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Article

Solar Powered Refrigeration with Integrated Phase Change Materials (PCMs)

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Abstract: Solar PV systems provide clean and renewable energy but face challenges related to intermittent power availability, particularly during low sunlight periods. Phase change materials (PCMs) mitigate this limitation by offering thermal energy storage, ensuring consistent refrigeration performance despite solar power fluctuations. However, the implementation of these systems at a real-world scale, particularly in weak/off-grid settings of rural areas, remains underexplored. This literature review aims to identify the reasons behind the slow implementation of PCM-assisted solar PV refrigeration systems by examining existing gaps in solar-powered fridge systems, fridge systems with PCMs, numerical modeling, and real-scale applications. Drawing from the literature on material availability and optimization, we propose a low-cost PCM formulation comprising glycerine, water, and alcohol mixtures as a practical solution for freezing compartments in solar-assisted refrigeration systems tailored for off-grid applications. By reviewing material optimization, system design, and real-world applicability, this literature review establishes a foundation for advancing energy-efficient and sustainable cooling technologies, improving refrigeration access especially in rural and underserved communities.

Keywords: solar powered refrigeration; phase change materials (PCMs); computational fluid dynamics (CFD); PCM storage

1. Introduction

Solar photovoltaic (PV) technology has rapidly evolved in recent decades and has become a critical part of the global transition towards renewable energy. As a clean and sustainable energy source, PV systems offer significant advantages in reducing carbon emissions and dependency on fossil fuels (Gielen et al., 2019). Solar PV applications are diverse, ranging from power generation for residential use to large-scale industrial applications. Their ability to harness solar energy directly and convert it into electricity has positioned PV technology as a crucial driver in the global energy conservation movement (Kabir et al., 2018). One of the major areas of energy consumption globally is refrigeration, which is essential for food preservation, medical applications, and industrial processes. However, traditional refrigeration systems are known to consume substantial amounts of electricity, contributing significantly to energy demand and consequently, to greenhouse gas (GHG) emissions. The energy-intensive nature of these systems has prompted researchers to explore sustainable solutions that can mitigate their environmental impact. To address this issue, researchers are exploring sustainable solutions like integrating solar PV systems into refrigeration processes. This approach uses renewable energy to power cooling systems, reducing their environmental impact (Khosla et al., 2021).

The integration of solar PV with conventional refrigeration systems offers a dual advantage: the reduction of grid dependency and a decrease in GHG emissions. By utilizing solar energy to power refrigeration units, especially in regions with high solar irradiance, this approach offers the potential for both economic and environmental benefits. Despite these advantages, there are notable challenges associated with such integration, primarily due to the intermittent nature of solar energy and the fluctuating power demands of refrigeration units (Saha & Azad, 2024). This is where phase change materials (PCMs) play a pivotal role. PCMs can store thermal energy during the day, when solar irradiance is high, and release it when energy demand peaks or when solar power generation decreases (Jarimi et al., 2024). The combination of PCMs with solar PV-assisted refrigeration systems can significantly enhance energy efficiency by providing a continuous supply of cooling, even when solar energy is not available. The latent heat storage capability of PCMs helps in stabilizing temperature fluctuations, improving the overall performance of refrigeration systems (Riffat et al., 2021a).

This paper offers a comprehensive review of the current research and developments in solar photovoltaic (PV)-assisted refrigeration systems integrated with phase change material (PCM) storage. We first review advancements in solar PV technology and its applications within refrigeration systems. The discussion is followed by a detailed discussion on the role of PCMs in improving the energy efficiency of these systems, highlighting key findings from recent studies. The methodology for conducting numerical modelling using computational fluid dynamics (CFD) simulations and performance analysis of solar PV refrigeration systems with PCM storage is then outlined in the literature. Comparative results on the thermal performance and efficiency of various system configurations are presented, offering insights into the available technologies. We then finally discuss the potential of low-cost PCM materials suitable for the solar powered refrigerator integrated with PCM storage. The paper concludes by discussing the implications of these findings for future research and potential real-world applications, along with recommendations for further investigations in this field of research.

2. Literature Review

2.1. Solar Powered Vapor Compression Refrigeration Systems

The integration of solar photovoltaic (PV) systems with traditional vapor compression refrigeration systems represents a significant advancement in enhancing energy efficiency and sustainability across various applications. The use of solar PV systems to power a refrigeration system highlights the use of renewable solar energy, thereby reducing reliance on traditional energy sources. Also, by using solar energy, these systems aim to significantly reduce dependency on the electrical grid and lower greenhouse gas emissions. This approach is particularly beneficial in regions with abundant solar resources, where refrigeration is critical for food preservation, medical storage, and various industrial processes. Furthermore, solar-powered vapor compression refrigeration systems also offer a clean approach in addressing the high energy consumption typically associated with refrigeration, especially in off-grid and remote areas. As summarised in Table 1, a number of studies have been explored by researchers to explore the integration of solar PV with vapor compression systems. However, most studies only focus on lab-scale implementation of technology with very little discussion has been done on the technological needs and design of the system in meeting specific application in rural areas.

