/kg	PDF
RT 31	31°C	165 kJ/kg	PDF
RT 35	35°C	160 kJ/kg	PDF
RT 35 HC**	35°C	240 kJ/kg	PDF
RT38	38°C	170 kJ/kg	PDF
RT 42	42°C	165 kJ/kg	PDF
RT 44 HC	44°C	250 kJ/kg	PDF
RT 47	47°C	160 kJ/kg	PDF
RT 50	50°C	160 kJ/kg	PDF
RT 54 HC	54°C	200 kJ/kg	PDF
RT 55	55°C	170 kJ/kg	PDF
RT 60	60°C	160 kJ/kg	PDF
RT62HC	62°C	230 kJ/kg	PDF
RT 64 HC	64°C	250 kJ/kg	PDF
RT 65	65°C	150 kJ/kg	PDF
RT69HC	69°C	230 kJ/kg	PDF
RT 70 HC	70°C	260 kJ/kg	PDF
RT 82	82°C	170 kJ/kg	PDF
RT 80 HC	78°C	220 kJ/kg	PDF
RT 90 HC	90°C	170 kJ/kg	PDF
RT100	~100°C	120 kJ/kg	PDF
Rt100hc	100°C	180 Kj/Kg	Pdf

Table 1: Types of rubetherm PCMs.

For the simulation, two phase change materials, Rubitherm RT21 (melting range of 21°C to 23°C) and RT28 (melting range of 28°C to 31°C), are utilized. The mathematical modeling and simulations assess the thermal and electrical characteristics of photovoltaic panels combined with RT21 and RT28 under different weather conditions. The results indicate that the addition of PCM lowers the PV panels' surface temperature, leading to a 6% improvement in efficiency and a 16% increase in electrical output. In particular, with a PCM that melts at 21°C, the peak cell temperature during summer drops from 65°C to 38°C. Comparable temperature declines are noted with PCM RT28, showing that the appropriate choice of PCM can substantially reduce panel temperatures, thereby improving the overall performance of the photovoltaic system.

Methodology

The analyzed PV-PCM system includes the photovoltaic module, which has a phase change material layer inserted between two sheets of aluminum. The thermophysical characteristics of the elements forming the PV module, along with the specifications of the aluminum enclosure that holds the PCM, are outlined in the figure provided below.

	C kJ/kg·K	k W/mK	density kg/m^3	Thickness mm
Glass	0.500	1.8	3,000	4.0
EVA	2.090	0.35	960	0.5
Silicon-cell	0.677	148	2,330	0.3
Tedlar	1.250	0.2	1,200	0.1
Aluminium	0.903	211	2,675	4.0

Figure 2: Thermophysical properties of the PV-module.

A thickness of six centimeters for the phase change material (PCM) was selected, as this is recommended for environments experiencing intense solar exposure in the dry season, elevated temperatures, and significant rainfall, typical of the Niger Delta. Two setups are examined: the first utilizes PCM Rubitherm RT-21 (PV-PCMRT21) and the second utilizes PCM Rubitherm RT-28 (PV-PCMRT28). Both types of PCM are capable of absorbing large amounts of energy during their melting and solidifying phases and exhibit excellent durability.

For the numerical simulations, a PV module oriented towards the south with a 30-degree tilt was utilized, based on climate data from the Niger Delta (4° 49' 30" N - 6° 59' 22" E).

Results

Comparative analysis of energy efficiency between standard PV and PV-PCM units

This section evaluates the energy efficiency of a standard photovoltaic (PV) system alongside two types of PV-PCM units: PV-RT21 and PV-RT28.

Temperature analysis during the dry season peak

The illustration below presents the temperature readings of photovoltaic cells for both PV-PCM units and the traditional PV module throughout the dry season. The two PV-PCM units demonstrate the ability to maintain lower temperatures in the PV cells when compared to the standard PV module. Notably, the PV-RT28 consistently records lower cell temperatures during the day when compared to the conventional module, with the largest temperature differential reaching 20°C at noon. Between 6:00 AM and approximately 10:00 AM, the PV-RT21 exhibits the coolest cell temperatures. However, as the phase change material (PCM) completely melts, there is a sudden increase in temperature, although the peak cell temperature remains around 8.0°C less than that of the conventional PV module.