Table 1. A summary of studies on solar powered vapour compression refrigeration system.

Ref	Description	Research Gap
(Jaddoa, 2024)	Testing under temperatures of 25 °C, 28 °C, 31 °C, 34 °C in controlled room conditions.	The research focusing mainly on the PV performance rather than the relationship between the solar PV panels and the performance of the refrigerator in detail
(Yusof, Kassim and Wan Shuhaimi, 2022)	Testing battery performance and load for 2 hours with temperature control at 16 °C.	Further testing on long-term battery durability and system portability should be investigated.
(Al-Dabbas, 2021)	Two sets of experimental tests: Vapor compression fridge and hybrid solar compression fridge.	Expanding the system to other regions with harsher climates and improving the hybrid integration.

2.2. Investigations of Refrigeration System with PCM Storage

Phase change materials (PCMs) as thermal energy storage systems have attracted significant attention in various applications. By taking advantage of the phase change temperature of these materials, heat can be stored and released at the desired temperature, depending on the application and the selection of a suitable PCM. As a result, temperature or thermal regulation in building services and industrial processes is made possible. In addition, PCM storage can be utilized to store intermittent renewable energy sources in the form of thermal, be it at low to medium to high temperature- ensuring the efficient application of solar energy (Kalidasan & Pandey, 2025). With the focus of PCM utilization in refrigeration systems, it has attracted significant attention due to their ability to store and release large amounts of thermal energy during phase transitions. PCMs were found can be strategically integrated into refrigeration systems to maintain stable temperatures, even when power input is disrupted or fluctuating (Riffat et al., 2021a). This characteristic makes them particularly useful in off-grid applications or in environments with unreliable electricity supply, where maintaining consistent cooling is critical for preserving food, vaccines, and other temperature-sensitive products.

Several studies have been summarised in Table 2 focusing on optimizing the integration of PCMs in refrigeration systems. Elarem et al., (2017) for instance conducted a detailed investigation into the integration of PCMs in the heat exchangers of household refrigerators. Their work utilized 2D unsteady CFD simulations to model the behavior of the system with different PCM configurations. The study found that the integration of PCMs could reduce power consumption by 12% and improve temperature stability by 86.66%, effectively stabilizing the internal temperature of the refrigerator for extended periods without requiring additional power. However, the researchers noted that increasing PCM coverage beyond 75% did not result in additional benefits, suggesting a diminishing return on PCM integration once a certain threshold is reached. This finding underscores the need for further optimization of PCM placement within the refrigeration system, ensuring that the material is utilized efficiently.

Riffat et al., (2021b, 2022) focusing on PCM-enhanced refrigeration systems in weak-grid and off-grid locations. Their study combined lab and field testing to assess the performance of these systems under real-world conditions. The PCM-enhanced fridges tested in the field were able to maintain internal temperatures between 7 °C and 11 °C during a 5-hour power outage, demonstrating their potential as a reliable solution for areas with unstable power supplies. However, the researchers also identified areas for improvement, particularly in the design of the condenser, which was shown to influence the transient power consumption of the system. Modifications to the condenser reduced power consumption by 26%, highlighting the importance of optimizing both the PCM integration and the overall system architecture for maximum efficiency.

Another innovative approach to PCM integration was explored by Abuelnour et al., (2024), who investigated the use of a saltwater PCM solution in a solar-powered refrigeration system for scorpion antivenom storage. Their study aimed to develop a system capable of maintaining low temperatures in harsh, remote environments where reliable electricity is scarce. The results showed that the system could maintain a consistent temperature of 4 °C during power outages, ensuring the safe storage of the antivenom. However, the research also pointed to the need for further optimization of the salt concentration in the PCM solution to improve its thermal retention capacity. Future research in this area could explore alternative PCM compositions and configurations to enhance the thermal performance of these systems.

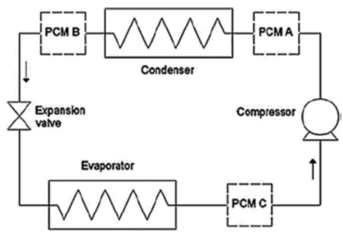
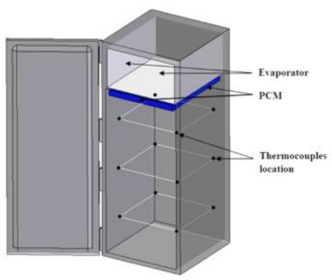
Literature indicates that PCMs have been widely integrated with solar-powered refrigeration systems. However, much of the research to date has focused primarily on laboratory applications, with very little attention given to justifying the proposed technology, such as the social reasoning and implications of its installation. While experimental, lab-scale research is valuable, its principal limitation is that, in practice, the system will be significantly impacted by the intermittent nature of solar energy. Hence, a case study is considered essential to bridge the gap between theoretical research and real-world applications.

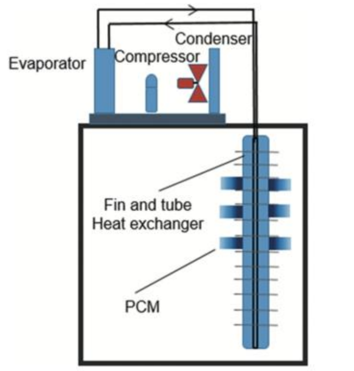
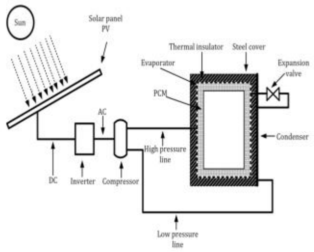
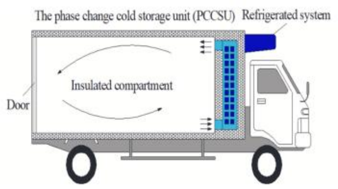
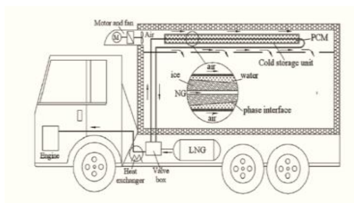
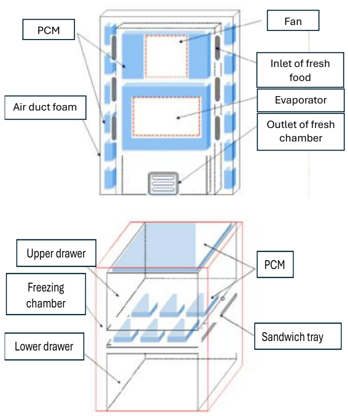
2.3. Numerical Studies in Refrigeration System with PCMs

Numerical modeling has emerged as a crucial tool in understanding and optimizing the integration of PCMs into refrigeration systems. By simulating the thermodynamic interactions within these systems, researchers can test different configurations, materials, and operational conditions without the need for extensive physical testing. Computational Fluid Dynamics (CFD) simulations are particularly useful in this regard, as they allow for a detailed analysis of heat transfer processes and energy consumption patterns within the system. One of the key studies in this area was conducted by Elarem et al., (2017) who used a 2D CFD simulation to examine the effects of PCM placement within a household refrigerator. The simulation focused on how PCM emplacement could reduce power consumption and stabilize internal temperatures. The results showed that PCM emplacement could reduce power consumption by 12% and significantly stabilize temperature fluctuations, particularly during periods of power disruption. However, the study also highlighted several research gaps, particularly the need for more real-world testing to validate the simulation results under varying environmental conditions. While the CFD model provided valuable insights, the researchers emphasized that real-world factors such as ambient temperature fluctuations, frequent door openings, and varying cooling loads need to be accounted for in future studies. O. Ghahramani et al. (2018) took a similar approach by conducting a numerical study on the effect of different PCM volumes on cold storage systems. Their simulations tested various PCM thicknesses, ranging from 0.5 cm to 6 cm, to determine the optimal balance between energy storage capacity and space limitations. The study concluded that a 3 cm PCM thickness offered the best balance, providing sufficient energy storage without occupying excessive space. However, like Elarem et al., (2017) Ghahramani's study highlighted the need for further real-world testing to validate the numerical results. The researchers pointed out that factors such as door opening cycles and ambient temperature fluctuations were not accounted for in the simulation, which could significantly impact the performance of the system in practical applications.

Pavithran et al., (2020) also contributed to this body of research by conducting CFD simulations of various PCM configurations within refrigerators. Their study focused on how different PCM placements (horizontal vs. vertical) affected the thermal stability and compressor run time of the refrigeration system. The results indicated that horizontal PCM placement provided better thermal stability than vertical placement, leading to reduced compressor run time and improved energy efficiency. Despite these positive findings, the study called for further research into combining different PCM placements to maximize the system's overall effectiveness. In particular, the researchers suggested that integrating PCM into multiple locations within the refrigeration system (such as the evaporator, condenser, and storage compartments) could offer additional benefits in terms of energy savings and temperature stability.

Table 2. A summary of studies on solar powered vapour compression refrigeration system.