It is important to highlight that the cooling effectiveness of the PV cells in the PV-PCM units diminishes later in the afternoon. During this period, the PV-PCM units show higher cell temperatures than the standard PV module.

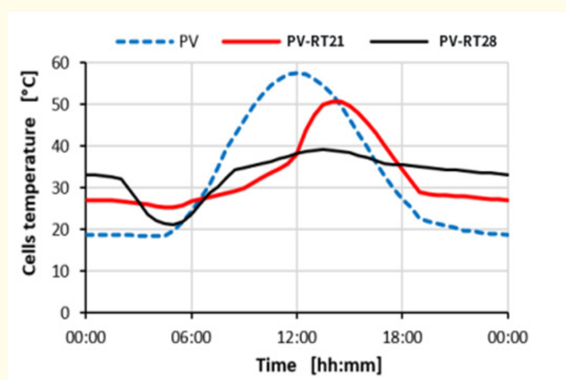

Figure 3: PV cell temperatures - Peak dry season.

Liquefaction rates of PCMS

Figure below illustrates the liquefaction rates of the two PCMs at 4:30 AM and 12:00 PM.

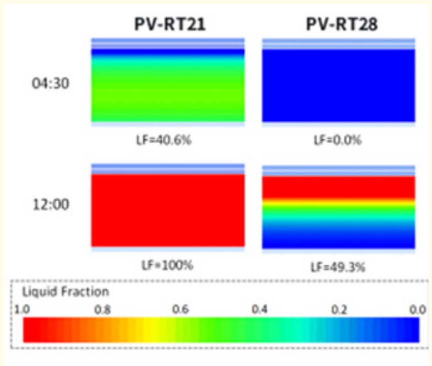

Figure 4: Liquid Fraction at Peak dry season.

At midday, the PV-RT21 has completely transformed into a liquid state. On the other hand, the PV-RT28, which has a higher melting point ranging from 27 to 29 degrees Celsius, contains a liquid ratio of 49.3%. Consequently, by 4:30 PM, the RT28 can accumulate heat, achieving a liquid ratio of 93.8%.

- **PV-RT21 and PV-RT28:** These represent the two particular phase change materials (PCMs) utilized in this research. RT-21 melts at 21 degrees Celsius, while RT-28 melts at 28 degrees Celsius.
- **PV Cell Temperature:** This refers to the temperature of the cells within the photovoltaic module.
- **Conventional PV Module:** This is an ordinary photovoltaic module that does not incorporate PCM technology.
- **Liquid Fraction:** This indicates the proportion of the PCM that is liquid at any specific moment.

Energy performance comparison of conventional PV and PV-PCM units

In this part, we assess the energy efficiency of a traditional photovoltaic (PV) module in relation to two PV-PCM units: PV-RT21 and PV-RT28.

Temperature comparison at peak dry season

During the peak dry season, both PV-PCM systems maintain lower temperatures for PV cells compared to traditional PV panels. In particular, the PV-RT28 consistently keeps cell temperatures lower throughout the day, with a notable peak difference of 20°C detected at midday.

From 6:00 AM until approximately 10:00 AM, the PV-RT21 records the lowest cell temperatures. Yet, as the phase change material (PCM) completely liquefies, there is a sharp increase in temperature, although the highest cell temperature stays approximately 8.0°C cooler than that of the standard PV module.

It is important to mention that later in the afternoon, the cooling effectiveness of the PV cells within the PV-PCM systems declines. At this period, the cell temperatures of the PV-PCM systems exceed those of the traditional PV module.

Liquefaction rates of PCMs

By midday, the PV-RT21 has entirely liquefied. Conversely, the PV-RT28, which has a melting temperature ranging from 27 to 29°C, exhibits a liquid fraction of 49.3%. Consequently, the RT28 is capable of absorbing heat throughout the day, ultimately reaching a liquid fraction of 93.8% by 4:30 PM.