Ref.	Experimental Setup	Research Gap	Design/Setup
(Karthikeyan et al., 2021)	Tested with no PCM, with PCM in different configurations (freezer, fridge, and condenser).	The long-term durability of PCMs in different configurations (freezer, fridge, condenser) and their impact on refrigerant flow are not deeply analyzed. Investigating the effect of PCM degradation over time is needed.	
(Deshmukh, Deshmukh and Chavhan, 2022)	Experimental analysis using low-temperature PCMs with nanoparticle additives in a VCC setup.	The study lacks experimental validation for combining two thermal enhancement techniques (LSHX and PCM) in VCC refrigerators. Further analysis needed on dual enhancement in different VCC setups.	
(Berdja, Hamid and Sari, 2019)	Theoretical and experimental tests on a conventional refrigerator with PCM and frost effects.	More research needed on frost mitigation techniques in PCM-enhanced refrigerators. The impact of frost on PCM performance needs in-depth investigation across various climates.	

(Riffat et al., 2021a, 2022)	Lab and field tests in the UK and Ghana, analyzing power consumption and PCM's impact on performance.	Further research needed to improve PCM performance in off-grid, low-power infrastructure. Long-term durability under power-limited conditions and optimal PCM integration for cost-effective cooling systems require attention.	
(Abuelnour, Abuelnuor and El-Kawi, 2024)	Tested under solar-powered conditions for scorpion antivenom storage in extreme climates.	More work required to optimize salt concentrations in PCM for maximum heat absorption and performance in solar-powered refrigeration systems, especially for medical storage. The interaction between PCM and varying solar radiation levels should be explored further.	
(Liu et al., 2022)	Experimental study on the integration of PCM in refrigerated vehicles under various temperature conditions.	Further exploration needed for PCM application under extreme conditions during transport.	
(Pahamli and Valipour, 2021)	Experimental analysis of different PCM types and container designs in refrigeration systems.	Further research needed on enhancing thermal conductivity and reducing costs of PCM systems.	
(Liu et al., 2017)	Tested under off-peak refrigeration mode with PCM and conventional refrigeration systems.	PCM placement optimization needed for better energy savings and thermal performance.	
(Purohit and Dasgupt	Experimental tests on different PCM materials and placements in	Research needed on retrofitting existing cabinets with PCM and	N/A

a, 2019)	refrigerated cabinets.	commercial viability.	

2.4. Real application of Solar PV Powered Fridge with PCM Storage

The real-world application of solar PV-powered refrigeration systems with PCM storage has proven to be a promising solution for off-grid and remote areas where reliable electricity is often unavailable. These systems highlight solar energy to power refrigeration units while using PCMs to store excess thermal energy, ensuring continuous cooling even during periods of low solar irradiance or at night. Such systems are particularly valuable for preserving food, vaccines, and other temperature-sensitive goods in regions with limited infrastructure. From the review by Mehling, (2023), while these real-world applications demonstrate the feasibility of using solar PV and PCM technologies in refrigeration and food preservation systems, further improvements are needed. The scalability of these systems, their long-term reliability, and their ability to maintain consistent performance under different climatic conditions remain areas that require further investigation. Ensuring that the PCM materials used in these applications can withstand the stresses of repeated thermal cycling without degradation is another critical area of focus for researchers and developers. Summarised from the paper is the list of studies focused on the implementation of the technology for real applications-see Table 3.

Table 3. A summary of studies on solar powered vapour compression refrigeration system.

Application	Key Features	Reference
Milk Cool-Down	Ice storage integrated with PV-powered coolers, absorption chillers	(Flammini et al., 2018; Al-Shannaq, Auckaili and Farid, 2022)
Solar Cooking	Solar thermal cookers with PCM thermal energy storage integrated into cooking systems	(Gorjian et al., 2022)
Beverage Cooling	Ice or PCM used for cooling without mixing with the beverage, large-scale coolers for commercial use	(Erdemir, Altuntop and Çengel, 2021)
Cold Storage for Frozen Food	Macro-encapsulated PCM for efficient cold storage in frozen food distribution facilities	(Cameron Murray, 2022)
Solar Freezer/Pre-Cooler	Off-grid, mobile solar-powered freezer, portable design with high cooling capacity	(Zafer Ure, 2022)

2.5. Summary of Literature

One of the key research gaps is in the selection of PCM materials. Many of the current studies, such as those by (Elarem et al., 2017; Pavithran, Sharma and Shukla, 2020) focus on traditional PCM materials like paraffin wax and salt hydrates. While these materials are effective at storing thermal energy, they have limitations in terms of thermal conductivity and long-term stability. Future research should explore the development of advanced PCM materials using locally available materials, with higher thermal conductivity, improved phase transition properties, and greater resistance to degradation over time. This would enhance the performance of PCM-enhanced systems and extend their operational life, particularly in off-grid and rural settings where system maintenance may not be readily available.

Another key gap is the real-world validation of numerical models. Studies like those by Ghahramani Zarajabad & Ahmadi, (2018) have produced valuable insights through CFD simulations, but these models often fail to account for the complex environmental factors that can affect system performance in practice. For example, frequent door openings in refrigeration systems can cause significant temperature fluctuations that are not always captured in simulations. Similarly, the impact of ambient temperature variations and direct sunlight exposure on solar PV performance requires further study in real-world environments. More extensive field testing is needed to validate these models and ensure that the systems perform reliably under a wide range of conditions.

The integration of hybrid systems that combine solar PV with traditional grid power also represents an area with significant research potential. Existing studies mainly focusing solely on off-grid systems, but hybrid systems could provide a more flexible and reliable solution in areas with intermittent grid power. These systems could use solar energy during the day and switch to grid power during periods of low sunlight, ensuring continuous operation without relying entirely on solar energy. Further research is needed to explore the technical and economic feasibility of hybrid solar-grid refrigeration systems, particularly in urban and semi-urban areas.

Another area of focus is the durability of PCM materials in real-world conditions. Repeated thermal cycling can cause PCM materials to degrade over time, reducing their effectiveness at storing and releasing thermal energy. Future studies should investigate the long-term performance of different PCM formulations in diverse climatic conditions to ensure that they can withstand the stresses of repeated use without significant degradation. This is particularly important for applications like cold storage rooms and medical refrigeration systems, where maintaining consistent temperatures is critical. Finally, cost-effectiveness remains a significant challenge in the widespread adoption of solar-powered refrigeration systems with PCM storage. While these systems offer clear environmental benefits, their initial cost can be prohibitive, particularly for users in developing regions. Future research then should focus on developing financing models that make these systems more accessible to small-scale users, such as farmers and rural healthcare providers.

3. Investigation into Suitable Phase Change Materials for Solar Powered Freezer

3.1. Methodology

Research in materials selection and synthesis is crucial for advancing sustainable refrigeration systems, as emphasized in the literature. Our study evaluates PCM blends made from glycerine, alcohol, and water, selected for their freeze-resistant properties, flexibility at low temperatures, and ability to optimize thermal storage. By referring to the work of Jarimi et al. (2024) as detailed in Table 4, six formulations were developed with glycerine concentrations ranging from 10–30%, alcohol from 5–10%, and water making up the remainder. These variations were analyzed to determine their melting temperatures and cooling performance. To ensure insulation and structural integrity, the solutions were sealed in bubble wrap, as shown in Figure 1, which prevented leakage during temperature fluctuations. Subsequent testing assessed freezing points, phase change rates, and overall consistency in temperature. In this study, we selected glycerine for its antifreeze properties, low toxicity, and flexibility at sub-zero temperatures, while alcohol improved thermal conductivity and further lowered the freezing point. Meanwhile, water served as the base material due to its high latent heat capacity and natural abundance. To further justify the selection of these materials, a comparison with alternative PCMs, such as paraffin wax and hydrated salts, was conducted. Paraffin wax is limited by poor thermal conductivity and flammability, while hydrated salts often experience supercooling and phase instability. This analysis highlights the superior advantages of the glycerine-alcohol-water blend, justifying its suitability for sustainable refrigeration applications.

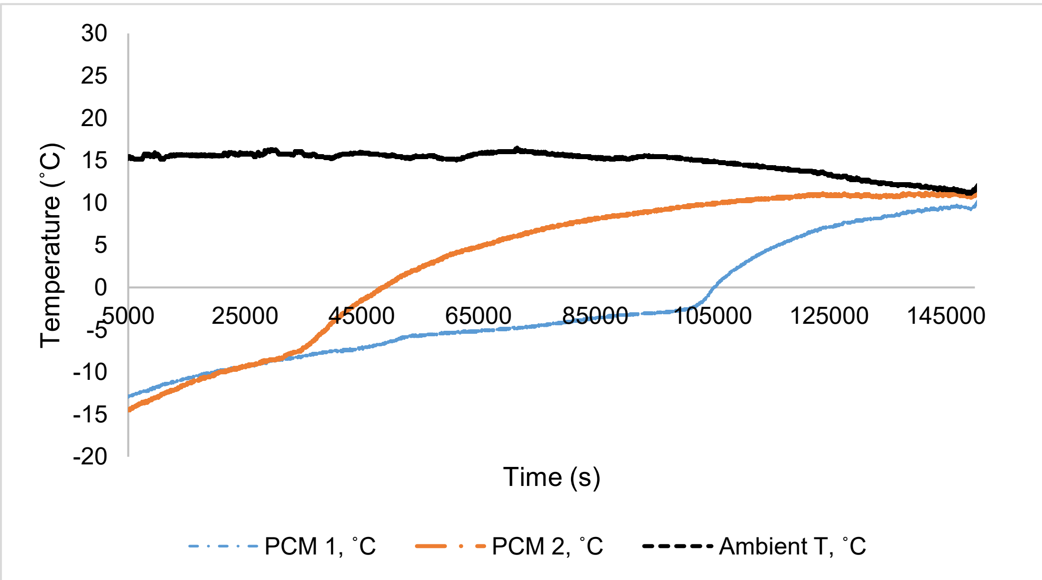
Table 4. The mixture of the PCM materials.