Nighttime solidification

The PV-RT28 does not solidify completely overnight, recording a liquid fraction of 40.6% at 4:30 AM. On the other hand, the PV-RT21 solidifies fully during the night, attaining a liquid fraction of 0% at 4:30 AM, thus making all of its heat of fusion available during the daytime.

Temperature comparison at seasonal changes

Throughout the rainy season and harmattan period, the two PV-PCM systems maintain lower cell temperatures compared to the traditional PV unit for most of the daylight hours. However, their cooling effectiveness is diminished, particularly in the case of the PV-RT28, due to its higher melting temperature, which slows the process of transitioning from liquid to solid under seasonal weather conditions. In the late afternoon, the conventional PV module exhibits lower cell temperatures than the two PV-PCM systems. However, this disadvantage is less impactful regarding energy output since solar radiation is weak during that time.

In the harmattan period, there are minimal differences among the three PV setups. The cell temperatures consistently stay below 30°C throughout the day, preventing the PV-RT28 from melting. The cell temperatures for the PV-RT21 hover around 28°C, nearing its melting threshold. Once more, the temperatures for the two PV-PCM systems are higher than those of the traditional PV module. This trend is attributed to the thermal insulation properties of the PCM layer, which hinders the cooling of the PV cells. Therefore, during the harmattan period, integrating the PCM does not significantly enhance the energy output of the PV module.

Electrical efficiency and power production

In both the height of the dry season and the rainy season, the two PV-PCM systems outperform the standard PV module in terms of efficiency and power generation. The electrical efficiencies for the PV-PCM units remain above 16% during the day, approaching the performance seen under standard test conditions.

During the rainy season, the performance of the two PV-PCM units is quite comparable, with a slight advantage for the PV-RT21 unit. Nevertheless, in the peak dry season, the PV-RT21 records its lowest efficiency in the afternoon since it has completely melted and is unable to hold any extra heat. A similar pattern is seen in the power output, which is closely linked to electrical efficiency.

At noon in the peak dry season, the PV-RT28 sees an increase in power production of roughly 10.00 W/m^2, representing a 10.0% boost over the conventional PV module. Likewise, at noon during the rainy season, the PV-PCM units experience a maximum increase in power production of approximately 9.1% for RT21 and 7.5% for RT28 when compared to the conventional PV module.

Throughout the harmattan season, the three PV modules do not exhibit any notable differences in either electrical efficiency or power output.

Daily electrical yields

During the harmattan season, all three PV-module setups yield identical electrical outputs. In contrast, during both the rainy and peak dry seasons, the two PV-PCM units produce more energy than the standard PV module.

The PV-RT21 and PV-RT28 units, respectively, deliver 4.6% and 5.6% additional power during the peak dry season when set against the conventional PV module.

Performance and cost-effectiveness comparison: PCM cooling vs. active and passive cooling methods

To improve the efficiency of photovoltaic (PV) panels, managing heat levels is crucial to counteract the negative impacts of elevated temperatures. This evaluation emphasizes the effectiveness and economic viability of phase change material (PCM) cooling in comparison with both active and passive cooling techniques.

PCM cooling performance

- **Temperature Management:** PCM cooling assists in managing the temperature of PV panels by capturing excess warmth during daylight hours and releasing it when it cools at night. For example, the application of RT-21 and RT-28 PCMs in the climate of the Niger Delta has resulted in a notable decrease in cell temperatures, keeping them below critical limits even during the hottest times.
- **Enhancement of Efficiency:** The introduction of PCM can result in higher PV efficiency. Research suggests that the proper choice of PCM can lower panel temperature by around 39%, leading to an approximate 6% improvement in efficiency and a 16% increase in electrical output.
- **Consistent Long-Term Stability:** PCMs like RT-21 and RT-28 deliver reliable thermal performance over extended periods, ensuring dependable cooling effects without requiring frequent upkeep.

PCM cost-effectiveness

- **Upfront Costs:** PCM cooling systems entail a moderate initial investment that covers the PCM material and its integration with PV panels.
- **Upkeep Expenses:** Generally, PCM systems demand low maintenance costs owing to their passive design, which does not require external power or mechanical components.
- **Cost Savings on Energy:** Through enhanced efficiency of PV panels, PCM cooling facilitates increased energy output and potential reductions in energy expenses.