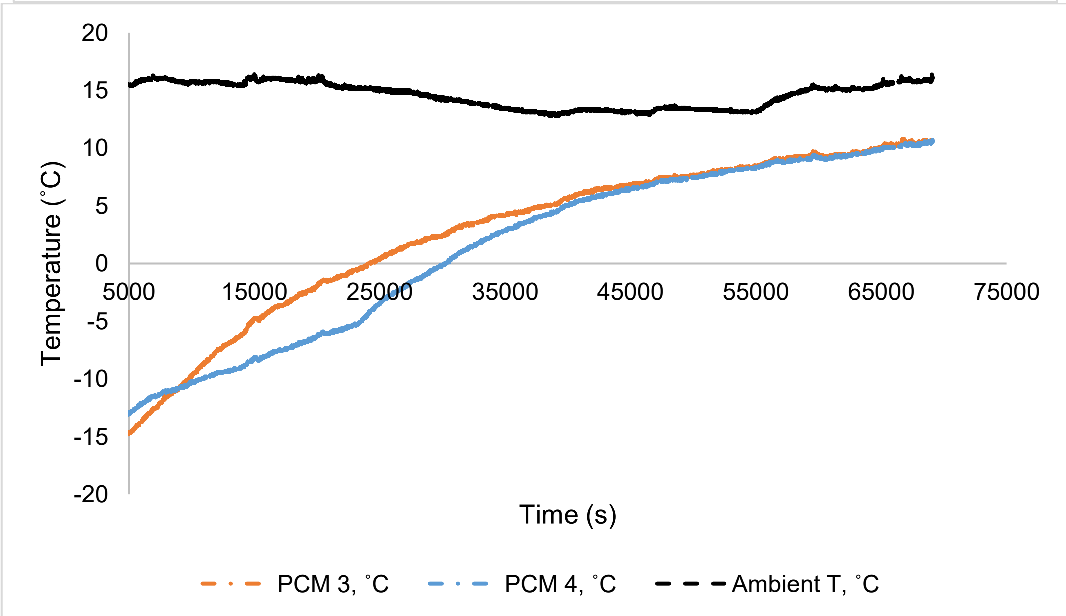
	Glycerin, %	**Alcohol, %**	**Water, %**
PCM 1	10	5	85
PCM 2	20	5	75
PCM 3	30	5	65
PCM 4	10	10	80
PCM 5	20	10	70
PCM 6	30	10	60

Figure 1. The synthesised PCMs packed in bubble wrap.

3.2. Results and Discussions

Our objective was to determine the melting temperatures for these different PCM Ice Pack mixtures to understand how these variations would influence their thermal performance. In understanding the performance, we have presented the temperature trend of the PCMs. The temperature profiles of PCM 1 and PCM 2, as depicted in Figure 2, exhibit distinct inflection points indicative of the onset of melting. This critical point, with respected to the well-established melting temperature of water at 0 °C, is where the PCMs transition from a solid state to a phase equilibrium of solid and liquid. PCM 1, composed of 10% glycerine, 5% alcohol, and 85% water, displayed a melting point at approximately −2.7 °C. In contrast, PCM 2, with 20% glycerine, displayed a lower melting point of approximately −8 °C, suggesting that increased glycerine concentration correlates with a decrease in the melting temperature of the PCM blend. As shown in Figures 2(b) PCM 3, which contains 30% glycerine, displayed a melting point at approximately −15 °C. This suggests that a higher proportion of glycerine contributes to a lower melting point, which can be beneficial for applications requiring maintenance of sub-zero temperatures. In contrast, by adjusting the alcohol percentage to 10% and retaining glycerine at 10%, PCM 4 exhibited a melting point of approximately −5.5 °C. Similarly, as illustrated in Figure 2(c) PCM 5 with 20% glycerine and 10% alcohol shows a melting point of around −12.7 °C. PCM 6, with the highest glycerine content at 30%, reaches its phase change at approximately −17 °C, marking the lowest melting point among the tested sample.





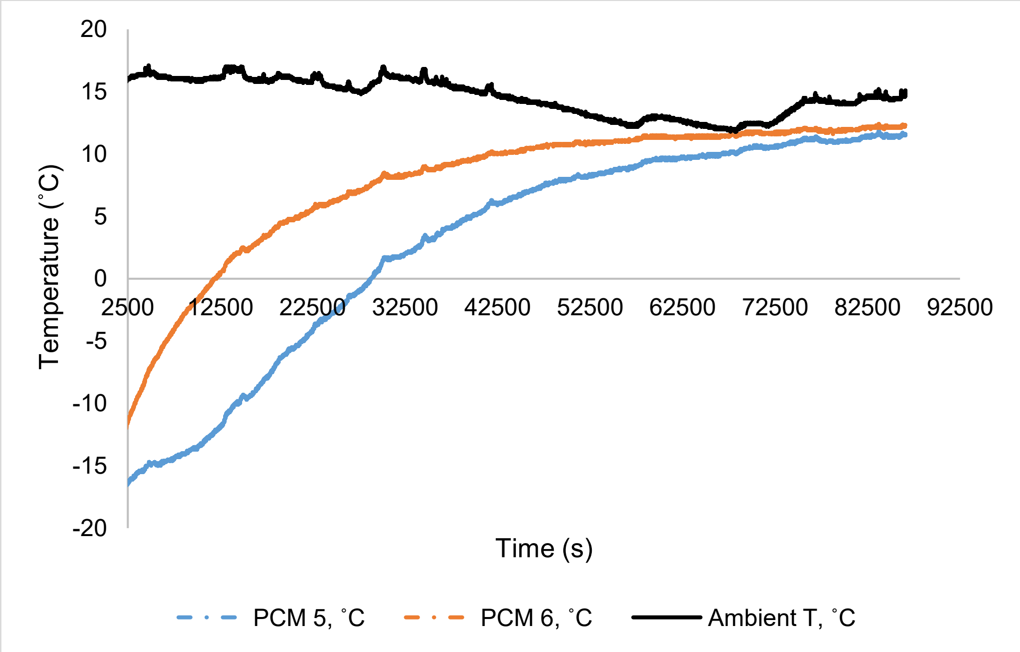


Figure 2. PCM ice pack 1-6 temperature changes with time.

Figure 3 illustrates a comparative analysis of the melting temperatures for the synthesised PCM Ice Packs namely PCM1-5 respectively. The graph elucidates the relationship between the concentration of glycerine and alcohol in the mixture and the resultant melting points. It is evident that for a constant alcohol concentration, an increase in glycerine content from 10% to 30% inversely correlates with the melting temperature. Specifically, PCM Ice Packs with 10% glycerine exhibit a melting point of −2.7 °C, whereas those with 30% glycerine have a significantly lower melting point of −15 °C. Conversely, when the glycerine concentration is held steady, an increase in alcohol percentage leads to a reduction in the melting point. For instance, PCM Ice Packs with 10% glycerine and 5% alcohol have a melting point of −2.7 °C, whereas an increase in alcohol to 10% decreases the melting point to −5.5 °C.

Based on the thermal analysis and melting point investigations, we have concluded that PCM Ice Gel with a melting point of −12.7 ℃ as the phase change material for freezing application. This particular PCM formulation was selected due to its suitability for maintaining temperatures that meet with the refrigeration requirements for extended periods, which is especially beneficial for the thermal management.