Active Cooling Performance

- **Temperature Regulation:** Active cooling techniques, including liquid and air cooling systems, offer accurate temperature regulation and can swiftly adjust to temperature changes.
- **Efficiency Increases:** Active cooling is often more efficient than passive methods in significantly lowering PV panel temperatures, thereby leading to immediate gains in efficiency.

Active cooling cost-effectiveness

- **Initial Expenses:** Active cooling setups usually involve higher initial costs due to the necessity for additional devices like pumps, fans, and control systems.
- **Operational Expenses:** These setups incur recurring operational costs, which include the energy required for the cooling systems to function along with routine maintenance to keep them operational.
- **Long-Term Financial Impact:** Although active cooling can lead to considerable efficiency enhancements, the ongoing operational and maintenance costs can be significant, potentially negating the energy savings over time.

Passive cooling performance

- **Heat Reduction:** Passive cooling approaches, such as heat sinks, fins, and natural convection, are crafted to facilitate natural heat dissipation from PV panels.
- **Efficiency Gains:** While passive techniques may not be as effective as active cooling, they still yield modest increases in PV efficiency through temperature reduction.

Passive cooling cost-effectiveness

- **Upfront Costs:** Passive cooling installations are relatively inexpensive initially since they primarily depend on physical modifications to the PV panels without needing extra mechanical parts.
- **Maintenance Expenses:** Minimal maintenance is needed for these systems since they do not have moving components or energy requirements.
- **Energy Cost Savings:** Although the efficiency improvements from passive cooling are usually lower than those from active systems, the overall cost-effectiveness is superior due to reduced ongoing and maintenance costs.

Performance comparison between PCMs, active and passive cooling system

PCM Cooling presents a well-rounded method, delivering notable temperature management and improvements in efficiency with minimal upkeep needed.

Active Cooling achieves the best results for rapid temperature adjustments and efficiency boosts, but it entails higher running and maintenance costs.

Passive Cooling yields moderate efficiency enhancements with the least expense and maintenance required, rendering it a budget-friendly choice for gradual performance enhancements.

Cost-effectiveness comparison between PCMs, passive and active cooling system

PCM Cooling stands out as a financially savvy option, owing to its reasonable initial outlay, minimal upkeep, and considerable long-term savings on energy.

Active Cooling is not as financially viable due to its substantial upfront and operational costs, even though it offers enhanced performance.

Passive Cooling ranks as the most budget-friendly in terms of startup and ongoing costs, albeit with more limited improvements in performance.

In conclusion, PCM cooling in the climate of the Niger Delta is a remarkably effective and economical strategy to boost the performance of PV panels, striking a better balance between initial costs and long-term advantages compared to active cooling solutions, while outperforming passive cooling options.

Conclusion

To summarize, cooling systems that utilize PCM provide a viable, effective, and economical approach to improving the efficiency of photovoltaic panels. By keeping temperatures at ideal levels, these systems enhance energy output and also aid in extending the lifespan and dependability of solar power setups. The advantages seen in the Niger Delta area highlight the capacity of PCM cooling to revolutionize solar energy production in analogous environments across the globe. Ongoing investigation, supportive policies, and integration within the industry can ensure that PCM cooling significantly contributes to achieving international renewable energy objectives.

Bibliography

1. Agrawal B and Tiwari GN. “Optimizing the energy and exergy of building integrated photovoltaic thermal (BIPVT) systems under cold climatic conditions”. *Applied Energy* 87.2 (2010): 417-426.

2. Ahmad MS., *et al*. “Advancements in the development of TiO2 photoanodes and its fabrication methods for dye sensitized solar cell (DSSC) applications: A review”. *Renewable and Sustainable Energy Reviews* 77 (2017): 1006-1023.

3. Al-Waeli AHA., *et al*. “Evaluation of the nanofluid and nano-PCM based photovoltaic thermal (PVT) system: An experimental study”. *Energy Conversion and Management* 151 (2017): 212-228.