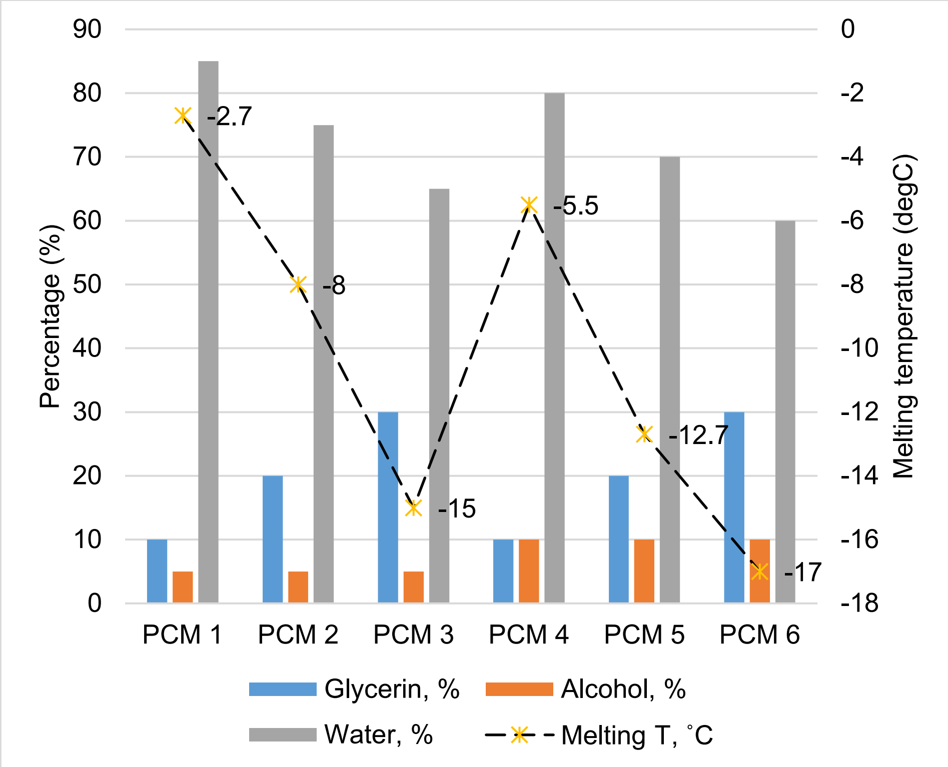


Figure 3. Six PCM Ice Packs melting temperature comparison.

4. Conclusions

The integration of phase change materials (PCMs) with solar photovoltaic (PV) refrigeration systems presents a promising solution for enhancing energy efficiency and sustainability in cooling applications. However, despite significant advancements in this field, notable gaps remain that must be addressed to fully realize the potential of these technologies. This review highlights several critical areas where further research and development are necessary. The key conclusions and identified gaps from this paper are as follows:

i) The first gap is on the practical applicability and geographical context. Due to variability in solar PV system performance, the performance of solar-powered refrigeration systems under laboratory conditions is often overestimated or underestimated. Hence, there is a need to investigate their performance under real-world conditions.

ii) The second research gap is methodological. In rural areas with limited access to electricity, solar-powered refrigeration systems require substantial electrical battery storage and PV panels. PCM packs have been introduced to address this issue; however, limited research has been conducted on the availability of locally sourced materials. Developing advanced materials that can be synthesized using locally available resources presents a promising approach for justifying the adoption of cooling technology in rural areas.

iii) The third gap also relates to theoretical and practical gap, with the literature survey emphasizing the need for more real-world testing to validate simulation results under varying environmental conditions. While computational fluid dynamics (CFD) models provide valuable insights, researchers highlight the importance of accounting for real-world factors such as ambient temperature fluctuations, frequent door openings, and varying cooling loads in future studies.Meanwhile, earlier research on PCM integration in refrigeration systems highlights the benefits of temperature stabilization and energy efficiency but lacks comprehensive optimization of PCM materials for low-cost, practical applications. Additionally, limited investigation has been conducted into the long-term durability of PCMs under repeated thermal cycling.

In this paper, we briefly address these limitations by systematically analyzing the thermal performance of low-cost glycerine-alcohol-water mixtures, providing insights into their suitability for real-world refrigeration systems. Our analysis demonstrates the effectiveness of PCM ice packs in maintaining low temperatures within refrigeration units, showing their significant impact on temperature stability during power outages. The ability of PCMs to remain solid at temperatures above −12.7 °C enables them to function effectively as thermal reservoirs. When powered on, the PCM absorbs excess heat, stabilizing the refrigerator's internal temperature and preventing temperature spikes that could lead to spoilage. During power outages, the PCM releases stored cold energy gradually, maintaining a cooler environment for approximately 10 hours. Conversely, a PCM with a melting point of −5.5 °C is advantageous for applications requiring less extreme cooling. While it maintains temperatures above freezing, it is still effective for items that do not require sub-zero storage, such as beverages and certain food items. This flexibility makes it suitable for maintaining freshness without deeper freezing. Incorporating PCMs with different melting points within the same refrigeration system allows for a tailored cooling approach. For instance, a PCM with a melting point of −12.7 °C can manage freezer temperatures, while a −5.5 °C PCM can support the main refrigeration area. This dual strategy enhances overall energy efficiency by utilizing the thermal properties of each PCM to maximize cooling performance while minimizing energy consumption.

In summary, from the literature, the integration of solar PV and PCM technologies in refrigeration systems holds significant potential for providing sustainable and efficient cooling solutions in rural areas with weak/off-grid settings. However, significant challenges remain, including material optimization, rigorous field testing, exploring hybrid system configurations, enhancing cost-effectiveness, and ensuring long-term durability. Future research should also include socioeconomic studies to guide the implementation of these technologies effectively. Addressing these challenges seen as a starting platform for widespread adoption, advancing energy-efficient cooling systems while promoting sustainable environmental and refrigeration access for people of different locations.

Author Contributions

Jingdan Zhang: writing-original draft and editing, formal analysis and experimental work and analysis, Yanan Zhang: formal analysis, resources, and project administration, Hasila Jarimi: Supervision, funding, review original draft, project administration, James Riffat: review original draft, Ahmad Fazlizan: supervision, resources, project administration, Norasikin Ahmad Ludin: supervision, resources, project administration. Saffa Riffat: Original idea and funding. All authors have read and agreed to the published version of the manuscript.

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